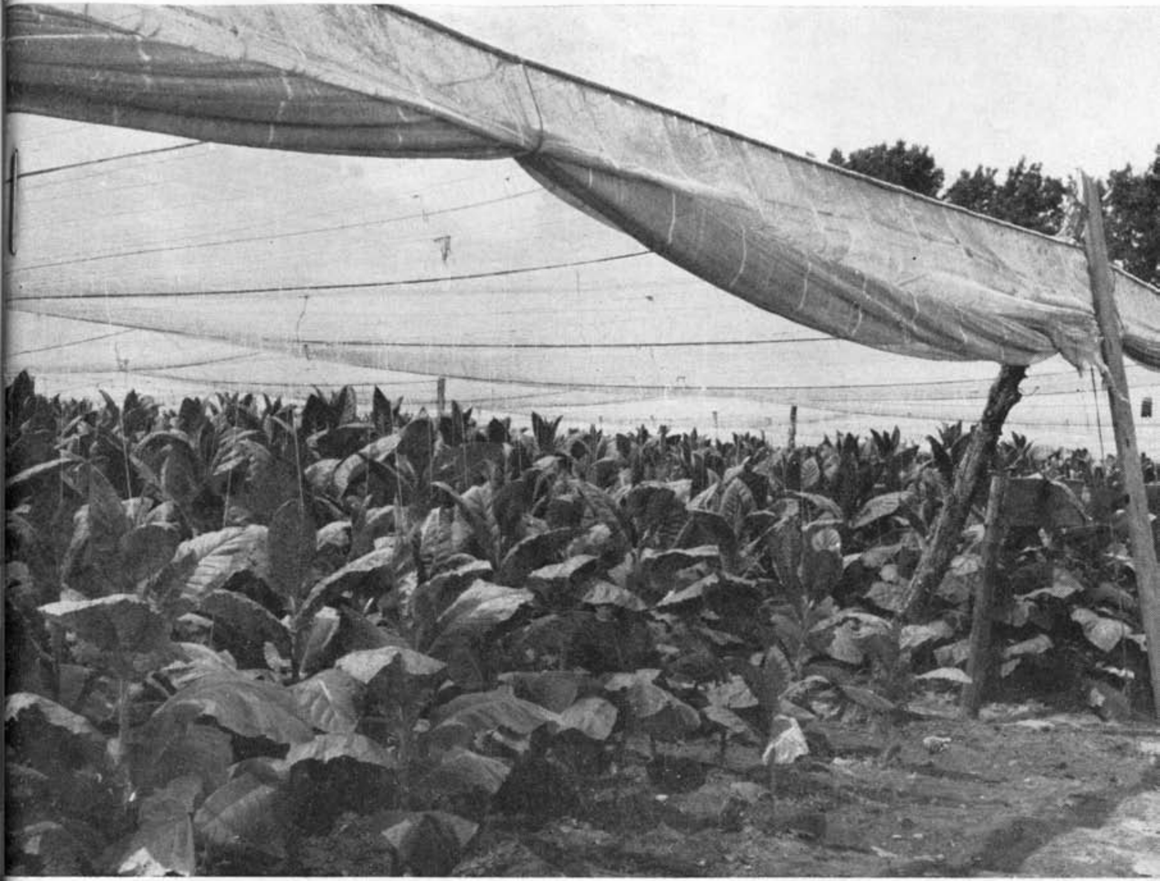

THE CLIMATE OF SHADE

A TOBACCO TENT AND A FOREST STAND COMPARED TO OPEN FIELDS

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THE CLIMATE OF SHADE

A Tobacco Tent and a Forest Stand Compared to Open Fields

Paul E. Waggoner **A. Boyd Pack** **William E. Reifsnyder**

> From the crest of the hill, acres and acres of land, covered with white cloth, stretched as far as the eye could see. A continuous tent, propped up with posts, looked in the glaring sunlight like an endless field of tree stumps in a countryside of snow, rising and falling with the contour of the land — a white ocean, ending at the horizon against the harsh brilliant blue of an unbroken skyline. And in the whole white expanse there was no hint of motion, not of tree or of man. Only the eye moved, following the cloth stretching out over the land.*

White tents of cloth cover eight thousand acres of the Connecticut Valley. Similar tents have been erected each spring for over half a century to produce the precious shade-grown tobacco leaves for wrapping cigars. We have observed the microclimate created by the tents that we may better understand their contribution to the art of growing tobacco. Further, the shade tent provides a simplified model of a leaf canopy that can improve our understanding of the microclimate of the forest.

Before 1801 not more than ten tons of tobacco were grown in Connecticut yearly. This narrow "shoestring" tobacco was mostly shipped to the West Indies in hogsheads, only a little remaining in the State to be made into "long nines" or "Windsor particulars." About 1833 B. P. Barbour of East Windsor brought a Broadleaf strain from Maryland, a tobacco with leaves better suited to cigar manufacture by their shape, texture, and neutral flavor. In the nineties, however, some manufacturers began to import wrapper leaves from Sumatra and Java. These leaves, grown under tropical conditions, were thinner and had smaller veins than the old Connecticut types and gave a smoother appearance to the cigars. The trade was pleased with these cigars and soon Connecticut growers saw the most lucrative part of their market gradually slipping away from them. Only by growing leaves that looked like Sumatra wrappers could they save their market. (Anderson; Jenkins, 1925).

Shade had already been tried in Florida for growing Sumatra tobacco. In Connecticut, tobacco was first grown under shade by The Connecticut Agricultural Experiment Station in 1900. After this trial at Poquonock with the cooperation of a Company of tobacco growers and the U. S. Department of Agriculture, Jenkins could ask "Can wrapper leaf tobacco of the Sumatra type be raised in Connecticut?" and answer "Yes." The opinions of leading men in the tobacco trade had to decide the merit of the shade-grown leaf relative to the leaf imported from the tropics. If the shade-grown leaf met their taste, it was all right; if it did not, it was all wrong. The grower and experimenter had to produce the kind of leaf the trade liked, a Sumatran leaf, however much they might differ in their estimate of what made a good cigar wrapper. The shade tent turned the trick (Jenkins, 1900).

**Parrish*, by Mildred Savage. Copyright 1958 by Simon and Shuster, used by permission.

Tents of cloth or lath provide shelter for other crops. They protect plants from insects, wind, and desiccation; they make shade-loving plants flourish; and they aid in flower production. Jenkins' tobacco merchants tell us that the shade tent makes tobacco "superior to (imported) Sumatra tobacco, both in color, yield, and burn." Compared to Havana Seed, the tent-grown tobacco "is much tougher, thinner, finer grain." "We think the (tent-grown) tobacco is an exact counterpart of the Sumatra grown on the Sumatra Islands." The precise physical and chemical changes wrought by the tent upon the tobacco are still not known, but the tent and the sandy loam of the Connecticut Valley mimicked the tropics to the satisfaction of the tobacco trade.

The tents are covered by "cheese-cloth" sewn to wires. In the first tents, the cloth was supported on beams of wood, but these disappeared long ago, being replaced by wires. The wires are fastened to poles set at the corner of squares one "bent" or about 11 meters on each side. The cloth is supported at a height of eight feet or about 2⅔ meters. The cotton cloth has eight threads per inch one way and ten the other. These threads have a diameter of about 0.6 millimeter and are spaced at intervals of about 2.5 millimeters. Reenforcements or more closely spaced threads are spaced at intervals of 18 inches one way and 14 inches the other way. Alternate coverings have evidently not been studied extensively. The cloth is used only one year on the top of the tent. A portion is doubled and used as sidewall the second year. The sidewalls are sewn to the top wires and extend to the soil where they are sewn to another wire. Doubling the cloth makes it a convenient width and provides a safety factor against the deterioration of the aged cloth. In the commercial tents which cover several acres, the sidewalls make no significant contribution to the light relations.

What were the changes in the environment through which the tent changed the tobacco plant? Jenkins (1900) noticed that the shaded crop was protected from drought. The "shade" of the tent was scarcely evident to the senses, and he opined that close planting probably shaded the leaves more than did the tent. Stewart (1907) made more quantitive observations. Essentially, the soil was more moist and evaporation was less inside the tent than outside. The tent also increased the relative humidity about 10 per cent on most days and the maximum temperature within an instrument shelter about 1°C. Breezes were stilled by the tent and winds slowed. Later, Street (1934, 1935) measured the visible light with a photoelectric cell and found that the tent decreased it 30 to 60 per cent. Reviewing his own results and foreseeing those of later workers, Stewart despaired, "The variables are so many that it is impossible to bring out sharp correlations between the different factors." We shall see if the advances in meteorological theory and instruments will permit a better description of the climate and an understanding of the physics of the shade tent.

The environment beneath a canopy of leaves is similar in many respects to that of the shade tent. We suggest, therefore, that the shade tent is a simplified model of a forest or similar vegetative cover. Major differences, not to be minimized, are that leaves transpire water, absorbing much energy; and the amount of heat stored in vegetative parts is probably not negligible. However, if the analogy is even roughly correct, many problems of the complicated heat and water budget of a forest may be reduced to manageable proportions, both experimentally and analytically.

THE TENTS AND SOIL

A growing crop of a large plant forms an ever-changing pattern of sunlight and shade on the soil and presents a heterogeneous mixture of sunlit and shaded leaves at many angles. The pattern of shade is much less complex in an empty tent; therefore, we first consider the principles of physics operating there, using observations made in 1957 by Waggoner and Reifsnyder. We then estimate the contribution of the crop, employing the light, temperature, and humidity observations of Pack taken in 1946.

The tent of 1957 covered bare soil (Figure 1). It was 4 by 5 bents or about 44 by 55 meters. Air and soil temperatures were measured at two locations, C and D, inside and at two locations, C and D, outside the most southerly wall of the tent. The flow of heat into the soil was measured at the same four locations. Radiation was measured at a single location, E, 8 meters inside and at a single location, E, 9 meters outside the same wall. Wind velocity was measured at sites, F, 16 meters inside and 21 meters outside the tent. Recording hygrothermographs were placed in louvered shelters at G and atmometers were placed at H. A recording potentiometer was located at B, an operations recorder at A.

