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# TREES MODIFY THE URBAN MICROCLIMATE[1]

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**Abstract**

A person's feeling of thermal comfort is affected by environmental conditions, including solar radiation, air temperature, wind, humidity, longwave radiation, and precipitation. Trees modify all of these variables and therefore affect individual thermal comfort. Shade and wind protection are well-recognized efforts. But trees and other vegetation also contribute to cooling the air by the evaporative process of transpiration. An urban shade tree can produce as much cooling as five room air conditioners running 20 hours a day. The lack of transpiring vegetation in cities is one reason why cities are often several degrees hotter than the surrounding countryside.

Humans have applied their technology to control the microclimate within buildings as precisely as desired. Temperature, light, humidity, and air movement can be regulated to assure indoor comfort. Why is it that we seldom consider the possibility of making the *outdoor* environment more comfortable in our residential and urban areas?

Comfort involves all the perceptions of an individual at any given time. Eight of our 14 senses (Ruch 1965) are involved in external or environmental sensing: hearing, vision, smell, taste, touch, balance, heat, and cold. Overly strong signals from any one of these cause discomfort. But simultaneous weak signals from several senses, each in itself insufficient to cause discomfort, may be integrated by the mind into a general feeling of discomfort. Psychologically, several minor annoyances with our environment can have a major effect on behavior. It may not be possible to assess the effect of a noisy, stuffy, and dirty environment, but we know it is an adverse one. Any improvement in an adverse environment has a beneficial effect.

Trees have beneficial effects on many of our senses, especially in urban environments. They absorb some excessive noise. They reduce glare and are aesthetically pleasing. They reduce wind, which affects our sense of balance. But I will limit discussion in this paper to the effects of trees on our two temperature senses, heat and cold.

Let's begin with a discussion of the factors that influence skin temperature, and thus our perception of heat and cold. Then we can see how an individual tree can alter our energy balance and other microclimatic variables. Finally we will look at the energy balance and microclimate of cities and how they could be modified by trees.

## The Control of Skin Temperature

Our temperature senses are separable. Our sense of warmth involves nerves that are triggered more rapidly as skin temperature increases. Our cold-sensing nerves pulse more rapidly as skin temperature decreases. A skin temperature around 32 degrees C (90 degrees F) seems subjectively to be thermally neutral. This temperature is maintained by a nude individual at a room temperature of about 28 degrees C (82 degrees F) and by a lightly clothed individual at 21 degrees C (70 degrees F) when there is no forced ventilation (Brengelmann and Brown 1965). If skin temperature varies more than a few degrees from 32 degrees C, we sense warmth or cold and our bodies react to increase or decrease our heat loss.

An inactive person generates about 50 kcal of heat per hour as a waste byproduct of metabolic processes. This heat must be dissipated to the environment. With exertion, this amount of heat increases by several times. The heat must first be transported to the skin surface, and this requires a skin temperature lower than the internal body or core temperature. Heat is transported partly by conduction through body tissues; but

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these are fairly good insulators, so most of the subsurface heat transfer is by capillary convection — the mass flow of warmer blood to the surface, where it cools; and then is returned. The body has good control over this process by constriction and dilation of capillaries; it can alter the effective subsurface conductivity by a factor of about 10 (Brengelmann and Brown 1965).

The heat reaching the body surface is lost in three different ways: by convection, by radiation, and by evaporation.

Convection or sensible heat transfer involves heating of the air next to the skin and then removal of this air and its replacement by cooler air. Ventilation increases convection loss.

Radiation loss is due to the emission of longwave or thermal radiation from the surface. Since the surface is simultaneously absorbing radiation from its surroundings, a net radiant heat loss occurs only if the surface is warm enough to emit more radiation than it gains from the environment. In a sunny environment, net radiation is a heat gain rather than a loss.

Evaporation loss of latent heat occurs whenever water evaporates: water vapor carries away into the atmosphere about 580 cal for each gram evaporated. For a resting person who is not perspiring, about half of the heat loss is by radiation and half is by convection, while evaporative heat loss is small and occurs mostly in the respiratory tract.

