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# Micrometeorological Principles of Protected Cultivation

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## Abstract

Protected cultivation is a broad term commonly used among producers of specialty crops. Techniques can range from complex fixed structures to field site selection, to straightforward cultural practices in the field. This introduction to the ASHS workshop "Protected cultivation for fruit crops" considers techniques of protected cultivation in the broad sense. The text presents the physical principles associated with protected cultivation, namely heat transfer to and from the crop as expressed by the surface energy balance concept. Common terminology is introduced with respect to spatial and temporal scales. The four modes of heat transfer are discussed via the energy balance equation: radiation, convection, conduction, and latent heat fluxes. Illustrative examples of current practices in protected cultivation are provided in the context of the aforementioned physical principles.


## Introduction and Common Terminology

For millennia humans have attempted to mitigate climatic limitations on plant agriculture. Well known examples exist from antiquity like the irrigation systems of ancient Egypt. Approaches to addressing climatic limitation can include selection of planting sites by topography; indirect control of plant temperature in the field by cultural practices; or imposition of structures for direct control of the plant environment. This introduction to the workshop "Protected cultivation for fruit crops" will discuss physical principles for the broad category of crop production that is referred to as protected cultivation, and will use illustrative examples from current practices in horticulture.

As a preface it is important to define common fundamental terminology. Firstly is the distinction between weather and climate, which is temporal: weather describes day-to-day variation in atmospheric conditions whereas a location's climate refers to average or extreme conditions over a longer period. Climate is a statistical description of weather. Commonly it is expressed by longterm normals, meaning the expected values for a location and time. In agricultural applications longterm normals often are reported as 30-year averages. Relevant times may be short, as in an average temperature for a given month, or longer, as in the annual pattern of rainfall distribution.

Secondly are the distinctions among macroclimate, mesoclimate, and microclimate, which are of spatial scale. These will be discussed in terms meaningful for agriculture. Upper and lower bounds on these spatial scales overlap based upon the phenomenon under study and the discipline of the investigator. Macroclimate refers to that from a global scale, the purview of global climate modelers, to the regional or synoptic scale. Macroclimatic limitations to agricultural production include average and extreme temperatures, the gradient from 'humid' to 'dry' climates, and the number of frost-free days per year. The number of frost-free days concerns all crop production whereas extreme temperatures during the dormant season, for example, are critical for perennial crops. Mesoclimate ranges from a region (upper bound) to a field (lower bound). It is influenced by topographical features like mountain ranges or broad valleys that cause a divergence from the location's macroclimate; one may conceptualize mesoclimate as moderating the macroclimate. Large bodies of water are

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significant variables affecting mesoclimate because of water's high heat capacity (4.18 kJ $kg^{-1}$ $K^{-1}$) as opposed to that of dry air (1.00 kJ $kg^{-1}$ $K^{-1}$; at atmospheric pressure and biologically relevant temperatures). In addition, topography, elevation, and aspect can be considerations in siting a field or selecting a crop. Microclimate has long been recognized from the scale of a field to its lower bounds on the order of single plants, or for example single leaves, insects, fungal spores, or individual fruits. Microclimate describes the environment from the surface itself to the level at which it is indistinguishable from the general conditions, or those of the bulk air. Despite the development of these definitions for atmospheric conditions, soil microclimate is exceptionally relevant to agriculture. The principles of agricultural micrometeorology include above- and below-ground processes. The horticulturist approaches mitigation of climatic limitations to crop production by 1) taking advantage of landscape features to produce a favorable mesoclimate, and 2) modifying the crop microclimate by means of protected cultivation.

## Principles

Microclimate modification is based upon thermodynamic principles, namely the conversion of one form of energy to another (heat transfer) and the direction in which energy flows. Heat transfer can be accomplished by radiation, convection, conduction, or latent heat—a change in phase of a substance, water in our case. In each mode of heat transfer, the direction of the energy flux is determined by a gradient in temperature between two bodies, be they for example the sun and a plant, the air and a leaf, or a mulch and the soil. The subsequent section will present illustrative examples of these principles in protected cultivation. Here, each form of heat transfer will be described in turn.

By the first law of thermodynamics, energy can be neither created nor destroyed. Therefore, heat transfer to and from crops and soil is described by the concept of a *surface energy balance* (net sum to zero) that quantifies heat transfer in the crop system and that can result in a change in temperature at the surface, in the case of a plant:

$$R_n + H + LE = 0 \qquad [1]$$

and in the case of soil:

$$R_n + G + H + LE = 0 \qquad [2]$$

where $R_n$ is the net sum of radiation at the plant or soil surface; H is sensible heat flux, or convection; LE is latent heat flux, or that from evaporation and condensation; and G is soil heat flux, or conduction. Heat storage by the surfaces is considered negligible. In Eqs. [1] and [2], heat transfer towards the surface is positive (e.g., air temperature > leaf temperature) whereas heat transfer away from the surface is negative (e.g., soil temperature > air temperature). For conciseness in this discussion, the surfaces described will be limited to a leaf and to the soil.

