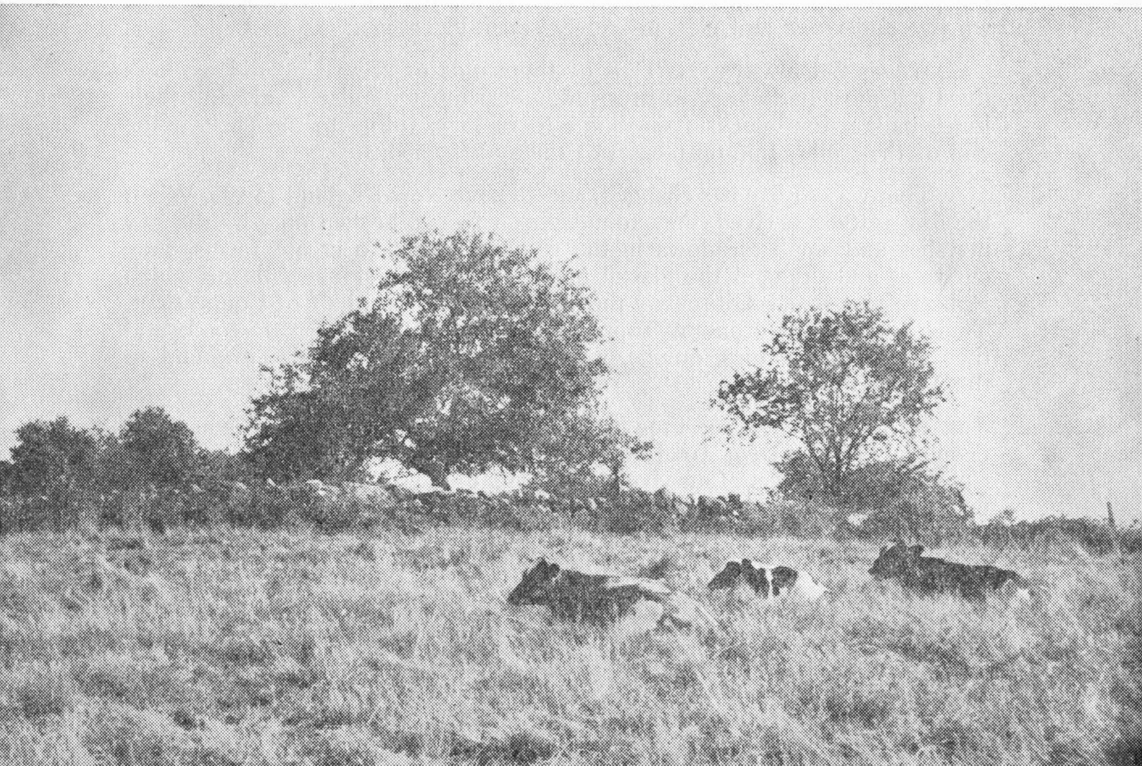
Plants, Shade, and Shelter

Paul E. Waggoner



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Foreword

In this Bulletin the reader will find a scientific study of microclimates, the peculiar and small climates of particular places in which many Connecticut people live, shop, and play. Some of these microclimates have been changed by man, others have been unchanged for centuries. Our interest in microclimates, artificial or natural, is directly related to our present-day mobility. Henry Ford put the nation on wheels, and now we live and work and play in widely separated areas.

It was not always so. Tens of thousands of New England workers lived out most of their lives in a few microclimates indeed, carrying their lunch pails a few blocks from home to factory, riding to the park at the end of the trolley line on pleasant Sunday afternoons.

That way of life has changed, and so have New England farms. When the first settlers arrived, they found virgin forest, broken only by the salt marshes and small meadows in the river valleys. To create farms, they cut trees and dragged the glacial boulders into the stone walls of which Robert Frost sings. Ultimately they cleared more than half of Connecticut. Their agricultural economy supplied most of their needs for food, and they exported potatoes, onions, meat, and tobacco to New York and to the West Indies.

It has been a long time since Connecticut farms fed Connecticut people. Now our cows are fewer, but they give three times the milk that Colonial cows gave. Our fruit, poultry, tobacco, and vegetable farms produce likewise, and still we rely more and more on the fields and orchards of the West and the South. Modern transport ties the nation together, releasing much of our land from farming.

Thus many of the fields once plowed or mowed have become thickets. As more and more people come to live in Connecticut, fields and woodlands have become developments, filled with houses and children and ranch wagons. With the people have come shopping centers, outdoor movies, and multi-lane highways, occupying land once farmed. Cottages and year-round residences line our Shore and surround our lakes. Hundreds of thousands live in the country.

At least it used to be called the country. In this new country living, citizens complain if the school bus is late or the driver is surly, they get fuel oil deliveries within the hour after calling, and they expect $50,000 worth of fire-fighting equipment to arrive in minutes to quench a smoldering TV set.