The observations began on May 28, 1957. The sun shone 89 to 100 per cent of the possible hours on the 28, 29, 30, and 31 of May. On June 1 the

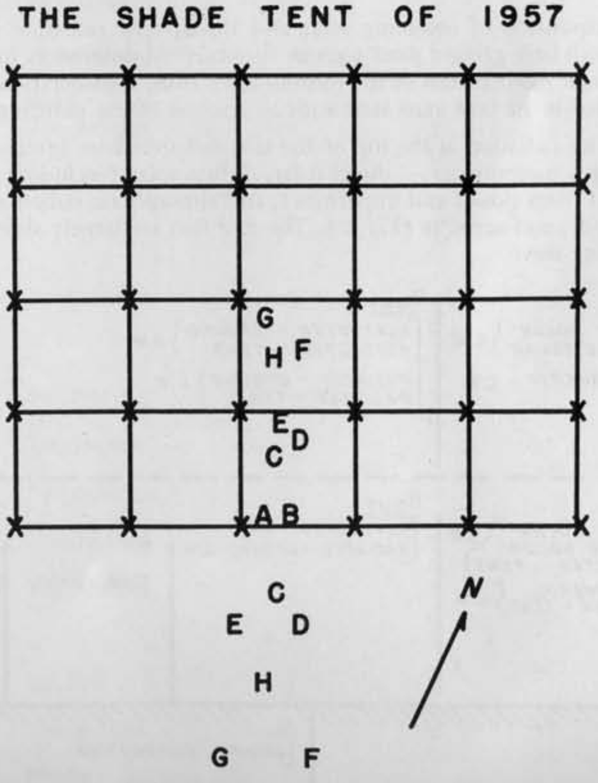

Figure 1. Diagram of the shade tent of 1957 showing approximate placement of measuring devices.

sun shone only 24 per cent of the possible hours. On June 2 the sun shone only 6 per cent of the possible hours and 0.33 cm. or 0.13 inch of rain fell when a cold front passed in the early afternoon. On June 3 the sun shone 55 per cent of the possible hours. (The sunshine durations were taken by the Weather Bureau at Bradley Field, 6 miles or 10 kilometers north of the Laboratory.)

The tent of 1946 covered shade-type tobacco plants set about June 1. During the period of observation, they were 1.5 to 2.5 meters in height. The tent was furnished by the Imperial Agricultural Corporation and covered several acres of land near and on the same soil type as the plots of the Tobacco Laboratory. The reference observations in the open were taken in the plots of the Laboratory, a few hundred feet from the tent.

Most of the observations were made in July and August, 1946. The sunny warm weather of late June continued through most of July, being interrupted only by a brief storm period from the 20th through the 23rd. Daytime temperatures were about 1°C. above normal, nighttime temperatures 1 to 2° below. The sun shone 65 per cent of the possible hours. August was cloudy and cool. The sun shone only 55 per cent of the possible hours, and temperatures were about 1° below normal.

RADIATION

The disposition of incoming solar and atmospheric radiation in the tent as compared with bare ground must account for observed differences in microclimate and consequent modification of the tobacco leaf. Thus, consideration of the physical system that is the tent must start with an analysis of the partition of radiation.

Incoming radiation at the top of the tent and over bare ground is composed of three major components — direct solar, diffuse solar (including that scattered and reflected from clouds and impurities), and atmospheric radiation from water, carbon dioxide, and aerosols (Fig. 2). The first two are largely short-wave, while the last is long-wave.

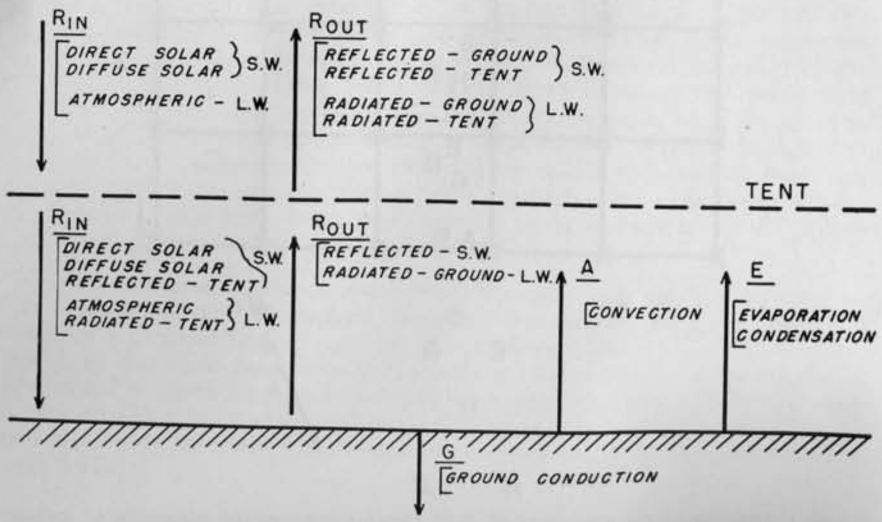

Figure 2. Energy budget of shade. S.W. and L.W. mean short- and long-wave.

Outgoing radiation from bare ground is composed solely of reflection and long-wave emission. Outward radiation from the tent is somewhat more complex, however. Consideration of this must follow analysis of the radiation balance within the tent.

Incoming radiation at the soil surface beneath the tent is affected by the tent material itself which absorbs some radiation from above, reflects some, and allows some to pass through. Since it has a temperature above absolute zero, it also radiates energy in the long-wave region. Also, some of the incident short-wave energy is reflected downward, and is the light by which we see the tent from be-

Table 1. Observations taken near noon on May 30, 1957

Hours:min.:sec.	Element	Site	Height, cm.	Tent or Open	*Observation*	
					Degrees C.	Cal./cm.^{2} min.
11:45:00	Temperature	C	100	T	27	
45:30				O	26	
46:00			10	T	29	
46:30				O	29	
47:00			1	T	32	
47:30				O	32	
48:00	Net radiation	E	100	T		.81
48:30				O		.98
49:00	In radiation	E		T		1.68
49:30				O		2.05
50:00	Blank					
50:30	Temperature	D	100	T	24	
51:00				O	26	
51:30			10	T	27	
52:00				O	28	
52:30			1	T	33	
53:00				O	33	
53:30	Blanks					
55:00	Temperature	C	0	T	52	
55:30				O	51	
56:00			—1	T	36	
56:30				O	38	
57:00	Soil heat		—1	T		.20
57:30				O		.19
58:00	Temperature		—10	T	23	
58:30				O	24	
59:00	Net radiation	E	100	T		.82
59:30						.97
12:00:00	In radiation	E		T		1.71
:30				O		1.91
1:00	Temperature	D	0	T	46	
1:30				O	50	
2:00			—1	T		
2:30				O	37	
3:00	Soil heat		—1	T		.18
3:30				O		.20
4:00	Temperature		—10	T	23	
4:30				O	25	
5:00	Blanks					
7:00	Repeat program					

Table 2. Total incoming radiation in the open as cal./cm² min. and beneath the tent as a percentage of that in the open

Hour	May 28		May 29		May 30		May 31		June 1		June 2		June 3	
	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent
0100					.38	123			.51	105	.55	104	.42	93
0200					.40	119			.56	98	.55	104	.43	88
0300					.39	120			.52	106	.55	105	.42	88
0400					.41	116			.52	102	.55	105	.42	88
0500					.46	112			.56	102	.58	103	.48	89
0600					.61	115			.67	95	.65	99	.65	88
0700					1.07	92			.68	99	.83	96	.76	94
0800					1.24	89			.87	97	1.21	94	1.26	78
0900					1.70	78			1.02	94	1.22	89	1.69	74
1000					1.90	85			1.81	86	1.28	92	1.01	88
1100					2.05	82			1.63	91	.82	103	2.19	84
1200					2.02	83			1.90	78	.89	93	2.19	88
1300					1.91	84			1.79	92				
1400					1.72	84	1.69	85	1.64	79				
1500			1.44	85	1.47	85	1.68	83	1.49	83				
1600			1.36	85	1.17	88	1.27	85	1.02	91				
1700	.90	86[a]	1.02	88	.84	93	1.04	85	.63	107				
1800	.62	94	.58	107			.61	99	.60	111				
1900	.41	122	.46	123			.43	125	.55	107				
2000	.39	123	.43	122			.42	122	.45	121				
2100	.40	119	.44	117			.49	104	.51	110				
2200	.38	124	.40	121	.42	120	.40	122	.54	106	.44	100		
2300	.37	124	.40	120	.40	118	.41	119	.54	98	.41	100		
2400	.38	125	.42	117			.41	119	.54	101	.43	96		

[a] Calculated before rounding radiation data to hundreths.

low. Thus the radiation perceived from below (that received by the ground) is made up of three short-wave components and two long-wave components (Figure 2).

Outgoing radiation from bare ground beneath the tent is composed of the same two components as over ground with no tent. Outgoing radiation above the tent, however, has the components added by the tent itself.

At night when the large contribution from the sun is absent, the long-wave radiation from the tent is relatively more important. The cloth absorbs and emits radiation in the long wave lengths, probably very nearly as a black body. The temperature it reaches, together with the equivalent sky temperature, will determine how fast the ground beneath cools.

Total radiation in the tent over bare soil. All wave lengths contribute to or subtract from the energy that warms the soil and air and evaporates water in the open and beneath the tent. Therefore, radiation was measured in 1957 by a radiometer sensitive to all wave lengths (Gier and Dunkle, 1951). The voltage produced by the radiometers per unit of radiant-flux density had been calibrated by the manufacturers, Beckman and Whitley. The voltage was measured by a recording potentiometer located at B in Figure 1.

Two radiometers were placed outside, two inside the tent. One of each pair measured the "incoming" radiation, the total radiant energy which came from the hemisphere above and which reached a horizontal plane one meter from the soil. The other radiometer measured the net flow of radiant energy through the same plane. The automatic program of observations was designed to permit comparison of a measurement within the tent with the corresponding one outside in a total of one minute and to provide two sets of radiation measurements during each program. An example of the program is shown in Table 1 for 1145 to 1207 hours on May 30. The net radiation inside and outside the tent can be compared during the minutes beginning at 1148 and 1159. The incoming radiation inside and outside can be compared during the minutes beginning at 1149 and 1200. The data for the tables were obtained by averaging four consecutive observations during the day or two at night.

During the day, radiation from the sun and from the clouds, dust, and gases in the sky warmed the exposed soil. The radiation varied from maxima of near 2 cal./cm.² min. on clear days to near 1 on the overcast day (Table 2). The tent absorbed some of this energy and emitted radiation itself. The net result was an 8 to 22 per cent depletion of the energy reaching the sheltered soil on clear and partly cloudy days. On the overcast day, June 2, long-wave radiation from the sky and tent and diffuse light was relatively more important, and the depletion by the tent was never more than 11 per cent.

At night, the sky and tent are the only sources of incoming radiation. On the clear nights in May the sky radiated about 0.4 cal./cm.² min. to the exposed soil (Table 2), corresponding to an equivalent sky temperature of —8° C. When clouds appeared, as they did early on June 1, incoming radiation increased to nearly 0.6, corresponding to an equivalent sky temperature of 20° C. On the clear nights the cloth tent was much warmer than the cold gases in the sky. Therefore, the cloth absorbed less energy from above than it emitted downward, and the sheltered soil received 112 to 125 per cent as much radiation as the exposed soil. When clouds appeared, as before dawn on June 1, sky radiation

Table 3. Total outgoing radiation in the open as cal./cm.^{2} min. and beneath the tent as a percentage of that in the open

	May 28		May 29		May 30		May 31		June 1		June 2		June 3	
Hour	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent
0100					.50	108			.52	102	.57	102	.51	92
0200					.50	105			.58	94	.56	102	.50	89
0300					.50	106			.55	101	.57	102	.50	
0400					.50	103			.55	98	.56	102	.50	90
0500					.51	104			.55	100	.57	102	.52	99
0600					.52	111			.59	97	.60	99	.57	99
0700					.66	100			.56	104	.63	101	.58	97
0800					.72	94			.61	103	.70	113	.65	91
0900					.92	84			.60	107	.77	92	.78	88
1000					1.02	84			.87	97	.77	98	.59	93
1100					1.09	84			.86	103	.63	111	1.10	98
1200					1.05	82			1.15	94	.74	97	.95	102
1300					1.08	89			.75	112				
1400					1.03	83	.98	87	1.18	84				
1500			1.05	79	.92	89	1.05	85	.99	90				
1600			.94	83	.86	92	.90	91	.69	88				
1700	.74	90	.82	87	.77	94	.84	88	.63	105				
1800	.61	99	.63	104			.64	101	.59	111				
1900	.53	106	.59	105			.56	108	.59	103				
2000	.52	105	.57	105			.58	102	.55	109				
2100	.52	104	.56	103			.62	93	.55	105				
2200	.50	106	.52	105	.52	107	.53	106	.56	103	.49	108		
2300	.50	106	.52	106	.51	106	.53	104	.57	95	.54	95		
2400	.50	107	.53	104			.52	106	.56	98	.53	97		

increased to a density near that of the tent, and the sheltered soil received only 94 to 105 per cent as much radiation as the exposed soil.