Radiation is emitted by all bodies as a function of the forth power of their temperature; hence the difference in peak solar radiation emission (on the order of megawatts) and that emitted by terrestrial bodies like a plant (on the order of watts). Solar radiation at the earth's surface encompasses the shortwave spectrum (UV, visible, near-infrared) whereas terrestrial radiation represents the far-infrared portion of the longwave spectrum. During the day, solar radiation dominates $R_n$, and under clear skies, $R_n$ dominates the surface energy balance itself. At night, net radiation is determined by the difference in temperature between the leaf (or soil surface) and its surroundings. Leaves transmit, absorb, and reflect radiation according to their optical properties, as does the soil surface, with the exception of transmittance.

Sensible heat flux is a function of the speed with which air flows over a surface, and the difference in temperature between the surface and the near-surface air. Warm air moving over a transpiring leaf will transfer heat to the leaf, thereby raising the temperature of that leaf. By contrast, an increase in transpiration (LE) can balance H resulting in no change in leaf temperature (isothermal condition). It is important to note that LE and H are linked, or coupled, by wind speed. Latent heat flux is effective because of the large latent heat of vaporization of water (2.5 kJ $g^{-1}$) which is the energy transferred from the surface with the change in phase of water from liquid to vapor (and vice-versa). From a wet soil surface LE (evaporation) can be significant, but negligible when the surface is dry. For a dry soil surface, $R_n$ and H dominate the surface energy balance and thus surface temperature.

The combination of transpiration from a leaf surface and evaporation from the soil surface is termed evapotranspiration, a process driven by a gradient in humidity, or vapor pressure, between the surface and the air. In the case of a transpiring leaf, one assumes that the vapor pressure in the air of the stomatal cavity is at saturation, whereas in most instances (i.e., neither raining nor air at dew point) that of the air is lower. The same holds true for a soil surface. Temperature is an indirect driver of this process in that the saturation vapor pressure is a function of temperature; warmer air holds more water. The difference between saturation vapor pressure and actual vapor pressure is referred to as the vapor pressure deficit (VPD).

Soil heat flux, or conduction, is away from a warm soil surface (negative) during the day and the reverse at night, when more longwave radiation may be emitted from the soil surface than is received from its surroundings, or when cool air flows over the warm surface. Conduction in a solid like soil is less effective at transferring heat than is convection even at relatively low wind speed.

## Applications

Greenhouses (as distinguished from high tunnels) alter sensible heat flux to and from the plants both actively (fans) and passively (venting). Because it is coupled with wind speed, LE (i.e., transpiration) and H vary with venting. Net radiation at the plant surface is altered first by reduced shortwave radiation during the day, as a function of the cladding material; second, longwave radiation is exchanged between the plants and the inside of the greenhouse structure, which may be significantly warmer than the structure's surroundings. This is particularly pertinent at night when solar radiation is nil. Active heating of greenhouses can be considered a mitigation approach to macroclimatic limitations. High and low tunnels, and floating row covers function similarly to greenhouses in terms of changes to $R_n$. For this discussion, these approaches to protected cultivation are defined as having fixed ventilation potential based upon the covering material. To illustrate, H is higher for leaves under a nonwoven row cover than for leaves under polyethylene. During the day, given transpiration, humidity is higher under polyethylene than under a typical non-woven cover. Conversely, VPD and thus the driving force for transpiration is lower under polyethylene than for example, under spun-bonded polypropylene. Compared with a greenhouse, there is less overall control over H.

Windbreaks alter the crop microclimate for a distance generally 8 to 12 times the height of the windbreak, assuming a fairly dense hedge or a solid barrier. Within this distance wind speed is lower than that upwind of the windbreak and air flow is less turbulent; consequently, H is lower than outside the windbreak's effective zone. Because of the coupling between H and LE by wind speed, there generally is an increase in humidity in the effective zone. Windbreaks do not alter $R_n$ unless their proximity results in shading part of the crop. Tree shelters or grow tubes can be thought of windbreaks for individual plants with a low ventilation potential like that of a non-perforated tunnel or row covering. As with any covering, the tube's optical properties determine the reduction in shortwave radiation that impinges upon the plant.

Mulches offer an interesting case for both soil and plant energy balances, depending upon plant height. As an example, plastic mulches alter H and G as a function not only of their optical properties (absorption, reflection, transmission) but of the quality of their installation. Tightly stretched mulches have good contact between the plastic and soil surface; thus heat transfer by conduction is significant for those mulches with high absorptance for shortwave radiation. In this case, G is substantial. High absorption of solar radiation by the mulch material (e.g., black plastic) raises its temperature, leading to concurrent convective heat transfer toward the plant (negative value of H for the mulch surface; positive value for the plant surface). The effect is most significant for short, widely spaced plants such as newly transplanted blueberries for example. Materials laid loosely across the soil have poor mulch-soil contact and thus do not transfer heat effectively by conduction (i.e., low G). Instead, the energy absorbed by the mulch raises mulch temperature, and energy is transferred primarily by H and secondarily by the longwave radiation emitted by the mulch surface.

