SOIL CLIMATOLOGY AND METEOROLOGY

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Summary

Climate and soil processes determine the environment in which plants and soil organisms live. Therefore, to understand the life support systems of the earth, interactions of climate and soil must be understood. Methods have been developed to characterize agro-climatic zones in a systematic way for the earth=s lands. Such zones

are useful to determine general cropping or agricultural systems that might be suited to given location, but there is a great deal of variability of climate, soils, and topography within an agro-ecological region that can be of significance to particular organisms. The specific soil and climate environment that affects a particular organism or community of organisms is called the microclimate. This article provides an overview of radiation, temperature, water, and atmospheric properties and processes that interact to determine soil microclimate. Impacts of organisms and management on soil microclimate are also discussed. For example, the amount and type of vegetation present can have large impacts on soil microclimate. The article closes with an overview of recent measurement improvements that have improved our understanding of soil microclimate and applications of knowledge to new problems such precision farming, biotic and abiotic interactions in soils, rootzone processes, nutrient cycling, and absorption or emissions of gases from soils that are relevant to global atmospheric balances.

1. Introduction

Climate and soil processes determine the environment in which plant and soil organisms live, and therefore, to understand the life support systems of the earth, interactions of climates and soils must be understood.

1.1 Macroclimate and microclimate

Because of the importance of interactions between climates and soils and their importance to agriculture, many methods have been developed to characterize agro-climatic potential in a systematic way for the earth's lands. One example of such a system is the Agro-ecological Zones of the United Nations Food and Agriculture Organization (FAO). Such delineations are useful to determine general cropping or agricultural systems that will likely be successful for a particular location, but there is a great deal of variability of climate, soils, and topography within an agro-ecological region that is of significance to particular organisms. To understand the environment of a particular plant or animal, it is necessary to focus at a much finer scale. The specific soil and climate environment that affects a particular organism or community of organisms is called the microclimate.

1.2 Soil-plant-animal-atmospheric interaction

Every critical process of an organism is influenced by the environment around it. For terrestrial plants there is a critical interaction of soil and atmospheric processes that determine the environment and for terrestrial animals the environment of concern can be the atmosphere or the soil or a combination. Solar radiation drives the photosynthesis process, provides heat to maintain the earth's temperature, and is the energy source for all life. Radiation is greatly impacted by the atmosphere. Water is essential to all life processes and is available through the perpetual water cycle whereby water evaporates from plants and fresh and ocean waters, is transported through the atmosphere, falls to earth, is transported over and through the soil, and eventually evaporates again. Evaporation of water from plants and animals is critical to maintaining temperatures that favor healthy functioning of the organisms. For plants, water is required to maintain cells, stems, and leaves in a turgid state so that essential processes of growth and metabolism can proceed. A better understanding of physical processes in the soil-atmosphere system is essential to understanding environmental potentials and limitations to biological processes.

2. Radiation

The sun is the energy source that drives earth's physical and biological processes. Of the radiation reaching the earth's atmosphere, some is reflected and some is radiated back to the atmosphere, resulting in the net radiation, R_n, that provides energy to the earth. For a given horizontal surface, the energy balance, based on the principle of conservation of energy, can be expressed as:

$$R_n + G + LE + H + P = 0$$

where G is soil heat flux, LE is the evaporative flux times the latent heat of vaporization, H is sensible heat flux, and P is photosynthesis. All terms will have positive values when the flux is toward the soil-atmosphere surface and negative values when the flux is away from the soil-atmosphere interface. The R_n, G, LE, and H terms can be either positive or negative values, but for daily values, R_n is generally positive, LE is generally negative (energy flux away from the surface), and G or H can be either, depending upon the time period under consideration and seasonal weather patterns. Radiation utilized for photosynthesis, while essential, is often considered a negligible portion of the total solar energy and may be omitted from energy balance studies. When considering a layer, instead of a surface, change in energy stored within the volume of that layer must be considered.

As the direct beam radiation enters the earth's atmosphere, part of the radiation is intercepted by gaseous molecules and scattered, part is reflected, and part is transmitted (see Figure 1). Scattered radiation is termed diffuse or sky radiation and constitutes about 30-40% of the solar radiation reaching the earth's surface in the mid-latitudes. Diffuse radiation provides light when there is cloud cover and when the sun is just below the horizon at dawn and dusk. The fraction of diffuse radiation increases when the solar beam travels a longer distance through the atmosphere, such as late in the day, at high latitude, or during winter when the sun is at a lower elevation. Nitrogen, oxygen, and other gaseous components of the atmosphere are smaller than the wavelengths (λ) of solar radiation. Scattering is inversely proportional to λ^4, so blue light is scattered about 9 times more than red light. As radiation travels through the atmosphere, the ratio of blue to red light decreases and the near infrared is enriched, relative to visible light. Diffuse radiation is important because it penetrates into canopies better than direct beam radiation and can be very important for photosynthesis in under-story plants or on lower leaves of plants.