The soil surfaces also lost energy by radiation (Table 3). This outgoing radiation consisted of reflection during the day and emission from the soil, soil which had the same color, moisture, and topography inside and outside the tent. The radiation varied from maxima of 1.2 cal./cm.^{2} min. on clear days to minima of 0.5 at night. The tent decreased insolation and surface temperature on sunny days and, hence, the outgoing energy from the sheltered soil was as little as 82 per cent of that from exposed soil. On the cloudy days of June, we have seen how the tent caused only a small decrease in incoming radiation. Therefore, we were not surprised when any decrease in outgoing radiation was small and erratic; the variability with time on cloudy days undoubtedly contributed to this erratic nature of any decrease.

At night when the sky is clear, the surface receives more radiant energy beneath the tent than in the open and, hence, the surface is as warm or warmer beneath the tent as it is in the open. Consequently, on clear nights the outgoing radiation from the sheltered soil was 103 to 108 per cent of that from the exposed soil (Table 3). On cloudy nights the tent had no more consistent effect upon outgoing than it had upon incoming radiation.

Transmission of short-wave radiation by the tent. Visible radiation or light comprises the largest category of incoming radiation during the day and has an important and peculiar role in photosynthesis. Some light comes to the soil from the blue sky, some from the white clouds, and some directly from the sun.

The white threads cover 44 per cent of the area of the cloth and do two things to the light. They absorb, and they reflect, both outward and inward. Therefore, they do not have the same effect upon light of all kinds and at all times. These effects are analyzed here, employing measurements taken in the tent of 1946 and measurements taken in a colorimeter. We assume that 7000 foot-candles (f.c.) are equivalent to 1 cal./cm.^{2} min. (Kimball, 1924).

Light intensity was measured in the field with a Weston photoelectric cell. Observations were made at the 6 hours shown in Table 4 when the sky was either clear or overcast. The cell was pointed at the northern and at the southern sky. It was directed toward white clouds when they were present.

The light intensity from the clear, blue northern sky (Table 4) was about one-tenth of the 5000 to 10,000 f.c. received on a surface perpendicular to the sun's rays. The cloth of the tent decreased this diffuse fraction of the light to 72 to 97 per cent of the intensity in the open. Observations of the light from the southern sky showed the same result. Thus, the light intensity in a tent must be about 80 per cent of that outside when the source is diffuse as it would be from an overcast sky. This is in agreement with Hasselbring (1914) who observed practically no decrease in diffuse light beneath the tent.

The light from white clouds in an overcast sky (Table 4) is undoubtedly more direct than that from a blue northern sky. Assuming that 2000 to 3000 f.c. would be measured on a surface perpendicular to the sun's rays, we see that light from clouds is an important portion of the total light received. This portion was reduced by the tent to 56 to 75 per cent or about two thirds of the intensity in the open. Essentially, the same intensities and depletions were observed for light from clouds in the northern and southern sky. Of great interest is the constancy of the reduction regardless of the hour of the day.

Table 4. Light intensity in the open as foot-candles and beneath the tent as a percentage of that in the open. July-August, 1946

		North light		*Reflected light*		*Transmitted light*
Hour	Field	Diffuse	Reflected from clouds	Leaves	Soil	Leaves
0900	Open	625 f.c.	675	275	—	150
	Tent	72%	56	51	—	73
1000	Open	625	1200	300	—	160
	Tent	80	75	62	—	81
1100	Open	775	1475	375	390	250
	Tent	81	56	53	64	88
1400	Open	775	1100	350	575	295
	Tent	97	64	62	56	59
1500	Open	1000	1100	350	420	205
	Tent	78	64	57	68	80
1600	Open	700	—	280	450	120
	Tent	93	—	58	48	87

Two surprising aspects required explanation: the threads covered 44 per cent of the area but reduced direct light by only one-third, diffuse light by only one-fifth; and the reduction in intensity was not materially affected by the hour and the angle of the sun. Geometrical analysis provided an explanation.

In shade cloth, threads of unit diameter are woven in squares of width 4 as shown in Figure 3, A and B. The transmission through the cloth is expected to be $[(4\text{-}1)(4 \sin b\text{-}1)/(4^2 \sin b)]$ when the solar angle is b. The theoretical transmissions for several solar angles are set down in Table 5. This shows the decreasing transmission expected as the sun approaches the horizon. This expectation can be compared with the transmission through black shade cloth measured in a colorimeter and presented in the same table. This cloth transmits somewhat more light than expected, probably due to our imperfect measurements of thread diameters. More important, the transmission does decrease with the angle between cloth and beam in the manner predicted and does not decrease at the lower rate observed in a shade tent.

Table 5. Transmission of beams of light from several angles above the horizontal

Angle	90°	60°	45°	30°	20°	14°30′
Theoretical transmission						
Through shade cloth without reflection	.56	.53	.48	.38	.20	0
Black shade cloth						
Observed transmission	.61	.59	.53			
Observed relative to theoretical transmission	1.09	1.11	1.10			
White shade cloth						
Observed transmission	.68	.66	.62			
Observed relative to theoretical transmission	1.21	1.24	1.29			

The white cloth used in tents will, of course, reflect as well as transmit light into the tent. This is diagramed in Figure 3, C and D. The light that strikes the threads as low as the lower beams shown will be reflected directly into the tent; its density will be decreased according to the curvature and the reflectivity A of a plane of the reflector thus: A cos a. The light that is reflected from the first thread and approaches the second below a line parallel to one of its radii may be reflected repeatedly until it enters the tent; its density will be decreased

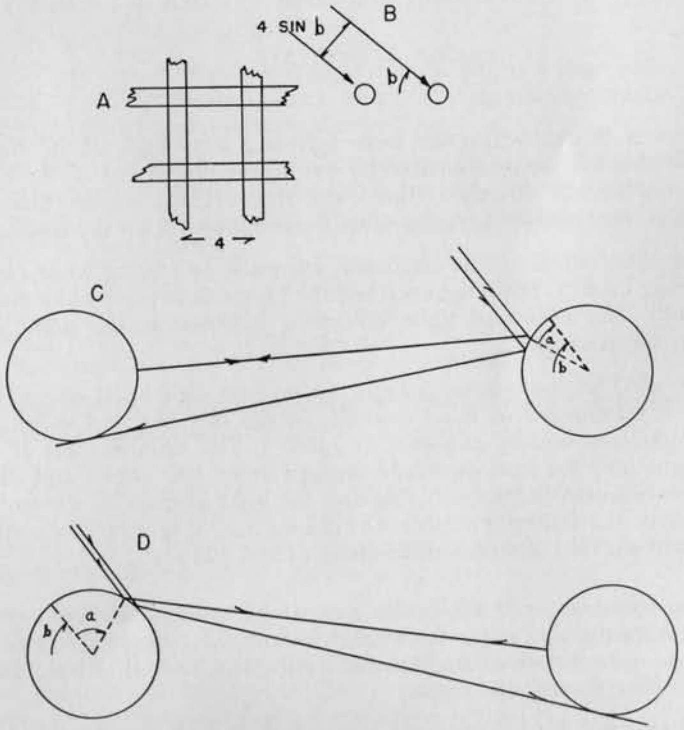

Figure 3. The dimensions of shade cloth.

to at least $A^2 \cos a$. The reflections into the tent have been estimated by this method for solar angles of 90° and 20° and for the north-south threads:

$$\text{Reflection, } 90° = 2A \int_{51° 25'}^{90°} \cos a \, da + \quad < 2A^2 \int_{47° 40'}^{51° 25'} \cos a \, da$$

$$= .44A + (< .08A^2)$$

$$\text{Reflection, } 20° = A \int_{14° 30'}^{90°} \cos a \, da + \quad < A^2 \int_{10° 40'}^{14° 30'} \cos a \, da$$

$$+ A \int_{87°}^{90°} \cos a \, da + \quad < A^2 \int_{83° 30'}^{87°} \cos a \, da$$

$$= .75A + (< .06A^2) + .01A + (< .01A^2)$$

$$= .76A + (< .07A^2)$$

The east-west threads will reflect more light at a solar angle of 90° than at 20°. However, this will be compensated by the higher proportion of the light striking the north-south threads at the lower angle. Thus, we see that reflection increases as transmission decreases when the sun moves from the zenith.

A qualitative test of this conclusion was made by placing white cloth in the colorimeter, Table 5. More light reached the photocell beyond white than beyond black cloth. The additional light, reflection, increased as the angle decreased, verifying our conclusion.

The effect of the tent upon light can now be seen in its essentials. Direct sunlight is transmitted in small amounts in the morning and evening and in larger amounts at midday as shown in Table 5. The white threads of the cloth reflect light into the tent, especially sunlight from low angles and diffuse sky light. Consequently, throughout clear days the light intensity in the tent is about two-thirds of the intensity outside. On cloudy days it is about four-fifths. This is consistent with the observations of Street (1934, 1935).

Short-wave radiation within the tent. If we examine the amount of light reflected from the soil and reflected and transmitted by leaves within the tent, we can test our estimate of transmission by the tent as well as trace the fate of the light within the tent and crop.

The reflected light from outer leaves and dry soil was measured on clear days by holding the photoelectric cell 15 to 25 cm. above the surface. The reflected light beneath the tent was 51 to 68 per cent of that in the open (Table 4). The effect of the tent did not depend upon the angle of the sun. Assuming equal reflectivity of the leaves and soil inside and outside the tent, we conclude again that the light intensity within the tent is about two-thirds of that outside.

The light that passed through leaves on clear days was measured by holding the photoelectric cell against the lower side of leaves. The light transmitted by leaves beneath the tent was 59 to 87 per cent of that transmitted in the open. Thus, the intensity of light beneath a leaf within the tent is about three-fourths of that beneath a leaf outside the tent although only two-thirds as much light reached it.