The special case of cooling plants in the field can be exemplified by overhead sprinkler or mist irrigation which leads to LE (negative value for the plant surface), or in common parlance, evaporative cooling. By contrast, freeze protection can be implemented by taking advantage of the latent heat of fusion of water (334 kJ $kg^{-1}$), the energy transferred to the plant as water freezes on its surface. Note that for water, its latent heat of fusion is less than that of vaporization, meaning about 7.5 times less energy is transferred per unit water undergoing a phase change. Mitigation of freeze or cold injury is possible under certain circumstances by mixing non-isothermal layers of air above the field. The technique is used under temperature inversion, where a near-surface layer of cold air is trapped beneath a layer of warmer air. Mixing is accomplished by 'wind machines' that one often sees in orchards and vineyards in valleys of northern latitudes. Drawing warmer air toward the surface provides the opportunity for positive H (heat transfer toward the crop). Wind machines can produce temperature changes on the order of 2 to 3°C. While this value may not seem significant, often it represents the difference between substantial and minimal winter injury given night temperatures that may be near critical thresholds for buds, xylem, or phloem damage.

In sum, microclimate modification for fruit crops takes many forms but all rely on the commonality of heat transfer principles and the surface energy balance. Modes of heat transfer are radiation, convection, conduction, and latent heat flux (evaporation and condensation in the case of this discussion). Heat transfer is relevant to both plant and soil temperatures, both of which are drivers of plant growth and development, and often fruit quality metrics. Growers of high-value specialty crops long have had these powerful horticultural tools at their disposal to address large and small-scale climate limitations. These tools continue to evolve via new technologies and improved efficiencies of the long-standing methods of protected cultivation.

## Disclaimer

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

## Selected Resources for Further Reading

Campbell, G.S. and J.M. Norman. 1998. An introduction to environmental biophysics. 2nd ed. New York: Springer.

Davis, J.E. and J.M. Norman. 1988. Effects of shelter on plant water use. Agriculture, Ecosystems & Environment. 22-23:393-402.

Grace, J. 1983. Plant-atmosphere relationships. New York: Chapman and Hall.

Hillel, D. 1998. Environmental soil physics. San Diego: Academic Press.

Jones, H.G. 1992. Plants and microclimate. 2nd ed. Cambridge: Cambridge University Press.

McNaughton, K.G. 1994. Effective stomatal and boundary-layer resistances of heterogeneous surfaces. Plant, Cell and Environment 17:1061-1068.

Monteith, J. and M. Unsworth. 2008. Principles of environmental physics. 3rd ed. New York: Elsevier.

Nobel, P.S. 1999. Physiochemical and environmental plant physiology. 2nd ed. San Diego: Academic Press.

Papadakis, G., D. Briassoulis, G. Scarascia Mugnozza, G. Vox, P. Feuilloley, and J.A. Stoffers. 2000. Review paper (SE—Structures and Environment): Radiometric and thermal properties of, and testing methods for, greenhouse covering materials. Journal of Agricultural Engineering Research. 77:7-38.

Poling, E.B., H.P. Fuller, and K.B. Perry. 1991. Frost/freeze protection of strawberries grown on black plastic mulch. HortScience. 26:15-17

Smith, D.M., P.G. Jarvis, and J.C.W. Odongo. 1997. Aerodynamic conductances of trees in windbreaks. Agricultural and Forest Meteorology. 86:17-31.

Tarara, J.M. 2000. Microclimate modification with plastic mulch. HortScience. 35:169-180.

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For

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**MANUSCRIPTS:** These should be sent electronically in Microsoft Word format to ***Dr. Esmaeil "Essie" Fallahi at efallahi@uidaho.edu , Department of Plant, Soil, and Entomological Sciences, University of Idaho Parma Research and Extension Center, 29603 U of I lane, Parma, Idaho 83660, USA by May 30, 2013.*** The Awards Committee (4) will judge the papers, which must be acceptable for publication in a coming issue of the Journal. See a recent Journal for editorial style. Society membership is not mandatory. Paper length - *about 1000 words or three to four pages in the Journal of the American Pomological Society including photographs, charts, and tables.* Oversize manuscripts will be returned for shortening, or not considered. Publishing expenses will be covered for first place award paper(s).

**PAPER CONTENT:** Paper content should relate to cultivars of deciduous, tropical or subtropical fruits as related to climate, soil, rootstocks, a specific pomological experiment, a breeding project, history and performance of new or old cultivars, a library review pertinent to pomology, an MS or Ph.D. thesis paper.

**AWARDS PRESENTED:** At the annual meeting of The American Pomological Society (APS) which is help in conjunction with the annual meetings of the American Society for Horticulture Science. Authors of the Award winning papers are encouraged to attend the annual meeting of APS and received their Award(s). Consult your advisor on location and time of the next meeting.

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