These newcomers to the Connecticut countryside, these exurbanites, have time and money to spend in their new microclimates of old field or woodland. Within limits, they can create microclimates that suit them, at least part of the time. The study here reported may help them understand the natural laws that define what can be done, and what cannot.

W. L. Slate
Station Director Emeritus

Contents

Acknowledgments

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Cover Photo

The pasture, one of seven sites where microclimate was studied.

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The migration from city and farm to the suburbs has caused homes to rise and lawns to spread across fields where corn or hay grew only last year. Or, as in so much of New England, where the farms were forsaken and the hills were last cleared a generation ago, the new lawns are clearings in a thicket of briars, honeysuckle, and trees struggling to make a forest. The immigrants to either the fields or the thickets both encounter extreme microclimates: Some of them find no trees to shade them, the others are smothered in their shelter. In this Bulletin we shall describe the climate and comfort of seven sites: the pasture and its shade tree, the thicket and its clearing, the beach, the lawn, and the parking lot.

The common indicators of climate and comfort, the temperature and humidity, differ very little among these sites and their microclimates. This perplexes the inhabitant, who surely feels a difference.

The perplexity arises because the thermometer in its louvered Weather Bureau shelter passively follows the temperature of the air, while the man's body strives to maintain an unchanging temperature. More, or less, heat is produced inside the man as he exerts himself more or less. If he is to be comfortable, this heat must be nicely balanced against several variable streams of heat that are entering and leaving the human system. If these are not balanced, his temperature will rise or fall, leaving him feverish or chilled. Thus comfort is determined not by the temperature of the air but by whether the man must sweat or shiver to balance several streams of energy and maintain his temperature unchanged.

How much he exerts himself and, hence, how much heat he generates is his affair. How much clothing he wears is also for him to decide. Our business is measuring the streams of energy in each site and presenting for each site the number of calories of heat that a lightly clad man could lose without sweating. We must also integrate the streams of energy in terms of the loss from a man who is soaked with sweat. If the weather is hot, or the work is heavy, the site with the greatest potential for loss will seem coolest and most comfortable. If the weather is cold, or the worker rests, the site with the smallest potential will seem warmest and most comfortable.

Calories are gained and lost via four routes. The first two are two sorts of radiation. Because radiation is given off in wavelengths and amounts fixed by their temperature, the incandescent sun emits radiation of relatively short wavelengths. This is the first route for calories. We call it sunlight, for much of its energy has waves so short that they are visible. We see it blocked and call the barrier "shade." For a man or tree, the sun's short-wave radiation is a one-way route of gain without loss.

The second channel for calories is also radiation, but its waves are long and invisible, for the radiators are relatively cool. It is a route of both gains and losses, for these long waves are the ones emitted by objects that have the temperature of man or tree. The amount given off is according to the temperature of the object.

A man gives off these long waves, while he receives others from everything about him. Thus, in the summer he feels the heat from a hot black pavement, and in the winter he feels a cold window. He is absorbing much long-wave radiation from the hot summer pavement and little from the cold winter window. Within sight of the window he wants shelter because he suffers a net loss by long-wave radiation, and the loss must be made up somehow.

The two remaining routes for calories are convection and evaporation. Convection is easily visualized: as cool air passes about the man and is warmed by his skin, calories are carried away from the man and into the atmosphere. Evaporation, the remaining route for calories leaving the man, can also be pictured: perspiration wets his skin, calories are taken from him to change the liquid into gaseous water, and this vapor is removed from his neighborhood by a turbulent atmosphere.

Here the two common indexes, air temperature and humidity, are useful indicators of comfort. The cooler and drier the air, the more calories will be carried away via convection and evaporation. Even here, however, air temperature and humidity will not serve alone, for ventilation as well as cold and aridity speed the losses. Thus when shelter stills the wind, it slows the loss of heat via convection and evaporation. Then they contribute less to the sum of themselves and radiation, and thus, the losses and comfort of the man are changed.

Since shade or shelter has most effect, and to us most significance, when the sun shines or the evening sky is clear, our observations were taken under unobscured midday sun or a cloudless evening sky. These conditions were most easily encountered in the autumn. Thus on September 20 through October 2, 1962, we collected the observations of radiation and ventilation, temperature, and humidity. From these nearly ideal conditions we shall surmise how the shade and shelter of plants might affect a man's loss of heat and, hence, comfort on a hot day or a cold evening.

The Sites

On Sachems Head, a projection of the Connecticut coast into Long Island Sound, idealized sites were found, and the landowners, Milton and Edwin Benton, kindly permitted us to carry cables and radiometers through their woods and pastures. The *pasture* site, in the background of Fig. 1, is on a knoll, 50 feet above the Sound which lies one-third mile to the south. Between pasture and Sound is a salt marsh as well as low fields where blueberries abound. In the other directions are hills covered by second-growth woods; the pasture extends several hundred feet, however, before the woods are reached. The native grass was not closely cropped and much was ripe and dry. Nevertheless, most of the grass was still green and formed a mat not more than 3 inches deep.