Cooling of an individual can result from increased ventilation, from a lowering or ambient temperature, from reduction of incident radiation, or, if the individual is perspiring, from reduction of humidity. The corresponding reduction in surface temperature tends to increase the subsurface heat flow. The body responds in several ways. First, capillaries constrict to reduce the effective subsurface conductivity. If this is not enough, shivering starts, increasing metabolism and producing more heat. The internal temperature of the extremities is also allowed to drop, thus decreasing the heat loss from them. Humans, of course, also have the ability to add clothing. This moves the heat-exchange surface out from the skin and effectively decreases the subsurface conductivity.

Heating of an individual can result from increasing metabolism through work or exercise, increase in ambient temperature, or increase in radiation load. The supply of radiation to the surface always includes longwave radiation and, when the individual is outdoors or near windows, solar radiation. The body can increase the loss of internal heat by capillary dilation, increasing blood flow to the skin. If this is not sufficient, sweating begins. If it is slight, all the secreted water evaporates and the skin stays dry. If sweating is more profuse, the water evaporates as fast as it can and the skin may become wet. At this stage the evaporation rate is controlled by the ventilation rate and the humidity of the air. Under hot conditions evaporative cooling may account for 90 percent of the total heat dissipation.

The skin temperature of an individual subjected to a normal range of environmental conditions can vary by as much as 15 degrees C (27 degrees F), especially at the extremities. The surface temperature of a clothed individual is obviously subject to even wider fluctuations. And the relative importance of the three modes of dissipation can also vary widely.

An individual can thus control his or her feeling of thermal comfort both by internal means and by changing clothing. She or he makes these changes in response to the microclimatic variables of air temperature, wind, solar and longwave radiation, and in warm weather, humidity. Furthermore, rain causes an increase of evaporative cooling from the wetted skin or clothing surfaces.

## How a Tree Affects Microclimate

The environmental factors that influence skin temperature are those that we commonly associate with microclimate: air temperature, humidity, wind, precipitation, solar radiation, and longwave radiation. So if we discuss how a tree affects these variables, we are also discussing how a tree affects skin temperature and thus comfort.

The most obvious microclimatic effect of a tree is shade. Trees absorb and reflect solar radiation. The importance of solar radiation to the energy balance of an individual is demonstrated by the way we seek shade in hot weather and sun in cold weather. Evergreen trees provide shade year round, but deciduous trees have an appropriate seasonal variation: shade in summer, and at least partial sun in winter. Buildings also provide shade, but it is only where tall buildings are already crowded close together that increased shading by trees would not be a welcome benefit in summer.

The absorption and scattering of the visible portion of solar radiation by trees plays an important role in reducing glare. Modern cities are made of light-colored materials with a lot of glass. Sunlight reflected from these surfaces is often too bright for the person in the street, causing visual discomfort. Trees help greatly to reduce these reflections. Glare from the direct light of the rising or setting sun is a serious problem long highways; it can also be reduced by trees.

Longwave radiation exchange goes on continually between an individual and his or her environment. Normally, a person outdoors emits more of this radiation than she or he receives from the surroundings, so the process is a cooling one. When the sky is clear, incoming longwave radiation is small; and at night, when solar radiation is not present, cooling of outdoor exposed surfaces is rapid. Trees interposed between an individual and the sky generally decreases the cooling of the individual. This is because the trees emit more longwave radiation than the sky they obscure. Therefore, nighttime temperatures are higher under trees than in the open, and the frost-free period is longer under trees. Clouds emit more longwave radiation than clear sky does; so trees have much less effect on longwave radiation when the sky is cloudy.

Wind increases convective cooling and evaporative cooling. We know wind plays an important role because we try to get out of it in cold weather and into it in hot weather. Trees reduce wind speed by increasing the resistance to wind flow. Within the crown of a single tree, or under a forest canpoy, wind is light and almost unrelated to the external wind. An isolated tree or a stand of trees acts almost like a solid barrier to the wind, forcing the air over or around. Thus wind speed can be increased at the edges of a tree or stand (Reifsnyder 1955). Wind can also cause discomfort by making walking difficult, or by driving rain and snow. The protection of trees is welcomed under these conditions. The effect of deciduous trees on wind changes with the seasons, but in an adverse direction, partially compensating for the beneficial change in their shade. They decrease wind most in summer and least in winter. Generally, then, the effect of trees on wind is beneficial in winter but a disadvantage in the summer.