These observations permit us to estimate the optical nature of the leaves. An intensity I is transmitted by the leaf when an intensity I_o enters its upper surface. The intensities are indicated by a "p" for the open and a "t" for the tent. Thus, within the tent we have observed a relative light intensity $I_{ot}/I_{op} = 0.67$ and a relative light transmission $I_t/I_p = 0.75$. Beers law expresses transmission as a function of, k, an absorption coefficient and, m, the gm. of leaf/cm.^{2}:

$$I/I_o = e^{-km}$$

The product km is often called optical density. Substituting our estimates in this equation, we find $(k_p m_p - k_t m_t) = 0.11$. Leaves commonly have a transmission I/I_o of about one-half (Miller, E. C. 1938), or $k_p m_p = 0.70$. From this, $k_t m_t = 0.59$ and corresponding transmissions are:

$$I_p/I_{op} = 0.50, \; I_t/I_{ot} = 0.56.$$

The 10 to 20 per cent difference in optical density, km, is a reasonable difference to be caused by differences in thickness and color between the mature leaves of plants grown in the open and beneath the tent.

The observations and conclusions concerning light can be summarized in a hypothetical example. Assume insolation to be 1.60 cal./cm.^{2} min. outside of the tent and 1.07 inside. Then the distribution of short-wave radiation for a reflectivity of 0.3 would be:

	Reflection	*Absorption*	*Transmission*
Open	0.48 cal./cm.^{2} min.	0.56	0.56
Tent	0.32 cal./cm.^{2} min.	0.33	0.42
Tent/Open	67 per cent	59	75

This explains the difference between the effect of the tent upon the intensity of light falling upon and being transmitted by leaves.

The difference between the effect of the tent upon total and short-wave radiation. The observed depletion of total (Table 2) and visible (Table 4) radiation during the day are not equal. An explanation is needed for this difference between the effect of the tent upon total and short-wave radiation.

First, we consider the case of an overcast day: The tent decreased total radiation by about 10 per cent (June 2, Table 2) and light by 20 per cent (diffuse north light, Table 4). An example based upon the data of overcast June 2 (Table 2) reveals the cause of the paradox. The estimate of long-wave radiation is obtained from the hours before dawn, the estimate of total radiation at 0900-1000 hours. The distribution of long- and short-wave radiation would be:

	Long-Wave	*Short-Wave*	*Total*
Open	0.55 cal./cm.^{2} min.	0.70	1.25
Tent	0.57 cal./cm.^{2} min.	0.56	1.13
Tent/Open	104 per cent	80	90

Second, we consider the difference between the effects of the tent upon total radiation and upon light on a clear day. The tent decreased total radiation by about 20 per cent (May, Table 2) and light by 33 per cent (light reflected from clouds, Table 4). The example is based upon the data of clear May 30. The estimate of long-wave radiation is obtained from the hours before dawn, the estimate of total radiation at 1200 hours. The distribution of long- and short-wave radiation would be:

	Long-Wave	*Short-Wave*	*Total*
Open	0.40 cal./cm.² min.	1.60	2.00
Tent	0.50 cal./cm.² min.	1.07	1.57
Tent/Open	125 per cent	67	78

The pre-dawn observations may well be lower than the long-wave radiation intensity at midday. If so, the examples would provide an even more dramatic explanation of the differential effect of the tent upon the total and short-wave radiation.

Thus, we see that the observations of light and of total radiation can be reconciled and summarized in the preceding examples. The paradoxical difference is due to the absorption and reflection of light by the tent while it emits long-wave radiation.

WARMING THE BARE SOIL

A portion of the net gain of radiant energy in the daytime heats the soil. At night, the net loss of energy through radiation is partially compensated by energy gained from the cooling soil. Thus the differences in radiation produced by the tent will surely produce differences in the warming of the soil. However, we should not expect large differences in the heating of the soil because the differences in radiation are not large; further, temperature differences are the result of equilibria where an increased gain in energy from one source is matched by an increased loss through another.

The net flow of heat into the soil was measured at two sites within the tent of 1957 and at two sites outside (Figure 1, C and D). The flow was measured by a sensitive plate (Gier and Dunkle, 1951) inserted in the soil at a depth of 1 cm. The voltage that the plates produced was measured by the recording potentiometer.

The observations of the two heat flow meters or thermocouples at a given depth and at the two sites inside the tent were averaged for each hour. For example, the average flow of heat into the soil inside the tent near noon on May 30 was (0.20 + 0.18)/2 or 0.19 cal./cm.² min. (Table 1). This observation was compared with observations outside the tent taken within the same pair of minutes, (0.19 + 0.20)/2 or 0.195 cal./cm.² min. The significance of differences between means was judged by the variation between replicates; in the above example, the difference was not significant. The data of Table 6 are the averages of four consecutive observations during the day, two at night.

The tent reduced the flow of heat into the soil during any day by 2 to 20 per cent, Table 6. This is a consequence of the reduced net radiation beneath the tent. The tent also reduced the nighttime loss of heat from the soil by about the same amount. On cloudy nights the reduction did not always occur. This reduction is a consequence of the reduced net radiational loss beneath the tent.

Table 6. The flow of heat into the soil in the open as cal./cm.² min. and beneath the tent as a percentage of that in the open[a]

	May 28		May 29		May 30		May 31		June 1		June 2		June 3	
Hour	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent
0100					—.06	84			—.02	105	0	(—.06)	—.06	77
0200					—.05	86			—.02	105	—.01	92	—.05	77
0300					—.05	86			—.02	105	—.02	93	—.06	77
0400					—.05	128			.02	106	—.01	100	—.05	76
0500					—.04	86			—.01	92	—.02	47	—.04	76
0600					—.01	(.02)			0	(0)	.01	100	0	(0)
0700					.05	85			.02	67	.02	104	.02	116
0800					.10	96			.05	85	.10	93	.08	85
0900					.15	97			.07	94	.08	96	.15	79
1000					.18	99			.17	84	.12	95	.12	65
1100					.20	99			.17	97	.05	92	.15	81
1200					.19	98			.17	106	.04	91	.17	73
1300					.18	97			.20	92				
1400					.14	96	.16	86	.08	92				
1500			.09	79	.11	92	.14	89	.14	91				
1600			.10	78	.06	82	.08	77	.04	89				
1700	—.03	69	.05	63	0	(0)	.05	67	.01	50				
1800	—.07	94	—.06	53			—.04	83	—.01	100				
1900	—.08	85	—.04	100			—.05	89	—.02	100				
2000	—.07	84	—.05	85			—.05	88	—.04	87				
2100	—.07	80	—.05	85			—.05	89	—.03	100	—.06	82		
2200	—.07	81	—.05	98	—.05	87	—.05	90	—.02	106	—.06	77		
2300	—.07	79	—.05	85	—.05	89	—.05	89	—.02	106	—.06	78		
2400	—.06	115	—.05	87			—.05	85	—.01	107				

[a] The percentages were calculated from data in thousandths of a cal./cm.² min. The bracketed data are in cal./cm.² min. and replace nonsensical percentages.

AIR AND SOIL TEMPERATURES

Portions of the net gain of radiant energy in the daytime are used to heat the air as well as the soil. At night, the net loss of energy through radiation is compensated by energy gained from the cooling air and soil. Once again, the differences in radiation produced by the tent will surely produce differences in temperatures, but we should not expect large temperature differences because the differences in radiation are not large.

Thermocouples were installed at two sites within the tent of 1957 and at two sites outside (Figure 1, C and D). A single bath of ice and water was used as a reference for all thermocouples. The thermocouples were newly manufactured from 30-gauge copper and constantan wire and were without visible corrosion. They were supported at heights of 100, 10, and 1 centimeter, pressed against the soil surface, and buried at depths of 1 and 10 centimeters. The voltage that they produced was measured by the recording potentiometer.

The observations of the two thermocouples at a given height at the two locations inside the tent were averaged for each hour. Thus, near noon on May 30 the temperature average for a height of 100 cm. inside the tent was (27 + 24)/2 or 25.5°C. (Table 1). This observation was compared with observations at the same height outside the tent taken within the same pair of minutes, (26 + 26)/2 or 26.0°C. The significance of differences between means was judged by their variation between replicates; in the above example, the difference was insignificant.

The observations of May, 1957, summarized in Figure 4, represent clear weather. Near midday, the outstanding effect of the tent is a 1.5 to 4.0°C. decrease in the temperature taken at the soil surface. This cooling was anticipated when we observed a decrease in outgoing radiation beneath the tent, radiation which is a function of temperature (Table 3). Midday temperatures 1, 10, and 100 cm. above the ground were little if any cooler inside the tent than outside. Near midnight, the salient effect of the tent was a 1.5 to 2°C. cooling of the air with little change in the surface temperature. The fact that nighttime outgoing radiation from the sheltered soil was consistently slightly higher than from the exposed soil (Table 3) suggested that the sheltered was slightly warmer than the exposed.

The observations of June 2, 1957, summarized in Figure 5, represent an overcast, dark day. Those of June 1 and 3 represent brighter, cloudy days. The significant point here is the near equality of the temperatures inside and outside the tent. The one exception, 1206 June 3, was produced when cloudiness decreased to six- to nine-tenths sky cover provided by cumulus in polar air. During these three cloudy days, as we saw when we investigated radiation, the effect of the tent was lessened by the clouds.

The cooling of the soil surface by the tent on clear days and the cooling of the air on clear nights makes physical sense. Less radiant energy reaches the sheltered surface during the day, and the sheltered surface does not become as hot as the exposed surface. On clear nights exposed soil loses energy by radiation to the sky, becomes cooler than the air, and cools the air; this is evident in the profiles near midnight on May 28, 29, and 30. But the tent also loses energy to the sky by radiation; hence, it becomes cooler than the air and cools the air above and below it. Thus, the air at 100 cm. beneath the tent is cooler than other air at the same height outside where there is no cold, perforated surface above.