Along the ridge about 60 feet from the pasture site stands the *apple tree,* Fig. 1. It is 15 feet tall. Its crown is 25 feet across, and

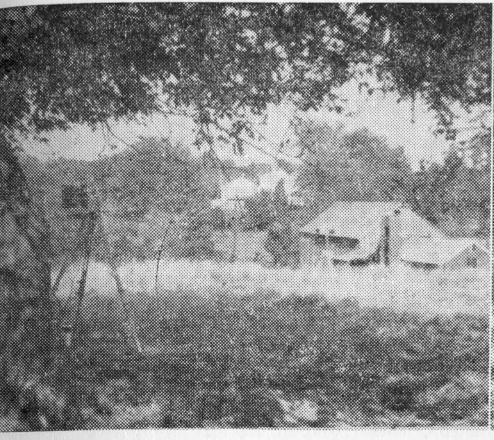

Figure 1. The apple tree.

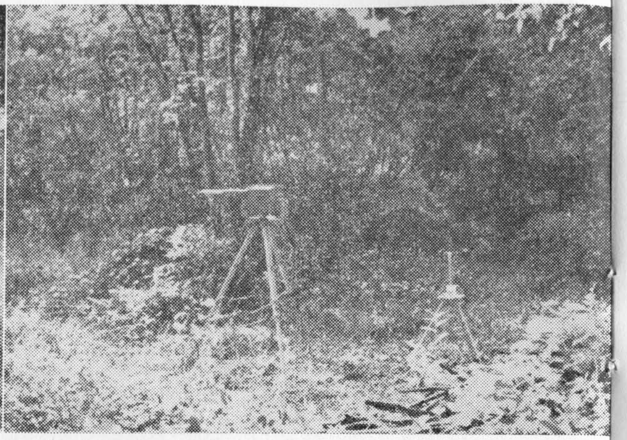

Figure 2. The clearing in the thicket.

beneath, it has been browsed to 6 feet. Cows enjoy its shade and fruit and have trampled the grass beneath. In the autumn much of its shadow does not fall beneath the crown, for the sun is low in the sky; thus one can stand in its shade but beneath the open sky. Twenty-five feet west of the apple tree is a 3-foot stone wall which separates one pasture from another (Cover photo).

Near sea level and 800 feet to the southeast lies the *clearing* in a thicket of red maple, tulip tree, speckled alder, black cherry, briars, and grape vines (Fig. 2). The clearing is 25 feet in diameter. The screen is thinnest to the southeast, the direction of the salt marsh. On the floor of the thicket, a sparse growth of briars had appeared, and it was cut before observations began.

In the *thicket* a few feet away, observations were taken among a tangle of briars and saplings. Where dim light fell upon the damp ground,

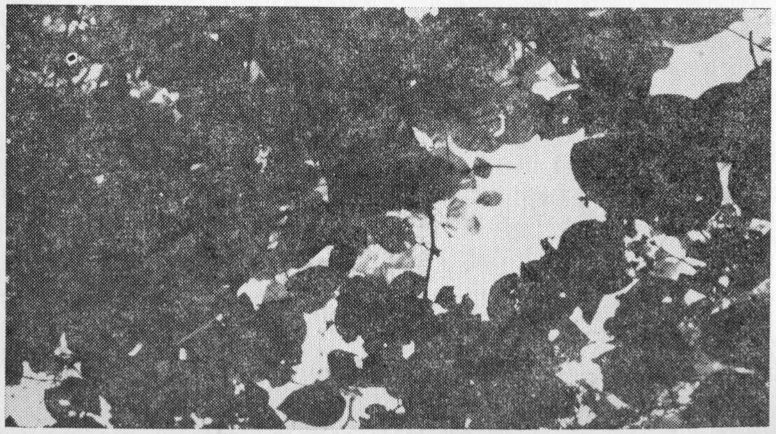

Figure 3. The tangle above the radiometer in the thicket.

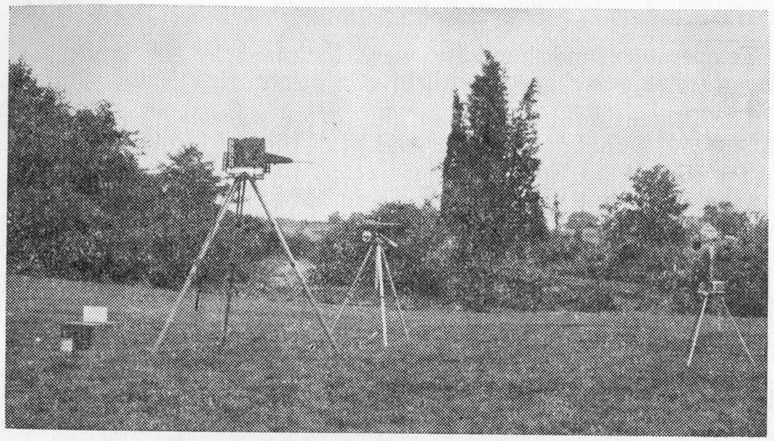

Figure 4. The lawn with the salt marsh and Sound beyond.

jewel weed grew. Overhead, maple and grape leaves covered the view (Fig. 3).