Rain and snow affect comfort primarily through the cooling effects of their evaporation and melting, but also through their wetness. In summer the cooling can be beneficial, but most often we seek shelter from precipitation. Trees provide some shelter by retaining and evaporating precipitation. A forest canopy intercepts all of the first few hundredths of an inch of rain and about 10 percent of any additional rain (Helvey and Patric 1965).

Trees raise atmospheric humidity in summer because they transpire. Transpiration is the evaporation of water from the insides of leaves. Humidity is high under a forest canopy, but this adverse effect is more than counteracted by lower air temperature. Alteration of humidity by individual trees is insignificant enough that we are not aware of it. Outdoors, the only effect of humidity on comfort is through its control of evaporative cooling by sweating on hot days.

Microclimatically, air temperature is a variable that depends on all the other atmospheric variables. It affects individual comfort by its role in determining convective heat loss. The effect of trees on air temperature is complicated and not well known. By evaporation trees dissipate energy that would otherwise be used in heating the air.

## Temperature Differences Between City and Country

Dozens of scientific studies have shown that the city is warmer than the surrounding countryside. This effect is known as the urban heat island. Cities are warmer in both winter and summer; mean annual temperatures are 0.5 degrees to 1.5 degrees C (0.9 to 2.7 degrees F) higher in the city (Kratzer 1956). The winter difference, produced primarily by heat generated by burning fossil fuels, is considered an advantage by most inhabitants. But in summer the city often becomes too hot for comfort. This summer difference is due largely to the scarcity of trees and other vegetation in the city and the consequent lack of cooling by transpiration.

Mean monthly temperature differences between city and country in summer are about 1.1 degrees C (2 degrees F) (Kratzer 1956). However, much greater differences occur in hot calm weather. Landsberg's (1956) data and other studies indicate that city-country differences are negligible during the day and are greatest — 2 degrees to 3 degrees C (4 degrees to 6 degrees F) — in early evening (Figure 1).

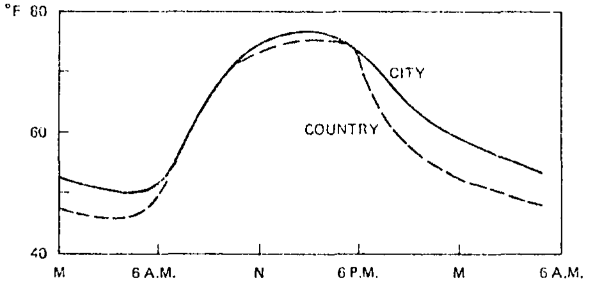

Figure 1.—Diurnal variation of city and country air temperatures for a clear day with little wind. Richmond, Virginia, 2 June 1953 (from Landsberg 1956).

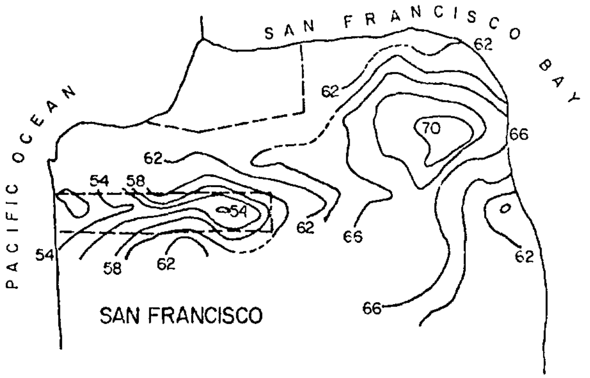

Figure 2.—The pattern of city temperatures in San Francisco at 11 p.m. on 26 March, 1952, as mapped by Duckworth and Sandberg (1954). The rectangle at left center represents Golden Gate Park.

The heat island has been studied in recent years by traversing the city with temperature sensors mounted on automobiles. Chandler's (1962) maps of London are classic examples of the results. Duckworth and Sandberg (1954) mapped San Francisco temperatures on 26 March 1952. They found night temperature differences of 5.5 degrees to 11 degrees C (10 degrees to 20 degrees F) between the built-up areas and the vegetated area of Golden Gate Park (Figure 2). These and other studies of the urban heat island have been reviewed by Kratzer (1956), Landsberg (1956), Munn (1966), Lowry (1967, 1969), Bornstein (1968), and Peterson (1969).