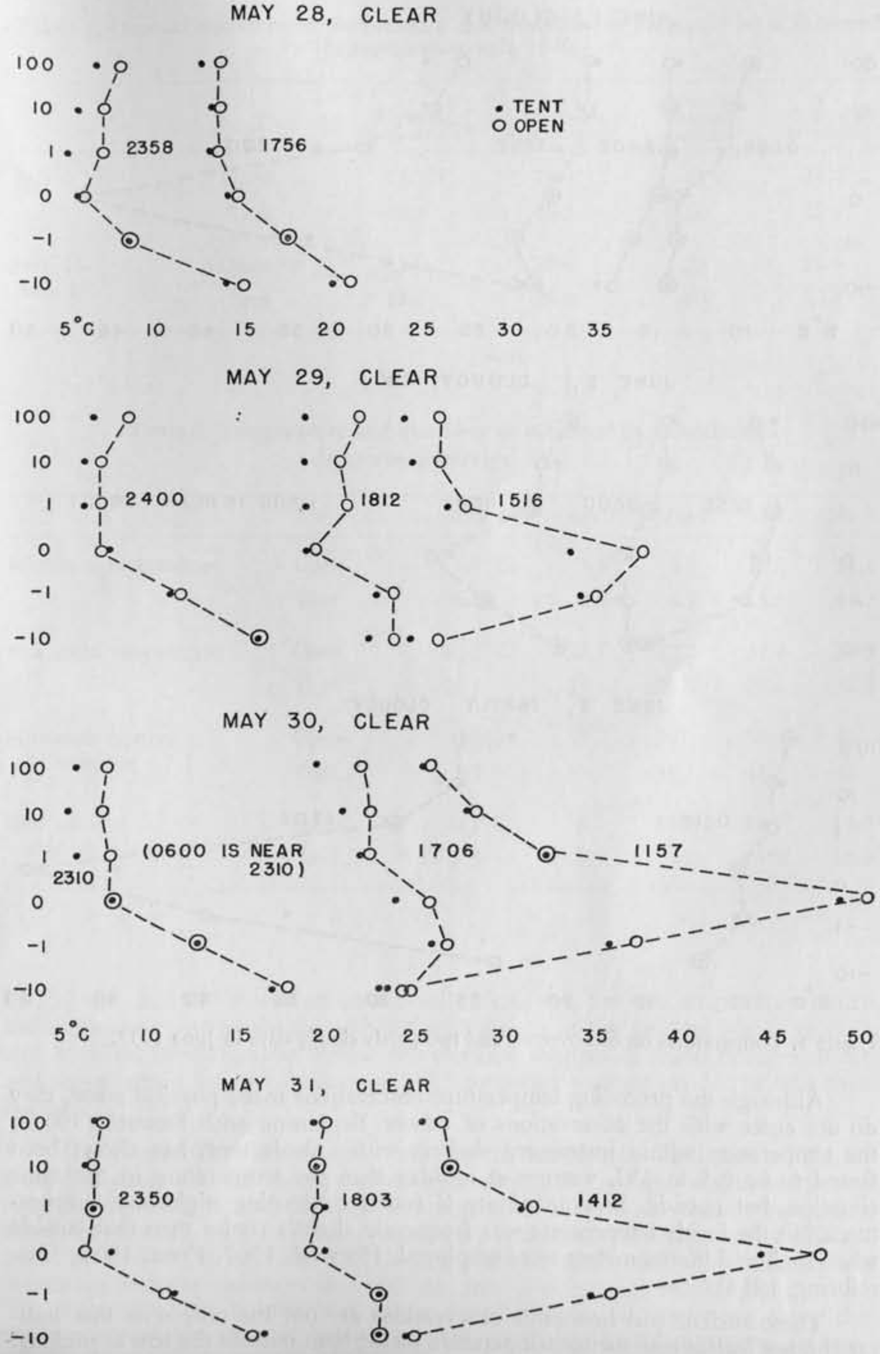

Figure 4. Temperatures in degrees Centigrade at heights of 100, 10, 1 and 0, and depths of 1 and 10 cm. on four clear days in May 1957.

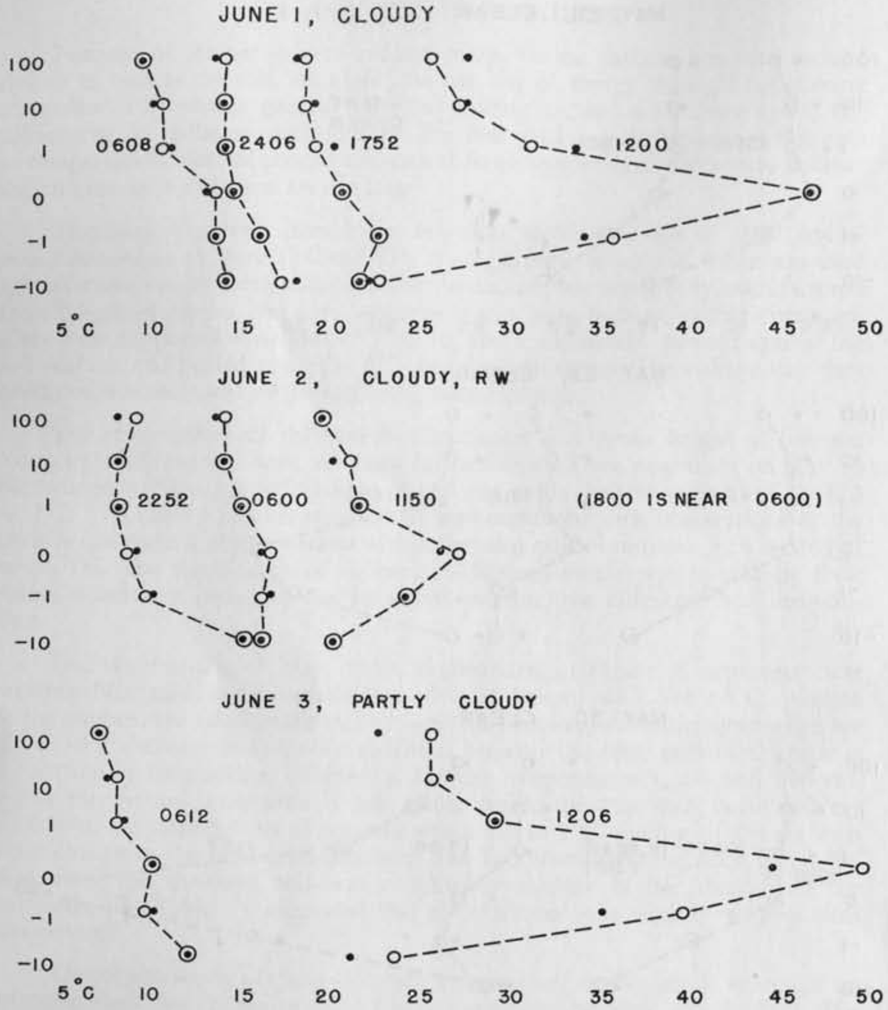

Figure 5. Temperatures on one overcast and two partly cloudy days in June 1957.

Although the preceding temperature observations make physical sense, they do not agree with the observations of others. Beginning with Stewart (1907), the temperature within instrument shelters within shade tents has always been found to be 0.5 to 3°C. warmer at midday than the temperature in the same situation, but outside. Less unanimity is found concerning nighttime temperatures, but the inside temperature was frequently slightly cooler than that outside when sheltered thermometers were employed. (Stewart, 1907; Frear, 1906; Hasselbring, 1914).

Table 7. Diurnal extremes of temperature and humidity as indicated by a sheltered hygrothermograph, 1946

		Minimum temperature	Maximum temperature	Minimum relative humidity	Dew point at midday
July 9-22	Open	15.3°C.	28.3°C.	43%	14.4°C.
	Tent	14.5	29.5	50	17.9
July 23-Aug. 19	Open	15.0	26.6	55	16.9
	Tent	14.2	26.8	60	18.3

Table 8. Temperature and humidity as indicated by a sheltered hygrothermograph, 1957

		May 29	May 30	May 31	June 1	June 3
Minimum temperature	Open	6.7°C.	7.8	8.3	12.2	11.1
	Tent	6.7	8.9	8.9	13.3	11.7
Maximum temperature	Open	26.1°C.	26.1	27.2	27.2	22.0
	Tent	26.1	27.8	27.8	29.4	22.8
Minimum relative humidity	Open	32%	35	34	38	46
	Tent	35	35	31	41	47
Dew point at midday	Open	8.1°C.	9.5	10.0	11.7	10.0
	Tent	9.5	10.9	9.2	14.8	10.9

These ancient and honorable observations are not the only ones that indicate higher instrument-shelter temperature inside than outside the tent at midday. During our investigations in both 1946 and 1957, hygrothermographs were operated in shelters. In 1946 the shelter was supported at the standard height of 150 cm., in 1957 it was set on the soil. Here, too, the maximum temperature became warmer in the shelter within the tent than in the one outside (Tables 7 and 8). The thermographs within the elevated shelters of 1946 became cooler and those within the low shelters of 1957 remained warmer inside the tent than outside.

The discrepancy is obviously one due to instruments and not to era or men. We chose the thermocouples as representing the natural situation for two reasons. First, bright and small thermocouples do not change their temperature when they are changed from an exposed to a completely shaded position (Waggoner and Shaw, 1952). Second, the observations taken with themocouples are consistent with the radiation observations: the air is warmer outside than inside. We suggest that the temperature within the shelter inside the tent is above the temperature of the free air because of low wind speeds. At night the thermographs show the temperature differences with height, as observed with thermocouples: the tent was relatively cool near the roof.

HUMIDITY

Humidity in the tent over bare soil. Humidity in the empty tent and in the field of 1957 was measured by means of the recording hygrothermographs in the shelters at G in Figure 1. The shelters sat upon the soil. These measurements are presented in Table 8 as the minimum relative humidities for the days of observation, data that were simultaneous with the maximum temperatures.

The relative humidities at midday were clearly equal inside and outside the tent. However, the temperature within the shelter inside the tent was higher than that outside. Thus, the attained vapor pressure and dew point temperature were generally higher inside than outside the tent. This derived result is set out in Table 8.

Do these results represent conditions within the tent as well as inside the shelters? We have already ascribed the higher shelter temperatures inside the tent to inadequate ventilation and said that the observations with thermocouples are nearer the truth (Figure 4 and 5). How does this influence the measurement of humidity? The heating of the shelter above air temperature due to lack of ventilation will not increase the amount of water in the air. Therefore, the dew point will not be affected. Or, the midday temperatures of the dew point measured in the shelters, Table 8, represent conditions in the air outside as well as inside the shelter. Since little evaporation from the soil did occur, we were not surprised to find the concentration of water in the still air of the tent little if any higher than in the turbulent air outside.

The nighttime humidity can be deduced from the preceding observations. (Our hygrometers were calibrated near 50 per cent relative humidity and are relatively inaccurate near saturation.) The daytime dew point is about the same or higher and the nighttime temperature is lower in the air of the tent than it is outside. From this we conclude that the air of the tent is saturated with water earlier in the evening than is the air outside. The hygrograph records — for what they are worth — support this conclusion.

Humidity in the tent over tobacco plants. Humidity in the tent and field of 1946 was measured by means of hygrothermographs. The diurnal minimum relative humidities for July 1 to 21 and July 29 to August 22 are presented in Table 7. (The data for the identical periods of the temperature records were not available, but the small time change evident in the means permits us to compare the temperature and humidity data.)

The results of 1946 are consistent with those of Stewart (1907): the midday dewpoint is higher inside the tent than it is outside. The difference in dew points is greater in the tent inhabited by plants than in a vacant one. This is not surprising since the evaporation and transpiration in the inhabited tent is about 30 mm. per day while the evaporation from the bare soil was less than one-tenth as great. We attribute the higher dew point within the tent to the slow transfer of the evaporated water from the neighborhood of the leaves and soil within the calm of the tent.

In the tent over plants, as in the tent of 1957, we can deduce the nighttime humidity from the daytime dew point. Since the dew point is higher and the nighttime air cooler inside than outside the tent, the air inside the tent must be saturated with water earlier in the evening than is the air outside.

Two sets of observations are available for comparison with the preceding statement. Both must be viewed with scepticism because of the inaccuracy of the hygrometers at high humidities. In the tent of 1946, we observed an average maximum humidity of 94 per cent, while outside the maximum averaged 99 per cent. Stewart's (1907) observations do not agree: after the plants had grown large, the maximum relative humidity inside was 1 to 10 per cent higher than that outside. We conclude, as before, that the hygrometers are poor indicators at night and that in the evening the air is saturated sooner inside than outside the tent.

WIND

The wind inside an empty tent. The tent breaks the wind and creates a calm atmosphere for the tall, columnar "shade" variety of tobacco. Wind movement was measured at a height of 1 meter at F (Figure 1) inside and outside the empty tent of 1957. The measurements were made with airways anemometers and recorded continuously on an operations recorder.