Between pasture and thicket is a *lawn* of nearly an acre, well watered and mown (Fig. 4). Few tall plants hinder the breezes from the Sound.

On the *beach* observations were taken above a level stretch of sand that had nearly dried after the tide had receded (Fig. 5). A few feet away, enclosed on three sides by *reeds* 6 feet tall, is a 20- by 25-foot patch of dry sand.

Behind the 5-foot dune that forms the beach and supports tall reeds is the salt *marsh* (Fig. 6). It is covered with the low grass and other plants that tolerate the salt water which wets the muck beneath. These plants were bent into a reddish-green mat about 3 inches thick. Beneath the mat, water stood on the soil and squished under foot.

The *parking lot* is inland, 3 miles from the other sites. It is paved with asphalt, and surrounded on two sides by a supermarket and houses.

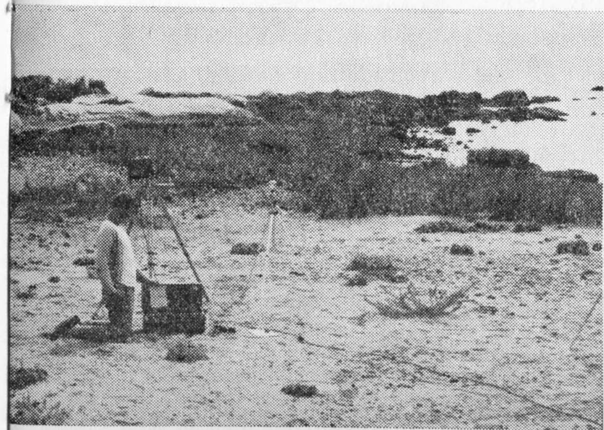

Figure 5. The beach.

Figure 6. The salt marsh.

The Instruments

Temperature and humidity were indicated by an aspirating psychrometer that was shaded and held at a height of 3 feet.

The R, density of the radiant flux of all wavelengths, was indicated by a Gier and Dunkle[1] radiometer and S, density of insolation or radiation from the sun, by an Eppley pyrheliometer. These meters are planes, and the radiation from the upper and lower hemispheres was observed separately, by directing the meters first upward (u) (Fig. 2) and then downward (d) Fig. 4). The direct insolation was estimated as $0.9S_u$, the scattered insolation and long-wave radiation from the upper hemisphere as $0.1\ S_u + (R_u - S_u)$, and reflected insolation and long-wave radiation from the lower hemisphere as S_d and $(R_d - S_d)$.

Wind speed was indicated 3 feet above the ground by anemometers made by Mr. William Wright. The dimensions were approximately those of an airways Weather Bureau anemometer, but the cups were thin plastic, the arms were slender aluminum rods and the counter was actuated when a small magnet in the hub passed above a proximity switch. The bearing was a metal point on which a glass hemisphere hung and turned. In the field, the four anemometers agreed within 3 per cent. In a steady draft in the laboratory, the anemometers were calibrated by means of a Velometer (Illinois Testing Laboratory, Chicago). Wind speed was measured more or less simultaneously by anemometers at each site, while the other factors were measured sequentially as I carried instruments from site to site.

Analysis

If a man is not to become cooler or warmer than normal, his metabolic heat and his receipt of solar radiation must be balanced by net exchange through long-wave radiation between him and his environment, by convection, and by evaporation. All of these streams of energy that enter and leave the human system have been described in the Introduction. Now they must be reduced to equations that will accept our numerical data.

Accordingly we write the exchange of energy with the environment as the sum:

Solar radiation + Long-wave radiation + Convection + Evaporation

During a midday hour, solar may add 150, long-wave radiation add 250 and subtract 400, convection subtract 200 and evaporation subtract hundreds of kilogram calories from each square meter (kg cal m^{-2} hr^{-1}). Small wonder that temperature and humidity alone do not reflect the "feel" of an environment or a microclimate. Our observations of the several factors are, therefore, integrated by an estimation of the net loss of energy.

This estimation requires a description of the man who experiences the losses because the warmer his skin and the more he sweats and the thinner his clothing, the more heat he loses. Since our primary interest is analysis of microclimates and not of men, we shall specify a standard man and move him from one microclimate to another, estimating his loss of energy in each. Although he will be ill-clad in some, his energy exchanges

[1] Gier, J. T. and R. V. Dunkle. 1951. Total hemispherical radiometers. Proc. A. I. E. E. 70:339-343.

in all will reveal the significant differences among the environments. The following generally follows Buettner[2].