### Energy Balance

The principles of energy balance can be used to study the temperature of the city and the country, just as we have already used them to examine the temperature of human skin. The surface of the land and the surface of an individual have the following properties in common: absorption of most of the incident solar radiation, absorption and emission of longwave radiation, gain or loss of heat to surrounding air by convection, loss of heat by evaporation, and exchange of heat with the subsurface material. The generation of heat by human metabolism has its equivalent in the city in the burning of fuels, but the vegetated environment has no such internal heat source.

Solar radiation supplies the energy for warming during the day. Hand (1949) and others (Peterson 1969) have shown that dust, soot, and other aerosols over cities reduce the incoming solar radiation to 80 to 85 percent of that received by the country. The city thus tends to warm more slowly than the country in the morning. Net longwave radiation loss is less in the city, because the atmospheric aerosols intercept part of the outgoing energy and re-radiate it back to the surface. This is one of the reasons for slower cooling of the city at night.

The net amount of radiant energy absorbed by the country surface during the day is dissipated in three ways: by heating the air, by heating the soil and vegetation, and by evaporating water. When the soil is not too dry, transpiration from trees and other plants removes most of the available heat. In the built-up areas of the city, little water is available to evaporate, so almost all the energy must go into heating the air and the solid subsurface materials.

The city is made largely of concrete, steel, brick, glass, and asphalt. All these are poor heat insulators. They conduct and store heat more rapidly than the soil of the countryside. Vegetation above the soil in rural areas provides insulation that further reduces the storage of heat in the soil. Thus in the city larger amounts of energy enter the subsurface materials during the day than in the country. This stored heat is then released at night. Consequently, evening temperatures in the city remain high both indoors and out.

The city also acts as a heat generator because of the burning of fuels in automobiles, factories, shops, and homes. The amount of heat produced is significant in winter; air temperatures are sometimes lower on weekends. However, in summer this heat source is insignificant except as a local modifier of the microclimate of a busy street or an industrial complex.

Tag (1968) and Myrup (1969) have made the first attempts to analyze energy-balance differences between a city and its vegetated surroundings quantitatively. Myrup's results for a freely transpiring rural area and for a dry city are summarized in Table 1. The temperature data show a larger heat-island effect at midday than in the evening. This is the contrary to other observations, and Myrup cannot adequately explain the discrepancy. But in other respects the model behaves well. The major conclusions are clear: Reduced evaporation and higher heat capacity and conductivity of the subsurface materials in the city allow much greater storage of subsurface heat during the day. This stored heat, released at night, keeps the city air temperature higher than that in surrounding areas.

Table. 1—Urban and rural energy balances and air temperatures for a June day as predicted by Myrup's (1969) theory. Values are for the particular set of conditions assumed by Myrup,, and are taken from his graphs.

| Time & place | Net radiation | Evaporation | Heating of air | Subsurface heat | temperatures |
|---|---|---|---|---|---|
| | *cal cm$^{-2}$ min$^{-1}$* | | | | oC |
| Midday: | | | | | |
| Rural | 0.9 | 0.7 | 0.1 | 0.1 | 28 |
| Urban | .9 | .0 | .4 | .5 | 34 |
| Evening: | | | | | |
| Rural | -.1 | .1 | -.1 | -.1 | 19 |
| Urban | -.2 | .0 | -.1 | -.1 | 24 |

## Complexity of City Microclimate

So far we have considered the city as a single entity. Actually the city is a complicated agglomeration of many types of natural and manmade structures: tall buildings, low buildings, factories, wide streets, narrow streets, parking lots, courtyards, parks, hills, lakes, rivers, and harbors. Each location has its own microclimate, determined by its local surroundings, by the weather, and by the character of upwind areas.

Street-level microclimates can be separated into three broad classes. The first includes areas with extensive evaporating or transpiring surfaces — parks, wide streets with trees, and the vicinities of rivers or lakes. The second includes wide treeless streets, squares, and parking lots, which are open to the sky but are dry. The third includes narrow streets and courtyards surrounded by relatively tall buildings. Kratzer (1956) showed diurnal temperature variations for three such locations in Vienna: an average with trees, a large square without trees, and a narrow street (Figure 3). He said:

> *The weather was calm, clear and hot . . . . The broad streets and squares which do not have trees are very hot at noon, but cool off more noticeably in the evening. The avenues and squares containing trees are cooler and have a narrower daily range in variation. The narrow streets, however, are distinguished by much greater coolness during the noon and afternoon hours, amounting to from 5 degrees to 6 degrees C lower than the temperature of the surrounding area. At night the difference disappears or the sign is reversed. It is the high degree of blocking of outgoing and incoming radiation that causes the great reduction of the daily variation curve.*

For narrow streets, orientation also plays an important role. North-south streets will not be shaded from intense noontime solar radiation. They will have higher temperatures than narrow east-west streets.