When the air outside the tent moved at less than 25 meters per min. (m./min.), that is less than about 1 mile per hour, the anemometers within the tent did not move.

The wind velocities inside the tent have been plotted as a function of the velocities outside (Figure 6). The velocities were estimated by counting the meters of air that passed in an hour. Only velocities greater than 25 m./min. outside are shown. The outside anemometer was in the lee of the tent when the wind had a northerly component; therefore, northerly winds were omitted.

The relation between the two velocities can be summarized in three parts: (1) when the velocity outside was less than 25 m./min., the air was nearly calm inside; (2) when the velocity was 25 to 50 m./min. outside, it was generally 0 to 4 m./min. inside; (3) when the velocity outside, u_p, was over 50 m./min., the velocity inside, u_t, could be approximated by the relation

$$u_t = 0.67 (u_p - 50).$$

The reduction in wind velocity by the tent can be explained logically by the methods of fluid mechanics. The velocity within the tent is a function of the drag coefficient which in turn may be a function of the Reynolds number. The Reynolds number is the product of the wind velocity, the diameter of the openings in the shade cloth, and the density and the reciprocal of the viscosity of air. For cloth with openings of 0.25 cm. diameter, the Reynolds number is approximately 200 times the velocity in m./min. Many experiments have shown that the drag coefficient increases with increasing wind until the Reynolds number reaches about 10,000. At higher winds and numbers the drag coefficient is constant.

The relation between the wind inside and outside the tent shown in Figure 6 can now be explained. As the wind outside increased from 0 to 25 m./min., the drag of the threads increased so rapidly that a calm essentially was maintained inside the tent. As the wind outside increased from 25 to 50 m./min., a measurable, but small, increase in air movement was produced inside the tent. Above 50 m./min. and the critical Reynolds number of 10,000, the wind inside increased in a linear fashion, ⅔ of a m./min. for each unit increase outside.

The wind inside a tent over tobacco plants. Stewart (1907) has provided us with observations of wind velocity in large stands of tobacco, within and without a tent. He measured the velocities plotted in Figure 7.

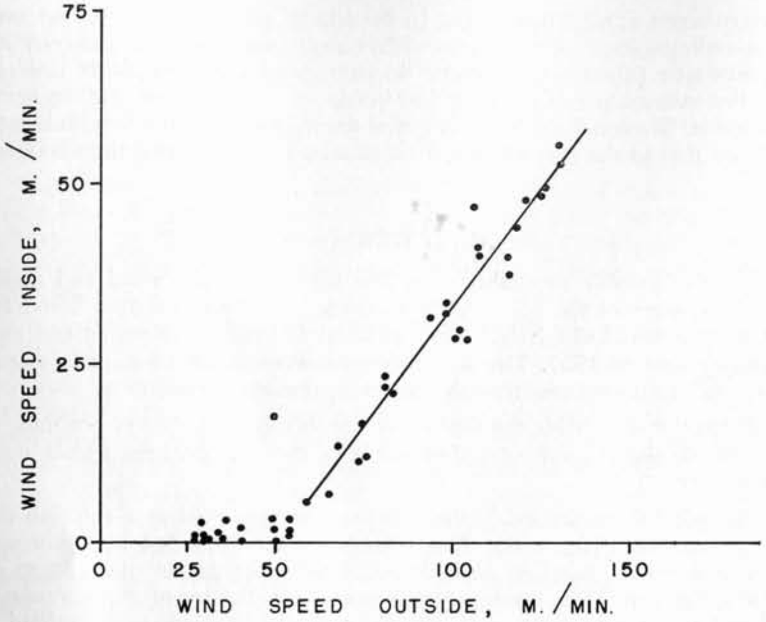

Figure 6. The relation between wind speed inside and outside the empty tent of 1957.

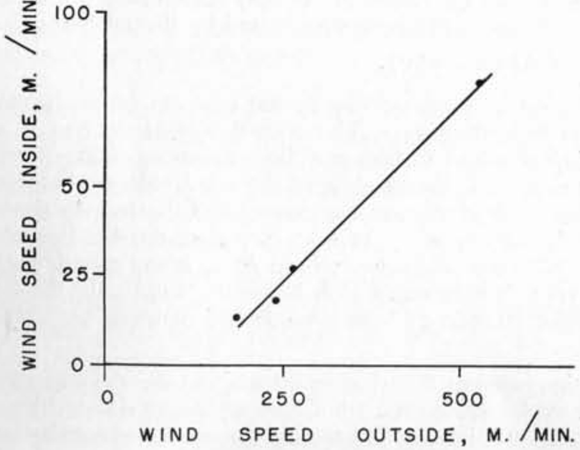

Figure 7. The relation between wind speed inside and outside of a tent over tobacco plants, Stewart (1907).

The form of the relation betweeen velocities inside and outside is the same in plants as over bare ground: at low velocities outside, the air is calm inside; at higher velocities the two speeds increase together in a linear fashion. However, the details in tobacco are different from bare ground: a higher wind speed is needed outside to start the wind inside and the rate of increase is lower. The two wind speeds are related by

$$u_t = 0.20\ (u_p - 135)$$

when the speed outside exceeds 135 m./min. In terms of fluid mechanics, two things are indicated. First, compared to a bare field and tent, a higher Reynolds number, 27,000, is required in a stand of tobacco for the drag coefficient of the tent to become independent of the wind speed. Second, the drag coefficient of tent plus tobacco relative to tobacco alone is higher than the coefficient of the tent relative to a bare field.

EVAPORATION AND THE HEATING OF THE AIR

Energy budgets. The gains and losses of energy at the soil surface can be set out in an easily comprehended budget of five accounts:

R_I = incoming radiation
R_o = outgoing radiation
S = conduction from the soil
A = vertical exchange with the air by conduction and convection
W = change of state of water or evaporation and condensation

Since the surface has no height or depth, the storage of energy or its lateral transport do not enter into our consideration. Therefore, proper signs can be assigned to the accounts and they will balance:

$$R_I + R_o + S + A + W = 0$$

The first three accounts, total incoming and total outgoing radiation as well as conduction from the soil, were measured in the empty tent of 1957 and presented in Tables 2, 3, and 6. Through the use of the above budget equation, these observations were employed to estimate the quantity of energy (A + W) available for heating the air and evaporating water. The estimates are given in Table 9.

Estimation by subtraction is generally subject to large errors. The errors of all observations and theories employed add to produce the larger error of the value estimated by subtraction. However, two facts limit the variability of the estimates of Table 9. First, the difference between incoming and outgoing radiation was, in fact, observed by a single instrument, a Gier and Dunkle net radiometer. Second, the conduction of heat into the soil was much smaller than the net radiation; for example, an error of 20 per cent in the measurement of conduction into the soil at 1200 on May 30 would produce an error of only 5 per cent in the estimate of energy available for heating the air and evaporating water. Thus, meaningful estimates were obtained by balancing the energy budgets.

The quantity of energy available for heating the air and evaporating water can be summed for 24-hour periods beginning and ending at 1600 hours. For the May 29-30 and May 31-June 1 periods this is accomplished by adding the hourly estimates in Table 9 and multiplying by the number of minutes in an hour. The sums are given in Table 10. The sum for June 1-2 was obtained by assuming 0.10 cal./cm.^{2} min. for 1300-1600 hours on the 2d. The sum for 1600 June 1 to 1200 June 2 was obtained by assuming the same energy was available from 1700-2000 hours on the 2d as was available during the same hours on the 1st. The quantities of energy available on May 30 were assumed to occur on May 29

Table 9. Heat lost to the air and to evaporation, 1957, expressed in the open as cal./cm.^{2} min. and beneath the tent as a percentage of that in the open[a]

	May 28		May 29		May 30		May 31		June 1		June 2		June 3	
Hour	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent	Open	Tent
0100					—.06	27			.01	314	—.02	(.04)	—.03	109
0200					—.05	20			0	(+.02)	.01	(0)	—.02	145
0300					—.05	14			—.01	(+.02)	0	(.01)	—.03	
0400					—.05	10			—.05	43	0	(.01)	—.03	150
0500					—.02	(.01)			.02	16	.02	96	0	(—.06)
0600					.10	108			.08	83	.05	100	.08	0
0700					.37	71			.10	81	.18	75	.16	77
0800					.42	64			.21	81	.40	60	.52	62
0900					.63	65			.35	74	.37	83	.84	65
1000					.70	81			.78	77	.39	77	.29	95
1100					.76	76			.60	74	.14	70	.94	67
1200					.77	81			.59	38	.11	70	1.07	78
1300					.65	71			.84	75				
1400					.55	84	.55	81	.39	62				
1500			.30	111	.44	74	.49	77	.36	62				
1600			.32	94	.26	78	.29	71	.28	97				
1700	.19	72	.15	98	.08	76	.15	73	0	(.01)				
1800	.09	62	0	(—.02)			—.01	(0)	.01	77				
1900	—.05	7	—.09	24			—.08	29	—.02	(0)				
2000	—.06	18	—.08	27			—.10	27	—.06	33				
2100	—.06	23	—.07	27			—.08	30	—.02	(.01)	.01	(—.04)		
2200	—.06	23	—.07	21	—.06	27	—.08	32	0	(.01)	—.06	83		
2300	—.06	25	—.06	26	—.05	31	—.06	22	—.01	(.01)	—.04	135		
2400	—.06	(0)	—.06	26			—.06	33	0	(.01)				

[a] The percentages were calculated from data in thousandths of a cal./cm.^{2} min. The bracketed data are in cal./cm.^{2} min. and replace nonsensical percentages.

Table 10. Heat losses per day beginning at 1600, 1957

		May 28-29	May 29-30	May 30-31	May 31-June 1	June 1-2[a]	June 2-3[b]
Energy available for heating the air and evaporating water, (A + W):	Open	319 cal./cm.^{2}[c]	308	309[c]	254	117[d]	218[d]
	Tent/Open	.86[c]	.84	.83[c]	.77	.86[d]	.64[d]
Energy used in evaporation, W:[e]	Open	25 cal./cm.^{2}	2	11	27	9	129
	Tent	48	30	—6	23	22	123
Energy lost into the air, A:	Open	294 cal./cm.^{2}	306	298	227	109	89
	Tent	226	228	262	173	78	17
Mean soil moisture concentration in upper 3 cm. on volume basis:	Open	5.9%	5.2	4.8	3.8	8.4	10.0
	Tent	7.7	5.4	4.8	4.4	8.7	10.2
Ratio of energy available for heating air to that used in evaporation, A/W:	Open	12.0	....	....	8.4	....	0.69
	Tent	4.7	7.6	....	7.5	3.5	0.14

[a] Rain of .33 cm. fell 13-1600 hours on June 2.

[b] Period ended at 1230 hours on June 3.

[c] Many large hourly values estimated.

[d] A few small hourly values estimated.

[e] Standard error of daily evaporation estimate — 7 cal./cm.^{2}.

and 31 where data were missing. The observations for 1800-1900 May 29 were employed for the same period on May 30. These estimates are shown in Table 10.