The man is clad only in shorts. His skin has a temperature of 33 C (91 F). He presents an area of 1 m^2 or about 1 square yard for the exchange of radiation with his surroundings, for the convection of the atmosphere, and for evaporation. For the receipt of the direct sun beam he presents only 0.25 m^2, but for the scattered and reflected sunlight he presents fully 1 m^2. He absorbs 0.65 of the insolation and 0.96 of the long-wave radiation which reaches him. We assume that the sum of the scattered and reflected solar and of the long-wave radiation from the two hemispheres that warms the radiometer plates indicates the radiation that warms the man. He emits 0.96 as much radiation as a perfect radiator that is as warm as his skin; thus he emits 414 kg cal m^{-2} hr^{-1}.

The gain of solar radiation is, therefore,

$$0.9\ S_u \times 0.65 \times 0.25 + 0.1\ S_u \times 0.65 \times 0.50 + 1.0\ S_d \times 0.65 \times 0.50;$$

the gain of long-wave radiation is

$$1.0\ (R_u - S_u) \times 0.96 \times 0.50 + 1.0\ (R_d - S_d) \times 0.96 \times 0.50,$$

and the radiation emitted by the man is 414 kg cal m^{-2} hr^{-1}. The loss by convection is $1.2\ v^{1/2}\ (t_s - t_a)$ kg cal m^{-2} hr^{-1} where v is wind speed in centimeters per second (cm sec^{-1}), skin temperature t_s is 33 C and t_a is air temperature. (A 1 mile per hour breeze is 45 cm sec^{-1}). When the man is dry he will lose little by evaporation, but when he is wet with sweat he loses

$$1.63\ v^{1/2}\ (e_s - e_a)\ \text{kg cal m}^{-2}\ \text{hr}^{-1}$$

where e_s and e_a are the vapor pressures (millibars) of the wet skin (50.1 mb) and of the air.

The net loss is the algebraic sum of emission, convection, and evaporation less the gains via solar and long-wave radiation.

As warned above, the man will be ill-clad for autumn evenings and even some days. For example, to balance the loss of 474 by a dry man in the pasture on the evening of September 21 would require the heat generated by brisk walking. This loss could easily be reduced by clothing. One unit of clothing maintains comfort when one is seated at 21 C (70 F), usual room temperature[3]. This clothing would reduce the loss from 474 to only 126, which equals the heat generated when one is merely working at a desk.

To balance the losses incurred by a wet man on the same evening would require exertion that would soon exhaust him. Nevertheless, the losses estimated for a lightly clad man in the different environments reveal the difference among them. This is our objective, and we turn to the data.

[2] Buettner, K. J. K. 1951. Physical aspects of human bioclimatology. *In* Compendium of Meteorology, T. F. Malone, ed. Amer. Meteor. Soc., Boston. pp. 1112-1114.

[3] Winslow, C. E. A. and L. P. Herrington. 1959. Temperature and human life. Princeton Univ. Press. p. 136.

The Pasture and Its Shade Tree, the Thicket and Its Clearing

Meteorological observations of radiation, wind, temperature, and humidity are presented in Table 1. They describe two mornings, three middays, and two evenings shortly after sunset at the pasture, under the apple tree, in the clearing, and in the thicket.

The radiation coming directly from the sun and scattered from the sky, occasional cumulus clouds, and nearby trees is tabulated in the first column of data. In the early morning when the sun is low, this sunlight is intercepted by the curtain of the thicket surrounding the clearing; hence insolation from above was decreased from the 0.60 cal cm^{-2} min^{-1} in the pasture to only 0.25 in the clearing. This difference was barely evident at 10 a.m. or 1000 hours on the 23d. By noon it had disappeared, and solar radiation was about the same in pasture and clearing.

The long-wave radiation that comes from the vapor or gases, occasional cumulus clouds, and nearby trees that are above the meter is tabulated in the second column. Generally it was greater beneath the apple tree or in the clearing than beneath the cold sky above the pasture. It was always great where the warm thicket enclosed the meter. At the same site, long-wave radiation from above will vary from time to time as the amount of water in the air varies; for example, between 1810 and 1900 hours (6:10 and 7 p.m.), it increased from 0.41 to 0.46 in the clearing because scattered cumulus had appeared in the sky. Further, the long-wave radiation from above depends upon how far beneath the canopy the observer stands; for example, near 1030 on September 30, it was 0.50 under a tree, 0.46 in the shade of the tree but outside the canopy, and 0.38 over the lawn.

The sunlight or insolation that is reflected by the earth and then strikes the radiometer plate from below is tabulated in the third column. Much was reflected from the sunlit grass of the pasture, little from the litter of the clearing floor, and least from shaded vegetation.

Long-wave radiation emitted from the earth and its cover is tabulated in the fourth column. This emission is proportional to the fourth power of absolute temperature, that is 273 plus the temperature in centigrade. Thus, the differences in radiation accompanying a few degrees difference in temperature between pasture grass and thicket web were small.

Wind speed appears in the fifth column. The shelter of the brush that both surrounded the clearing and comprised the thicket was distinctly revealed. Since the thicket was thinner on one side than another, the reduction in wind varied as wind direction varied.

