How Vegetation Affects Climate and Comfort

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The potential of an environment for the elimination of man's heat, not temperature and humidity alone, determine comfort. The modes of heat exchange are enumerated and placed in an analytic framework that permit man's heat to be estimated from micrometeorological observations. Open grassland and an isolated shade tree in it, a thicket and a clearing in it, and sand and asphalt surfaces are compared.

•WHEN THE motorist steps from his auto to rest at a wayside park, to fill the gasoline tank, or to await the tow truck, he steps unshielded into the microclimate of the forest, the lawn or the pavement slab. He may stand in the shade of a tree, smother in the shelter of a thicket, stroll on the green of grass, or squint in the heat from asphalt. We have investigated the climate and comfort of seven sites: the pasture and its shade tree, the thicket and its clearing, beach, lawn and parking lot.

EXCHANGE OF HEAT

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

His perplexity arises because the thermometer in its louvered Weather Bureau shelter passively follows the temperature of the air, but 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 traveler must pump a jack, the site with the greatest potential for loss will seem coolest and most comfortable. If the weather is cold or the traveler rests, the site with the smallest potential will seem warmest and most comfortable.

One stream of energy, sunlight or insolation, is visible and easily comprehended. This is the stream which is shut off by shade. Long-wave radiation is invisible, but the man will gain more from it than from sunlight in our sites. Long-wave radiation is emitted by all things according to their temperature. Thus, the warm man emits much. If he is within sight of a frosty window pane or winter sky and their scant radiation, he feels chilly. Here he wants shelter for he suffers a net loss by long-wave radiation, and the loss must be made up somehow.

The two remaining streams of energy are conduction and evaporation. As cool air about the man is warmed by his skin, calories are conducted away. As his perspiration is evaporated, calories are consumed. Here the two common indexes, air tem-

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perature and humidity, are useful because the cooler and drier the air, the more calories will be carried away.

Even here, however, air temperature and humidity will not serve alone because ventilation as well as cold and aridity speed the losses. Thus, when shelter stills the wind, it slows the loss of heat via the streams of convection and evaporation. Then the streams contribute less to the sum of themselves and radiation, and thus, the losses and comfort of the man are changed.

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. Now these streams of energy must be reduced to an equation that will accept our numerical data.

Accordingly we write the exchange of energy with the environment as the sum of solar radiation, long-wave radiation, convection, and 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/sq m/hr). 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. The gain of radiant energy by a man is estimated from measurements on plane horizontal meters. The foundation of most of the following analysis has been given by Buettner (1).

Micrometeorological observations have been converted to loss of energy from a man as follows:

$$\text{Solar radiation} = -0.9\,S_u \times 0.65 \times 0.25 - 0.1\,S_u \times 0.50 - 1.0\,S_d \times 0.65 \times 0.50 \quad (1)$$

$$\text{Long-wave radiation} = -1.0\,(R_u - S_u) \times 0.96 \times 0.50 - 1.0\,(R_d - S_d) \times 0.96 \times 0.50 + 0.96\,\sigma T_s^4 \quad (2)$$

$$\text{Convection} = +1.2\,v^{1/2}\,(T_s - T_a) \quad (3)$$

$$\text{Evaporation} = +1.6\,v^{1/2}\,(e_s - e_a) \quad (4)$$

Since we are estimating loss, gains appear as negative quantities. Nine-tenths solar radiation, S_u, measured on the upper side of a horizontal instrument is assumed to be a direct beam and 0.65 is absorbed by the man over 0.25 of his square meters of surface. The 0.1 S_u that is assumed scattered by the atmosphere is absorbed over 0.5 of his area. The upward reflected insolation, S_d, is absorbed over 0.5 of his area.

Long-wave radiation from above is the difference between the indication R_u of a horizontal meter that senses all wavelengths and the indication S_u of the pyrheliometer. The two streams of long-wave radiation reaching upward and downward facing horizontal meters are each 0.96 absorbed over a half of the man's surface. He loses long-wave radiation according to the fourth power of the absolute temperature T_s of his skin. If the flux density of radiation is measured in the meteorologist's calories per square centimeter per minute, it may be converted to the physiologist's kilogram calories per hour for the square meters of a man's surface by multiplying by 600.

In Eq. 3 for heat loss by convection, v is wind speed in centimeters per second (1 mph = 45 cm/sec) and $T_s - T_a$ is the difference between skin and air temperature.

Finally, if the man is wet with sweat, evaporation (Eq. 4) removes kilogram calories per square meter per hour according to ventilation and $(e_s - e_a)$ which is the difference between the water vapor pressure of the skin (50.1 millibars) and that of the air.

The net loss is the algebraic sum of emission, convection and evaporation less the gains via insolation and radiation.

As previously stated, the man will be ill-clad for autumn evenings and even some days. To balance production with loss of heat, 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 is the sort that maintains comfort when seated at 21 C (70 F), the usual room temperature (2). This clothing would reduce the loss from 474 to only 126, the heat generated when 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 differences among them.

OBSERVATIONS

Since shade or shelter has most effect and, therefore, most significance when the sun shines or the evening sky is clear, our observations were taken under unobscured midday sun or cloudless evening sky. These conditions were found in the autumn. From these nearly ideal conditions that we observed, we 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.

In Table 1 are given the observations in a pasture, P, and the shade of its isolated apple tree, A, and in a thicket, T, and its clearing, C, that was 25 feet in diameter. The reduction of the insolation S_u from above (upper hemisphere) is called shade, and this the apple tree and thicket provide. The clearing, of course, does not. The long-wave radiation, $R_u - S_u$, from the vapor or gases, occasional cumulus clouds, and nearby trees above the meter generally 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.