The importance of evapotranspiration is obvious in Figures 2 and 3. Golden Gate Park stands out as 8 degrees C (15 degrees F) cooler

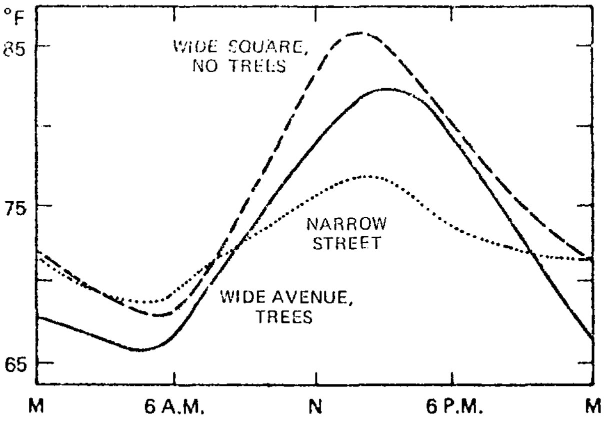

**Figure 3.—Diurnal temperature variation in Vienna on 4 and 5 August 1931 for a wide square with no trees, a wide avenue with trees, and a narrow street (from Kratzer 1956).**

than the surrounding city. All cities have summer evening isotherms that parallel the boundaries between urban and rural or suburban areas.

Wind plays an important modifying role in city microclimate. Two types of wind must be considered.

Strong winds caused by large pressure gradients tend to wipe out microclimatic differences. More of the available heat is carried away into the atmosphere, so air temperature near the surface remains cooler both day and night. Except for hot, dry, foehn or chinook winds, cities are cooler when the wind is stronger.

When the pressure-gradient wind is absent or light, local winds caused by temperature differences become important. Warm air tends to rise, causing a breeze by drawing in cooler surrounding air. For cities near oceans or large lakes, the sea breeze caused by warmer air rising over land helps keep temperatures down. Whiten (1956) has discussed winds produced on local city streets in the evening by warm air rising from hot, dry squares and cool air sinking in park areas. Finally, topographically induced nighttime winds — cool air draining downhill — can produce temperature effects even in a relatively flat city like London (Chandler 1962).

### Trees to Modify Microclimate

Trees can modify microclimate by their shading effect, by increasing longwave radiation, by reducing wind speed, by intercepting rain and snow, by cooling the air by evapotranspiration, and possibly by raising the humidity of the air. All these effects may influence the comfort of an individual through their influence on skin temperature. All the effects, except the insignificant humidity change, are generally beneficial.

It seems possible to specify an ideal relationship between trees and an individual home in the northeastern United States. A house lot should have conifers to the west and north for protection from cold winter winds, hardwoods to the south for summer shade and winter sun, and grass or shrubs to the east and southeast for a feeling of openness and for early morning sun. This arrangement provides optimal variety and microclimatic protection.

The most overlooked effect of trees and other vegetation is their effect on air temperatures through evaporation. Trees can be considered as nature's own air conditioners. An isolated 70-foot shade tree can transpire 100 gallons of water on a sunny day (Kramer and Kozlowski 1960). It takes 230,000 kcal to evaporate this much water, so such a tree can be equated with five average room air conditioners (2,500 kcal/h), each running 20 hours a day. It does not matter whether the tree is a hardwood or a conifer. Mature trees in a closed forest, surrounded by other trees, transpire much less than isolated trees, perhaps 15 gallons on a sunny day. Smaller isolated shade trees also transpire less. In isolated trees, transpiration is roughly proportional to the number of leaves on the tree, but in a closed stand, transpiration from each tree is proportional to the exposure of the crown at the top of the canopy.

One additional qualification is that the tree must be well supplied with water. I do not know if trees in the city regularly tap underground water supplies such as sewers, or if they are often subject to severe water stress. In the latter case, much of their advantage would be lost. Yet in general, the more trees (and other vegetation), the closer the city microclimate will approach that of the country.