Temperature and humidity of the air are set down in the sixth and seventh columns. As expected, the small differences in the heat and moisture content of the air that surely exist among these environments were obscured by our sampling in sequence rather than simultaneously. From the point of view of our use of the data, if these differences are too small to discover by sequential observation, they are inconsequential compared to the clear differences in radiation and ventilation.

The "feel" of the environments, integration of the microclimatic factors in terms of man's loss of energy, is tabulated in the remaining two columns. In the column entitled "Energy loss, Dry" is the estimated number of kg cal m^{-2} hr^{-1} that our lightly-clad standard man hypothetically

Table 1. The environment and estimated heat losses from a lightly-clad man in a pasture (P), beneath an apple tree (A), in a clearing (C), or in a thicket (T), September, 1962

		Radiation, cal cm^{-2} min^{-1}					Air		Energy loss, kg cal m^{-2} hr^{-1}	
		Upper hemisphere		Lower hemisphere						
Date and hour	Place	Insolation	Long-wave	Insolation	Long-wave	Wind, cm sec^{-1}	temp. C	humid. mb.	Dry	Wet
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
21 0737	P	.60	.28	.15	.50	182	9.3	6.4	480	1633
0751	A	.07	.33	.02	.47	157	9.4	7.3	526	1575
0658	C	.25	.39	.04	.50[b]	49	7.7	7.0	338	929
0711	T	.02	.46	<.01	.50	8	6.9	7.2	221	453
23 1020	P	1.08	.35	.21	.56	397	17.2	10.6	372	1913
1030	A	.18	.41	.05	.58	375	16.7	9.5	478	2021
0950	C	.88	.56	.14	.55	116	17.0	10.6	186	1020
1003	T	.09	.54	.02	.56	84	16.5	11.1	265	967
20 1324	P	1.10	.38	.19	.60	2.4	16.1	6.6	8	139
1337	A	.09	.58	.03	.56	6.1	16.1	7.3	121	336
1227	C	1.10[a]	.61[a]	.10	.55	3.6	18.1	7.1	—24	135
1247	T	.07	.59	.03	.58	0.6	17.8	10.0	77	137
21 1154	P	1.19	.45	.24	.58	225	15.6	6.9	256	1526
1203	A	.09	.47	.03	.53	194	15.7	7.0	399	1572
1138	C	1.27	.43	.17	.58	82	14.6	4.8	154	960
1130	T	.09	.54	.02	.54	20	14.2	5.3	189	583
30 1154	P	1.14	.44	.22	.61	397	18.5	13.0	293	1740
1217	A	.10	.51	.03	.62	406	17.8	12.7	440	1921
1111	C	1.07	.53	.12	.60	89	18.9	12.3	109	808
1125	T	.06	.57	.01	.56	30	19.6	14.1	168	553
20 1848	P		.34		.48	147	11.0	7.5	497	1506
1839	A		.48		.50	105	11.0[b]	7.5[b]	402	1259
1811	C		.41		.48	32	10.0	8.2	314	779
1758	T		.47		.50	9	10.6	8.7	215	460
21 1810	P		.34		.45	91	7.8	7.7	474	1267
1846	A		.48		.48	64	7.6	7.8	381	1045
1752	C		.41		.48	17	8.4	7.9	281	623
1743	T		.47		.49	0	8.4	7.9	211[c]	418[c]

[a] R_u measured, E_u estimated. [b] Assumed equal to conditions in nearest site. [c] Minimum $v^{1/2}$ was assumed 3.0/1.2.

lost in each environment if he did not perspire. In the last column are his losses if he were soaked. Marked differences are seen.

In the early morning while sunlight was at only half the midday intensity, the heat losses of either a dry or wet man were less than half as great in the thicket as in the pasture or beneath the apple tree. The clearing still seems cooler than the thicket.

About 1000 the clearing had become the warmest place for a dry man. Here the heat loss was only 186, less than half that beneath the apple tree and half that in the sunlight of the pasture. For the sweating man, the shade of the thicket seems no benefit. Because ventilation was slow, this wet man could lose only half as much heat as in the shade of the apple tree or even in the sunlit pasture. Of course, if temperatures are low, the shelter of the thicket or clearing is comfortable.

Breezes were slow at midday on September 20, and a dry man in the clearing would gain more heat than he lost. Losses were scarcely greater in the pasture, for the wind was nearly calm. The shade of the thicket was relatively important at this time, for the convective losses were slight everywhere. Nevertheless, beneath the apple tree, the open sweep for the breeze was evident in the greater loss.

Breezes were brisker at midday on September 21 and 30 and the familiar pattern was repeated: from a dry man, losses were least in the clearing; and from a wet man, losses were least in the thicket.