Much of the sunlight or insolation, S_d, reflected by the earth before striking the radiometer plate from below (lower hemisphere) was reflected from the sunlit grass of the pasture. Little was reflected from the litter of the clearing floor, and least from shaded vegetation.

Long-wave radiation, $R_d - S_d$, emitted from the earth and its cover 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.

On the 20th when little breeze blew, it was nearly calm in the thicket. On the 21st the stilling of the wind in the shelter of clearing and thicket can be seen.

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. They were, of course, employed in calculating the losses from a man.

TABLE 1

ENVIRONMENT AND ESTIMATED HEAT LOSSES FROM LIGHTLY CLAD MAN, SEPTEMBER 1962

Date	Hour	Place	Radiation (cal/sq cm/min)				Wind (cm/sec)	Energy Loss (kg cal/sq m/hr)	
			Upper Hemisphere		Lower Hemisphere				
			Insolation	Long Wave	Insolation	Long Wave		Dry	Wet
Sept. 20	1:24 PM	P	1.10	0.38	0.19	0.60	2.4	8	139
	1:37 PM	A	0.09	0.58	0.03	0.56	6.1	121	336
	12:27 PM	C	1.10[a]	0.61[a]	0.10	0.55	3.6	-24	135
	12:47 PM	T	0.07	0.59	0.03	0.58	0.6	77	137
Sept. 21	11:54 AM	P	1.19	0.45	0.24	0.58	225	256	1,526
	12:03 PM	A	0.09	0.47	0.03	0.53	194	399	1,572
	11:38 AM	C	1.27	0.43	0.17	0.58	82	154	960
	11:30 AM	T	0.09	0.54	0.02	0.54	20	189	583
	6:10 PM	P	-	0.34	-	0.45	91	474	1,267
	6:46 PM	A	-	0.48	-	0.48	64	381	1,045
	5:52 PM	C	-	0.41	-	0.48	17	281	623
	5:43 PM	T	-	0.47	-	0.49	0	211	418

[a] R_u measured, S_u estimated.

The "feel" of the environments, integration of the microclimatic factors in terms of man's loss of energy, is given as the estimated amount our lightly clad standard man hypothetically lost if he did not perspire (Dry) and if he were soaked (Wet). Marked differences are seen between environments.

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 10:00 AM the clearing had become the warmest place for a dry man. Here the heat loss was 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. A common pattern is seen: 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.

The shade of the thicket includes shelter. When a man is hot, the thicket is not as comfortable as the lone shade tree in the pasture. The clearing provides shelter without shade, and 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.

The observations of Table 2 were necessarily adjusted to the same incoming insolation. The measurements were taken above a beach, B, that also represents the bright surface of a gravel road, above a blacktopped parking lot, PL, and above a reference lawn, L.

Long-wave radiation from above was somewhat less on the open lawn than in the humid air of the beach or among the buildings and power lines of the parking lot. Much solar radiation was reflected from beach and lawn but less from the black asphalt of the parking lot. So great was emission from the black asphalt, however, that the sum of outgoing radiation of all wavelengths was greatest above the parking lot. The cool grass of the lawn stands in marked contrast. Ventilation and temperature were similar. Humidity was highest on the beach.

Integration of these microclimatic factors is given for a wet and one for a dry man. Most heat was lost by a man on the lawn. The wind blew freely and the income of radiation was about 50 kg cal/sq m/hr less than elsewhere. The surprise lies in the

TABLE 2

ENVIRONMENT AND ESTIMATED HEAT LOSSES FROM A LIGHTLY CLAD MAN[a]

Place[b]	Radiation (cal/sq cm/min)				Wind (cm/sec)	Energy Loss (kg cal/sq m/hr)	
	Upper Hemisphere		Lower Hemisphere				
	Insolation	Long Wave	Insolation	Long Wave		Dry	Wet
B	1.09	0.41	0.21	0.65	256	189	1,291
L	1.09	0.38	0.20	0.56	258	222	1,389
PL	1.09	0.43	0.08	0.72	208	156	1,212

[a]Observations taken on Oct. 2, 1962, between 11:34 AM and 1:37 PM (EST) and adjusted to insolation at 11:34:1.09.
[b]B = beach, L = lawn, PL = parking lot.

similarity of loss on beach and asphalt. Thus, the pleasure of the beach must be in part light clothing and the cooling of evaporation after a swim. In the meanwhile, the shopper clad in heavier clothes walks among the heat and exhaust of engines.

In strictly highway terms, the bright gravel and black asphalt subject the man exposed above them to surprisingly similar radiation quantities because the gravel reflects much sunlight and the asphalt emits much long-wave radiation.

A fuller description and analysis of these observations has been published elsewhere (3).

SUMMARY

When a man steps from his auto, trees may shade and shrubs may shelter him, making him more comfortable. Or he may find the plants make a stopping place less pleasant. They change temperature and humidity little, however, and these two common indicators of climate alone will not 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 from a dry or from a sweating man. If he is comfortable and his body becomes neither chilled nor hot, he has balanced the 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. He loses by invisible long-wave radiation from himself, convection and evaporation, for all consume calories from his body. If these caloric accounts are not easily balanced, the man must shiver or sweat. Therefore, 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, i. e., 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, since 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 sand.

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, which 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.

REFERENCES

1. Buettner, K. J. K. Physical Aspects of Human Bioclimatology. In Compendium of Meteorology, pp. 1112-1114. Boston, Amer. Meteor. Soc., 1951.
2. Winslow, C. E. A., and Herrington, L. P. Temperature and Human Life. P. 136. Princeton Univ. Press, 1949.
3. Waggoner, P. E. Plants, Shade, and Shelter. Conn. Agr. Exper. Sta. Bull. 656, 1963.