At night less heat was gained from the air and condensation at the sheltered surface than at the exposed surface. During the day, when the quantities of energy were larger, the surface of the tent lost 60 to 80 per cent as much energy to the air and to evaporation as did the exposed surface. Consequently, the daily quantity of energy for these twin processes was 64 to 86 per cent as great beneath the tent as in the open. The variation in this ratio was not correlated with the total available.

Partitioning energy between the heat loss to the air and the loss of heat to evaporation in an empty tent. The logically simplest device for allocating the quantities of energy tabulated in Tables 9 and 10 to the two processes of transfer to the air A and evaporation W is to measure evaporation and allocate the remainder to A. This course was followed in the empty tent of 1957.

Soil moisture was estimated each afternoon at 1600 hours except at 1230 hours on June 3. Cores with depths of 3 cm. and surface areas of 38 cm.^{2} were taken at 20 random sites within and at the same number without the tent; their moisture content was determined gravimetrically. The changes from day to day, corrected for any rainfall, provided estimates of evaporation with a standard error of 7 cal./cm.^{2} when the losses of water were converted into equivalent amounts of energy, Table 10.

The moister soil beneath the tent lost more water than the drier soil in the open during the first two periods. During the remainder of the time no significant differences were observed between open and tent. The mean moisture concentration, also presented in Table 10, is obviously the factor which affected evaporation most. Thus, evaporation was as high or higher in the tent than in the open because the soil was moister; this occurred despite the smaller quantity of energy in the tent. The effect of soil moisture was also evident in the ratio between the energy lost by transfer to the air and that lost by evaporation. This is the so-called Bowen ratio. A smaller fraction of the energy available for the two processes was lost to the air in the tent than in the open on all days. Even more dramatic, a smaller fraction was lost to the air on June 2-3 following a shower than during the preceding periods when the surface was nearly dry. Now we shall examine the more important case of a tent populated by moist surfaces such as tobacco leaves.

Partitioning energy between the heat loss to the air and the loss of heat to evaporation from a wet surface in an empty tent. During the greater part of the season the tent will be filled by the moist leaves of shade tobacco. Therefore, the separation of energy available for heating air and evaporating water between these two processes must be studied in situations where water is plentiful. A theoretical estimate was made of the ratio of evaporation from wet surfaces inside and outside the tent. The sources of the theory can be found in a review by Penman (1956). The evaporation from the wet atmometer bulbs in the tent of 1957 provided a check upon these estimates.

By combining the energy balance equation with an aerodynamic equation, Penman has provided a means of estimating evaporation that employs the observations found in Table 8 and 10:

$$W = \left\{ \frac{(A + W)}{s} \frac{de}{dt} + f(u)\,(e_d - e_a) \right\} \left\{ \frac{1}{s} \frac{de}{dt} + 1 \right\}$$

The de/dt is the change in vapor pressure per change in temperature, s is the psychrometric constant of 0.49 mm. Hg/°C, and $(e_d - e_a)$ is the vapor pressure deficit of the air at the mean daily temperature. The f(u) is a function of wind speed which Penman suggests be:

$$2/3\ (1/2 + u/160)$$

where u is the kilometers of wind movement per day. When Penman's equation is used for an estimation of the ratio of evaporation from a wet surface inside and outside of the tent, it becomes

$$W_t/W_p = \left\{ \frac{(A + W)}{s} \frac{de}{dt} + f(u)\,(e_d - e_a) \right\}_t \Big/ \left\{ \frac{(A + W)}{s} \frac{de}{dt} + f(u)\,(e_d - e_a) \right\}_p$$

The data of May 29-30, 1957, have been substituted into the equation for W_t/W_p. The daily accumulations of energy for $(A + W)$ were 258 and 308 cal./cm.^{2} in the tent and open (Table 10). The mean air temperature inside and outside the tent was about 16°; this sets $\frac{1}{s}\frac{de}{dt}$ at 0.89/0.49. Together with the dew points shown in Table 8, the mean air temperature also leads to estimates for $(e_d - e_a)$: 4.4 mm. in the tent and 5.0 in the open. The wind movement was 20 km. in the tent and 62 in the open. When these data are substituted in the equation for W_t/W_p, we see that the simple ratio $(A + W)_t/(A + W)_p$ or 0.84 provides a close approximation to W_t/W_p:

$$W_t/W_p = (1.8 \times 258 + 0.4 \times 4.4)/(1.8 \times 308 + 0.6 \times 5.0) = 0.84$$

Thus the ratios of 0.64 to 0.86 for the energy available for heating the air and evaporating water in the tent and open, line 2 of Table 10, provide ready estimates of the ratios of evaporation from wet atmometer bulbs in the tent to evaporation from bulbs in the open.

The evaporation from black Livingston atmometers was measured daily. Two bulbs were supported at a height of 35 cm. at both locations H in Figure 1. The daily losses from each bulb were transformed into logarithms and analyzed. The ratio between the loss inside and out was not affected significantly by the day. The mean ratio W_t/W_p was 0.84 with 5 per cent fiducial limits of 0.80 to 0.89. This observation agrees in general with the ratios of $(A + W)_t/(A + W)_p$ in Table 10 as predicted and permits us to state with confidence that evaporation from a wet surface in the tent will be about 0.8 of evaporation from a wet surface in the open.

The relative quantity of energy for heating air inside and outside a tent A_t/A_p can be determined by the same devices as used for the determination of relative evaporation. As expected, the ratio of the energy for both the heating of air and the evaporation of water serves as an estimate of the relative amounts of energy for heating. Thus, the diurnal change in temperature in the tent should be 0.8 of that outside. Any quantitative test of this prediction by the observations of Figures 4 and 5 is rendered impossible by the contribution of the tent roof to nighttime cooling. Nevertheless, the relatively lower daytime air temperatures within the tent are consistent with the prediction.

Evapotranspiration. In the preceding section theoretical and experimental indications were presented showing that the ratio of the energy for heating air and evaporating water inside to that outside the tent provided a simple and accurate estimate of the relative evaporation from wet bulbs in an empty tent. The temperature and humidity in a tent and field of moist tobacco leaves are given in Table 7 and the wind movement in Stewart's report (1907). Substituting these in the equation for W_t/W_p, one arrives at the same conclusion as for the empty tent: the ratio of the energy for both heating air and evaporating water is a close approximation to the ratio for evaporation alone. Evaporation here is evaporation from the soil plus transpiration from the leaves. Assuming that no major change in the estimate of $(A + W)_t/(A + W)_p$ is produced by the presence of plants and that it remains independent of the day, evapotranspiration or the consumption of soil moisture in a tent should be 0.8 of the consumption outside.

This prediction can be tested by comparing it with observations of transpiration made in Cuba by Hasselbring (1914). His data provide a test of the generality of the prediction because the observations were continued for 60 days and, hence, a variety of weather in a climate different from that of the Connecticut valley. Five plants were grown singly in weighing lysimeters both inside and outside the tent. The cheese-cloth in Hasselbring's tent was the same as we use today. The transpiration for the 60 day period for each of the 10 plants was transformed to logarithms and analyzed statistically. The mean transpiration in the tent was 0.77 of that in the open with 5 per cent fiducial limits of 0.69 to 0.91. A ratio of 0.75 prevailed for the last 5 days before harvest. These are consistent with the hypothetical ratio of 0.8 based upon observations of the energy budget and Penman's equation as well as upon atmometer observations. The inclusion of evaporation from the soil with transpiration should not alter the ratio significantly.

A generalization now seems possible with safety: throughout the season the consumption of soil moisture inside a tobacco tent will be about 0.8 of the consumption outside. This generalization makes possible the easy application to shade tobacco of available methods for estimating the consumption of water and the probability of drought (van Bavel and Verlinden, 1956; Palmer, 1958).

HUMAN COMFORT

Workers comment upon the tropical conditions within shade tents, even before the plants are set. If the insolation within a tent is only two-thirds of that outside and if the temperatures and humidities are equal, this seems strange. And yet it is so.

The comfort of men in a tent can be analyzed by a heat balance reminiscent of the one presented in the previous section for soil and plant. The analysis follows that of Buettner (1951).

At noon on a temperate day such as May 31, 1957, a man whose temperature is constant will gain heat from respiration and insolation and lose heat by convective and evaporative cooling. We assume he will have no net exchange of heat by long-wave radiation because the soil line is warmer and the sky is cooler than he; he will gain energy from the soil and lose it to the sky with little net gain.

Respiration will produce 120,000 cal./m.^{2} hr. where the area is that for convective heat loss to the air. Insolation of 1.2 and 0.8 cal./min. for each square centimeter of horizontal surface in the open and tent will add 120,000 and 80,000 cal./hr. for each square meter of skin area available for convective heat loss if the man's reflectivity is one-third and if he absorbs energy over an area one-fourth as great as the area for convective loss. Thus, a man outside of the tent must dissipate 240,000 cal./m.^{2} hr., one inside only 200,000 cal./m.^{2} hr.

Heat loss by convection is a function of the difference between skin temperature, 34.5°, and air temperature, 26°. It is also a function of the wind speed: $955\ u^{1/2}$ {cal./m.^{2} hr. °C} where u is the wind speed in m./min. (Buettner, 1951). Thus, the heat losses by convection from men standing in breezes of 100 m./min. outside and 33 m./min. inside a tent would be:

$$\text{Open: } 955 \times 100^{1/2}(34.5 - 26) = 81{,}000.$$

$$\text{Tent: } 955 \times 33^{1/2}(34.5 - 26) = 47{,}000 \text{ cal./hr. m}^2.$$

The quantities of heat that remain for dissipation by evaporation are (240,000 — 81,000) or 159 thousand cal./m.^{2} hr. for the man outside and (200,000 — 47,000) or 153 thousand cal./m.^{2} hr. for the man inside the tent.

Heat loss by evaporation is a function of the difference between saturation vapor pressure at skin temperature, 41 mm., and the vapor pressure in the air, 9 mm. on May 31. It is a function of wind speed: $h_w = 2075\ u^{1/2}$ cal./m.^{2} hr. mm. (Buettner, 1957). Finally, it is a function of p, the proportion of the surface which is wet:

$$p\,h_w + c\,(1 - p).$$

The c reflects the rate of evaporative cooling from the portion of the surface that is not wet; as an approximation we set c equal to 0.2 h_w. Then evaporative cooling is $2075\ u^{1/2}(0.8\ p + 0.2)\ (41 - 9)$ cal./m.^{2} hr. The evaporative heat losses must equal 159 and 153 thousand cal./m.^{2} hr. outside and inside the tent if the men are not to become warmer. Substituting the wind velocities of 100 and 33 m./min. for u and solving for p,

$$\text{Open: } 159{,}000 = 2075 \times 100^{1/2}(0.8\ p + 0.2)\ (41 - 9),\ p = 0.05$$

$$\text{Tent: } 153{,}000 = 2075 \times 33^{1/2}(0.8\ p + 0.2)\ (41 - 9),\ p = 0.25$$

Thus, this analysis shows that for maintenance of a constant temperature a larger portion of the skin must be wet if a man is working inside than if he is outside a tent. No doubt the sweating laborer inside the tent is less comfortable than his drier partner outside, even though the air temperatures are the same.

Another factor adds to the sheltered man's discomfort. As the plants grow, the vapor pressure inside becomes greater than that outside and an even greater wet surface is required to maintain a constant body temperature.