After sunset, the shelter of the thicket clearly reduced loss of heat from dry or wet men. Even in the clearing, where the thicket provided a windbreak without overhead shelter, it reduced losses. The canopy of the apple tree radiated more energy than the cold sky above the pasture and provided detectable shelter; but half the advantage was in the slower breeze that blew beneath the tree.

In concluding the consideration of these environments, we must recall that the effects of shade will be starkest under the clear skies we have observed. Also they will be greatest when leaves are on the branches, as when we visited the sites. In winter only a framework of branches remains to intercept sun and wind.

The shade of the thicket includes shelter. When a man is hot, the thicket is not as comfortable as beneath the lone shade tree in the pasture. The clearing provides shelter without shade, and here eliminating excess heat is most difficult. In the evening the reduced losses in the shelters can still be felt, and would be enjoyed in cold weather. Having summarized these four microclimates, we now compare other microclimates.

The Beach and Marsh, the Lawn and Parking Lot

Meteorological observations on beach, marsh, lawn, and parking lot are set down in Table 2. They describe midday, October 2.

Solar radiation decreased as the hours passed, and the sun moved lower. At the same site the long-wave radiation from above, however, varied little with time. This was seen at the lawn where it varied from only 0.35 to 0.36 between 1305 and 1424 hours. Instead, long-wave radiation varied among sites rather than among times. On the beach and marsh, where the air was laden with water from the Sound, long-wave radiation from above was greater. Also, among the buildings, power lines, and neighboring trees of the parking lot, this radiation was greater than on the lawn.

The solar radiation reflected from below is tabulated in the third column of data. Beach, marsh, and lawn reflected much, but the black asphalt reflected little. So great was the emission of long-wave radiation from the asphalt, however, that the sum of outgoing radiation of all wavelengths was greatest above the black paving. In contrast to this, the succulent, well-watered, and cool grass of the lawn emitted less than the marsh or beach.

Ventilation was similar in all sites except among the sheltering reeds. Temperature differences were slight, but the differences in humidity reflected the proximity of the Sound.

The integration of these microclimatic factors appears in the final two columns of Table 2. Most heat was hypothetically lost by a man standing on the lawn. Here the wind blew freely, and the income of radiation was 40 to 61 kg cal m^{-2} hr^{-1} less than at the other sites, for the grass underfoot reflected and emitted little radiation. On the other hand, the least heat was lost from a man among the sheltering reeds and on the warm sand of the beach.

The surprising outcome is the nearly identical heat losses on beach and parking lot. Some of this was caused by the decline of the sun between observations on beach and lot. To compensate for this imperfection in observation, insolation densities may be set equal. Then the losses of a dry man in the parking lot become only 156, and of a wet one only 1213. The radiant heat loads would then be nearly identical on beach and lot. In addition, if the parking lot were inland and had a temperature 2 C degrees warmer than the beach, the losses would become still less: 129 and 1185. Under these circumstances a dry man would lose fully 189 on the beach but only 129 in the parking lot.

Still, these seem surprisingly similar. Thus the pleasure of the beach must lie in large part in the cooling of evaporation as one dries after swimming and in the light clothing worn on the beach. In the parking lot, meanwhile, the shopper clad in heavier clothes walks among the heat and exhaust of engines. We shall extend the discussion of our results still further by creating other idealized situations.

Summertime

Since much of the interest in shade comes in the summer, we shall estimate the heat that our standard man would lose on an idealized summer day. In his book *Physical Microclimatology,* F. A. Brooks, of the University of California, provides us with the sort of data we have employed in Tables 1 and 2. The day was much warmer than we observed, however, reaching 32 C or 89 F in Davis, California, and the ground was bare.

In the first line of Table 3, these observations from a warm summer noon are set out in the same form as were ours in the earlier Tables. In this case, the dry man would actually gain rather than lose heat and would necessarily sweat to prevent his body temperature from rising.

(Brooks' observations included the radiation received by a black sphere: 636 kg cal m^{-2} hr^{-1}. This can be compared to our estimate of radiation received by a man who reflects about one-third of sunlight: 550. It may also be compared with a summary of our radiometer observations that assumes complete absorption of all radiation: 684. Thus our analysis of observations of plane radiometers in terms of receipt by man's 3-dimensional shape is reasonable.)

Table 2. The environment and estimated heat losses from a lightly-clad man on a beach (B); among reeds (R); on a marsh (M); lawn (L); or parking lot (PL), October 2, 1962

		Radiation, cal cm⁻² min⁻¹					Air		Energy loss, kg cal m⁻² hr⁻¹	
		Upper hemisphere		Lower hemisphere						
Hour	Place	Insolation	Long-wave	Insolation	Long-wave	Wind, cm sec⁻¹	temp. C	humid. mb.	Dry	Wet
1134[b]	B	1.09	.41	.21	.65	256	20.6	15.0	189	1291
1151	R	1.08	.40	.19	.64	90	20.6[a]	15.0[a]	103	752
1240	M	1.00	.45	.18	.60	188	21.1	13.6	165	1144
1305	L	.97	.35	.20	.55	258	21.0	12.9	243	1410
1337	PL	.88	.43	.08	.71	208	21.2	12.8	179	1235
1424	L	.71	.36	.16	.56					

[a] Assumed equal to conditions in nearest site. [b] Approximate solar noon.