Myrup (1969) was able to study the effect of different fractions of freely evaporating area in the city. His model predicted a temperature reduction of up to 3.5 degrees C (6 degrees F) when the evaporating area was increased from 25 to 35 percent of the total area. When less than 20 percent of the area was wet, there was no effect on the city microclimate. The 20-percent threshold seems to me to be an incorrect conclusion, resulting from his assumption that surface relative humidity was equal to the fraction of surface that was freely evaporating. This assumption does not consider the local advection effect, which is most pronounced for an isolated tree (well supplied with water) in the midst of hot dry surroundings. Such a tree is prodigious at removing heat from the air and using it to evaporate water. The addition of another tree adjacent to the first doubles the area covered, but probably does not double the amount of heat removed because the second tree is influenced by the first. Thus the effect of added vegetation should be most significant when there is *no* preexisting vegetation, and not when the area is 20 to 30 percent covered.

I can only conclude, as others have, that more research is needed before the effect of parks, greenbelts, rooftop gardens, and isolated trees on city temperatures can be predicted quantitatively.

## Literature Cited

Bornstein, Robert D. 1968. *Observations of the urban heat island effect in New York City.* J. Appl. Meterol. 7:575-582.

Brengelmann, G., and A.C. Brown. 1965. *Temperature regulation.* **In** Physiology and biophysics (Ruch, T.C., and H.D. Patton, eds.) 19th ed., p. 1050-1069. W.B. Saunders, Philadelphia.

Chandler, T.J. 1962. *London's urban climate.* Geog. J. 128: 279-302.

Duckworth, Fowler S., and James S. Sandberg. 1954. *The effect of cities upon horizontal and vertical temperature gradients.* Am. Meteorol. Soc. Bull. 30:242-254.

Helvey, J.D., and J.H. Patric. 1965. *Canopy and litter interception of rainfall by hardwoods of eastern United States.* Water Resour. Res. 1: 193-206.

Kramer, Paul J., and Theordore T. Kozlowski. 1960. Physiology of Trees. 642 p. McGraw-Hill, New York.

Kratzer, P. Albert. 1956. *The climate of cities.* Vieweg and Sohn., Braunschweig. Trans. AFCRL 62-837, 1962, CFSTI ADZ 84776.

Landsberg, H.E. 1956. *The climate of towns.* **In** Man's role in changing the face of the earth. (William L. Thomas, ed.) p. 584-606. Univ. Chicago Press, Chicago.

Lowry, William P. 1967. *The climate of cities.* Sci. Am. 217 (2):15-23.

Lowry, William P. 1969. Weather and Life. An introduction to biometeorology. 305 p. Academic Press, New York.

Munn, R.E. 1966. Descriptive Micrometeorology. 245 p. Academic Press, New York.

Myrup, Leonard O. 1969. *A numerical model of the urban heat island.* J. Appl. Meteorol. 8:908-918.

Peterson, James T. 1969. The climate of cities: a survey of recent literature. U.S. Dep. Health Educ. Welfare, Natl. Air Pollut. Control Adm. Pub. AP-59, 48 p.

Reifsnyder, E.E. 1955. *Wind profiles in a small isolated forest stand.* For. Sci. 1: 289-297.

Ruch, T.C. 1965. *Somatic senation.* **In** Physiology and Biophysics (Ruch, T.C., and H.D. Patton, eds.) 19th ed., p. 302-317. W.B. Saunders, Philadelphia.

Tag, P.M. 1968. *Surface temperature in an urban environment.* Masters thesis, Pa. State Univ. Dept. Meteorol., 69p.

Whiten, A.J. 1956. *The ventilation of Oxford Circus.* Weather 11:227-229.

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# ABSTRACT

Fogel, Robert. 1975. **Insect mycophagy: a preliminary bibliography.** U.S. Forest Service Gen. Tech. Rept. PNW-36. Pacific NW Forest and Range Expt. Sta., Portland, Oregon.

For well over a century, certain insects have been known to feed on fungal fruiting bodies. Spore-eating insects have been presumed to be vectors of the fungi eaten. Only recently, however, have spores been demonstrated to remain viable after passage through an insect's digestive tract. These works have reawakened interest in the role of insect mycophagy in dissemination of pathogenic, mycorrhizal, and other fungi. References in this bibliography are intended to provide an entry into the insect mycophagy literature.