The discomfort experienced within a shade tent is not caused by a higher air temperature, rather it is compounded of the stillness of the air and — when plants are present — of a high vapor pressure that diminish convective and evaporative cooling more than the tent roof decreases radiational heating.

THE TENT AS A MODEL OF A FOREST

Energy budget of a forest. It was suggested earlier that a shade tent presented a simple shade situation that might be compared to the shade produced by a canopy of leaves. Are the two comparable? In what respects do the two types of shade differ?

Both the tobacco tent and a leaf canopy absorb some radiant energy, reflect some, and allow some to pass through to the ground beneath. The radiation balance on the ground is therefore similar in both, neglecting qualitative changes in spectral composition of the light transmitted through a leaf canopy as compared with that passing through the cloth tent.

Table 11. Radiation above the forest canopy as cal./cm.^{2} min. and below the canopy as a percentage of that above

Hour centered on	*Total incoming radiation*				*Total outgoing radiation*			
	Clear August 4-6		Cloudy August 13-15		Clear August 4-6		Cloudy August 13-15	
	Above	Below	Above	Below	From canopy	From ground	From canopy	From ground
1630	1.09	64	.93	74	.74	86	.70	94
1730	.83	80	.69	93	.69	91	.68	91
1830	.64	98	.62	100	.66	94	.66	92
1930	.63	98	.61	100	.66	92	.65	92
2030	.61	102	.63	98	.65	94	.64	94
2130	.60	104	.62	98	.64	95	.64	94
2230	.59	103	.57	104	.64	94	.62	95
2330	.54	107	.57	102	.63	92	.62	94
0030	.52	110	.57	102	.61	93	.62	94
0130	.50	111	.58	100	.61	95	.63	92
0230	.51	109	.60	97	.63	90	.63	92
0330	.50	109	.62	95	.61	92	.62	94
0430	.50	107	.60	97	.61	92	.61	95
0530	.54	101	.64	92	.60	93	.62	95
0630	.76	75	.69	88	.69	77	.61	98
0730	1.09	61	.77	83	.64	91	.64	94
0830	1.32	55	.80	80	.65	98	.65	92
0930	1.56	50	1.01	71	.66	105	.61	103
1030	1.73	48	1.12	67	.67	101	.70	96
1130	1.83	45	1.22	67	.68	94	.56	125
1230	1.81	44	1.17	65	.71	96	.63	105
1330	1.74	45	1.18	65	.73	99	.72	90
1430	1.56	45	1.23	62	.71	93	.69	97
1530	1.30	55	1.07	67	.65	100	.73	90
1630	1.08	62	.88	79	.71	89	.66	100
1730	.85	74	.73	90	.73	84	.68	94
1830	.60	99	.65	98	.67	88	.67	93
1930	.51	111	.62	100	.62	92	.66	92
2030	.50	113	.60	101	.60	95	.65	92
2130	.51	110	.60	101	.60	95	.64	94
2230	.52	107	.63	98	.62	92	.63	95
2330	.54	103	.60	100	.60	93	.64	94
0030	.53	102	.57	105	.60	93	.64	94

In the matter of the canopy itself, however,differences exist. Whereas the shade tent can be practically considered to have neither heat capacity nor thickness, a forest canopy has a considerable volume of air, water, and woody substance which can act as a reservoir for heat. In addition, evapotranspiration is a large sink of energy that is present in a living canopy but not in the empty tent.

Observations of radiation and heat flow made by Reifsnyder in a pine plantation in the summer of 1958 permit comparisons between the two systems. The plantation, established in 1915, consists primarily of red pine, with a few white pines. In 1958, the average stand height was 20 meters and the height to base of crown was 10 meters. Although originally planted to a 2 by 2 meter spacing, natural and artificial thinning resulted in a 1958 spacing of about 4 by 4 meters. Crown closure was incomplete, allowing considerable space between crowns; and crown density was low, permitting sky to be visible through the crowns.

Basic instrumentation was the same as that for the tobacco tent study. Whole-spectrum incoming radiation was measured above the stand and beneath the canopy with Gier-Dunkle radiometers. Net radiation was observed at the same levels. Measurements were recorded on a potentiometer. Elements were sampled for half-minute intervals several times each hour on a cyclical basis.

Table 11 presents hourly averages of radiation data obtained by averaging all measurements obtained during the hour. Two periods are presented: the first a period of clear weather; the second a cloudy period.

Transmission of radiation through the forest canopy. With the shade tent, it was seen that, contrary to expectation, the depletion of solar radiation by the tent was not materially affected by the hour and angle of the sun. The same is true for a forest canopy during the midday hours (Table 12), although certain reservations must be made. Reflection downward from the single-layered tent is

Table 12. Solar radiation above the forest canopy as cal./cm.^{2} min. and below the canopy as a percentage of that in the open

Hour centered on	Clear day, August 5		Cloudy day, August 14	
	Above	Below	Above	Below
0430	0	—	0	—
0530	0	—	.05	0
0630	.14	4	.08	9
0730	.44	14	.14	12
0830	.66	15	.16	9
0930	.87	16	.34	20
1030	1.02	17	.43	20
1130	1.11	14	.51	26
1230	1.09	12	.48	16
1330	1.01	10	.48	18
1430	.84	4	.53	15
1530	.60	6	.38	11
1630	.39	2	.20	13
1730	.18	0	.07	5
1830	.01	—	.01	0
1930	0	—	0	—

more efficient than from the forest canopy. In addition to having a lower reflectivity, the mass of pine needles acts as a greater barrier to downward reflection, intercepting reflections from above, absorbing some of this energy and reflecting part. With low solar angles, most of the solar energy reaching the ground beneath the canopy will be reflected light plus some diffuse light from the sky. With high solar angles, a greater portion will be from direct rays of the sun passing through the canopy. Thus we would expect somewhat higher percentages of the radiation to pass through in midday.

The tent was observed to have a differential effect on total and short-wave radiation, decreasing light more than total radiation on an overcast day, with a similar, though greater effect on clear days (page 17). The same is true of the forest canopy. We assume that the equivalent sky temperature is equal to the temperature of the plate of the radiometer. The comparison for the forest can be made from the following radiation data from midday:

	Clear day			Cloudy day		
	Long-wave	*Short-wave*	*Total*	*Long-wave*	*Short-wave*	*Total*
Above canopy	.72 cal./cm.^{2} min.	1.11	1.83	.71	.51	1.22
Below canopy	.66 cal./cm.^{2} min.	.16	.82	.67	.14	.81
Below/Above	92 per cent	14	45	94	27	66

The forest canopy depletes the long-wave radiation very little. (Because we estimate the long-wave radiation by assuming that the equivalent sky temperature is the same as the radiometer plate temperature, certainly an overestimate, the long-wave radiation below the canopy is likely greater than that above, agreeing with the tent measurements). But the canopy takes out more short-wave energy on a sunny day than it does on a cloudy day. Thus the canopy and the tent act similarly with regard to depletion of short-wave energy, although the forest canopy removes a much greater amount, being much denser than the tent cloth.

Radiation relationships are thus similar in the two systems, and the shade tent can be used as a model for the pine forest, within the limitations set forth at the beginning of this section.

Air and soil temperatures. Temperatures of the top of the litter layer beneath the forest canopy showed wide variation during daylight hours on the clear day. This fluctuation, as much as 16° from one measurement to the next (about 20 minutes), was caused by flecks of sunlight moving across the forest floor. The highest value recorded was about 13° higher than the average value for the hour in which it occurred. This gives a rough estimate of the effect of the canopy on surface temperature on a clear day, and may be compared with the maximum 4° difference produced by the shade tent under similar sunny conditions. At 1.5 meters, in standard weather shelters, the temperature under the forest canopy was 1.5° cooler than in the open, under sunny conditions. Under the tent, air at this level was not significantly cooler than that outside; with the smaller difference in surface temperatures, this is to be expected.

During clear nights, air temperature under the forest canopy was about a half degree warmer than in the open.

On cloudy days, the surface temperature of the litter varied less than 2° from the hourly means, usually varying less than one degree. Air temperatures at 1.5 meters in the forest were less than one-half degree lower at midday than those outside, implying that surface temperatures under the canopy were only slightly less than those in the open. At night, the differences in air temperature were even less, and surface temperatures were probably very nearly the same inside the stand as in the open. In the forest, therefore, the differences were measurable, greater than those found with the tent, but understandable in terms of the relative densities of the cloth and leaf canopy.

CONCLUSIONS

For half a century the shade tent has been used in the production of tobacco leaves for wrapping cigars. One can now see changes in the climate created by the tent that are dramatic and may be significant in producing valuable wrapper leaves. Of course, the final test of their significance in physiology must be made in controlled experiments. One can also see by comparison the salient features of forest shade.

The light intensity beneath the tent on clear days is only two-thirds of the intensity outside. Reflection of light into the tent by the threads permits this relative light intensity of two-thirds although the threads cover nearly half of the surface. Reflection also maintains the two-thirds intensity early and late in the day and increases the relative intensity to four-fifths on cloudy days. A one-third to one-fifth depletion of light causes a reduction in the net fixation of carbon in other plants during early morning, late afternoon, and cloudy weather (Thomas and Hill, 1937; Moss 1959). A similar reduction in fixation may occur in tobacco. This is not contradicted by the equal yields of dry matter beneath the tent and in the open (Hasselbring, 1914) if one assumes that other limitations to growth operate in the open; it is consistent with the observation of relatively low sugar concentrations in shaded tobacco leaves (Zucker, 1959).

Evaporation is only four-fifths as great beneath the tent as it is outside. Thus the shaded plant must be subjected to fewer droughts and checks in growth than exposed plants and should have fewer of those attributes generally ascribed to "hardening."

The wind outside the tent is much stronger than within. Whitehead (1957) has shown how strong winds cause stomates to close and decrease the accumulation of dry matter. This deleterious effect of wind is partially, at least, due to dessication, which has already been shown to be higher in the open. If, however, it is also due to decreased transfer of carbon dioxide to the leaf, this effect will add to the effect of decreased light intensity and produce reduced assimilation beneath the tent. Decreased assimilation in shade leaves has already been suggested.

The changes in air and soil temperatures and in humidity seem slight relative to the other changes noted and relative to the changes required to evoke a response in plants.

The decrease in evaporation caused by the tent has significance in irrigation practice. Less water is required by shaded than by open-grown tobacco for the maintenance of a desired moisture level in the soil. If an amount adequate for open-grown tobacco is applied to shaded tobacco, water and nutrients will inevitably be wasted as they leach beyond the reach of the roots of the shaded tobacco.

Men often find the climate within the tent uncomfortably tropical despite the equality of temperatures inside and out. The decrease in insolation within the tent is more than compensated by the decrease in convective and evaporative cooling that accompany the sharp reduction in wind. Hence, men perspire more inside the tent than outside to maintain a constant body temperature.

Lastly, in relations involving the depletion and reflection of radiation, and air and soil temperatures, the tobacco shade tent approximates a forest canopy. It can therefore be used as a simplified model of a forest. Caution must be used, however, because a forest canopy is a major source and sink of heat, whereas the tent contributes but little to a storage and release of heat.

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