Table 3. The observations of F. A. Brooks at Davis, California, July 8, 1954, and four hypothetical microclimates constructed from them

		Radiation, cal cm⁻² min⁻¹					Air		Energy loss, kg cal m⁻² hr⁻¹	
		Upper hemisphere		Lower hemisphere						
Date and hour	Place	Insolation	Long-wave	Insolation	Long-wave	Wind, cm sec⁻¹	temp. C	humid. mb.	Dry	Wet
7/8/54										
1203	Observed	1.40	.39	.34	.77	190	32.0	13.0	—129	873
	Open, shade	.14	.71	.07	.71	190	32.0	13.0	— 7	995
	Clearing	1.40	.39	.34	.77	48	32.0	13.0	—138	373
	Thicket	.14	.71	.07	.71	3	32.0	13.0	— 20	232
	Lawn	1.40	.39	.34	.65	190	32.0	13.0	— 85	917

In the second line of Table 3 is constructed a microclimate as would be found under an apple tree. Insolation is reduced to one-tenth, long-wave radiation from both directions is changed to the density of that from a perfect radiator at air temperature, and reflected insolation is reduced. Ventilation is unchanged. This shade, of course, reduces the heat load of the dry man from 129 to 7 and requires him to sweat only slightly more than enough to balance his metabolic heat, rather than enough to balance metabolic plus radiational heat.

In the idealized clearing, Table 3, line 3, the load is greater because we have assumed that convection is reduced to half, as it was at midday on September 30 (Table 1). On the summer day (Table 3), however, changes in convection are less important than in the autumn (Table 1), for the temperature gradient between the man and air is small in summer, large in autumn. The decreased ventilation will be missed, nevertheless, when excess heat must be lost by evaporation.

In the idealized thicket, Table 3, line 4, the shade reduces the heat load considerably, since the accompanying reduction in convection is relatively unimportant in the warm air around a dry man. The capacity for balancing metabolic heat with evaporation is, nevertheless, least in the thicket.

Over the hypothetical lawn, Table 3, last line, can be seen the effects of the cool grass. The lawn of October 2 had a long-wave emission corresponding to a perfect radiator that was 7 C cooler than the air. A similar adjustment leads to an emission of 0.65 cal cm^{-2} min^{-1} from the summer lawn (Table 3). Over a small tract, as a lawn, the air would be essentially unaffected. Hence, we estimate that the heat load upon the dry man would be reduced from 129 to 85 by grass under foot.

Summary

Trees may shade and shrubs may shelter a man, making him more comfortable. Or he may find the plants make a place less pleasant. They change temperature and humidity little, however, and these two common indicators of climate alone won't measure comfort.

Instead of temperature and humidity alone, we observed the streams of calories in shade and shelter and then summarized them as loss of heat energy from a dry or from a sweating man. If he is comfortable, the temperature of his body becoming neither chilled nor hot, he has nicely balanced many streams of energy that enter and leave him. Against losses, he must balance the gains of visible sunlight, invisible long-wave radiation from warm things around him, and his metabolism. His losses leave via invisible long-wave radiation from himself, via convection and via evaporation, for all consume calories from his body. If these caloric accounts are not easily balanced, the uncomfortable man must shiver or sweat. Thus in several sites on clear days and nights, we measured radiation and ventilation in addition to air temperature and humidity. From these observations we calculated the net gains and losses, the heat a standard man could eliminate in each environment. Obviously an environment that permits great losses will be comfortable on a hot day and uncomfortable on a cool one.

A clearing in the woods is a sheltered place where heat is lost slowly, for the sun shines there as brightly as on the pasture or lawn, long-wave radiation is greater, and ventilation, especially, is less. The shade of a tree that stands in the pasture, where breezes can blow freely, subtracts most of the radiation of the sun and is an unmixed benefit on a hot day. The shade and shelter of a thicket, however, subtract ventilation with sunlight, and heat may be even more slowly lost in the shade of the thicket than in the sunlight of the pasture.

Heat was lost more rapidly by a man standing on a lawn than on a parking lot and — surprisingly — than on a beach.

In hot weather, when the air is nearly as warm as the skin, convection is relatively unimportant. Blowing warm air over a warm, dry body cools little, and the shelter of clearing and thicket matters little. In hot weather, therefore, even the shade of the thicket increases the loss of heat from the dry man. To lose heat created by himself, however, requires perspiration, and it is evaporated slowly in the shelter of a clearing and thicket.

Thus air temperature and humidity are scarcely changed by plants, but within their shade and shelter they greatly alter the heat a man can eliminate and, hence, greatly change his comfort. They can both shade the traveler in the desert of the parking lot and smother the dweller in the thicket of the second-growth suburban forest.