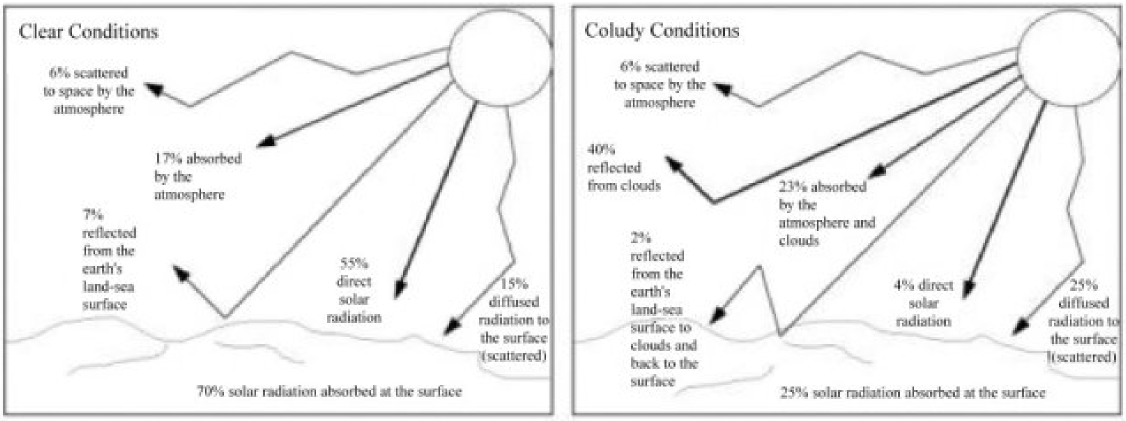

Figure 1. Solar radiation on clear and cloudy days [Source: Lutgens and Tarbuck, 1995, using data from R. G. Fleagle and J. A. Businger, An Introduction to Atmospheric Physics. 1963. Academic Press].

2.1 Radiation Laws

The amount of energy reaching earth's atmosphere normal to the source (called the solar constant) is about 1370 W m^{-2}. The velocity, c, of radiation traveling through space, or any vacuum, is $3 \cdot 10^8$ m s^{-1}. The wavelength, λ, is given by

$$\lambda = c / \nu$$

where ν is the frequency or number of cycles per second. Electromagnetic radiation has both wavelike and particle characteristics that are critical to different processes. The particle concept was described by Plank, in which electromagnetic radiation consists of a stream of particles, often called quanta. The energy, E, of each quanta is proportional to the frequency as follows:

$$E = h\nu$$

where h is Plank's constant equal to $6.625 \cdot 10^{-34}$ J s^{-1}. Since wavelength and frequency are inversely related, wavelength is inversely related to energy per quantum.

When radiation is intercepted by a body it is either reflected, absorbed, or transmitted. The reflectivity, ρ, absorptivity, α, and transmissivity, τ, of a body are dependent upon λ and

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1 \qquad 0 \leq \alpha, \rho, \tau \leq 1$$

Reflection is generally diffuse but at low sun angles and smooth surfaces can be "specular" or direct beam. Albedo is a term used to describe reflection in the shortwave or visible waveband. On a global basis, albedo is about 30%. Soils are generally more reflective than plants. Water is a poor reflector but snow reflects a very high fraction of shortwave radiation. Variability in how plants, soils, water, and other material reflect or emit radiation in different wavelengths or wavebands provides the basis for remote sensing technologies.

According to Kirchoff's Law, the absorptivity of a material at a given wavelength is equal to the emissivity, ϵ, at the same wavelength, i.e.,

$$\alpha(\lambda) = \varepsilon(\lambda)$$

A body that perfectly absorbs and emits radiation at all wavelengths is called a black body. Few natural materials behave as black bodies, but may be nearly perfect absorbers and emitters in certain wavelengths or wavebands.

All bodies that are warmer than 0 $^\circ$K emit radiation proportional to temperature with the flux intensity, I, given by

$$I = \sigma \cdot T^4$$

where T is in ^{o}K and σ is the Stephan-Boltzman constant, equal to $5.37 \cdot 10^{-8}$ W m^{-2} $^\circ K^{-4}$. As described by Wien, the maximum energy per unit wavelength, λ_m, is given by

$$\lambda_m = 2897 / T \ \mu m$$

For T = 6000 $^\circ$K, the temperature of the sun, λ_m is 0.48 μm and for T = 300 $^\circ$K, the earth's approximate average temperature, λ_m is 9.7 μm. The waveband for the sun's radiation is about 0.15 to 4 μm, ranging from the ultraviolet, through the visible, into the infrared. This range is considered short wave radiation in energy balance studies. The range of wavelength of the earth's radiation is 3 to 80 μm, and is considered long wave radiation in energy balance studies. Figure 2 illustrates atmospheric absorption of energy at different wavelengths, and shows how solar and earth radiation are affected by atmospheric constituents.

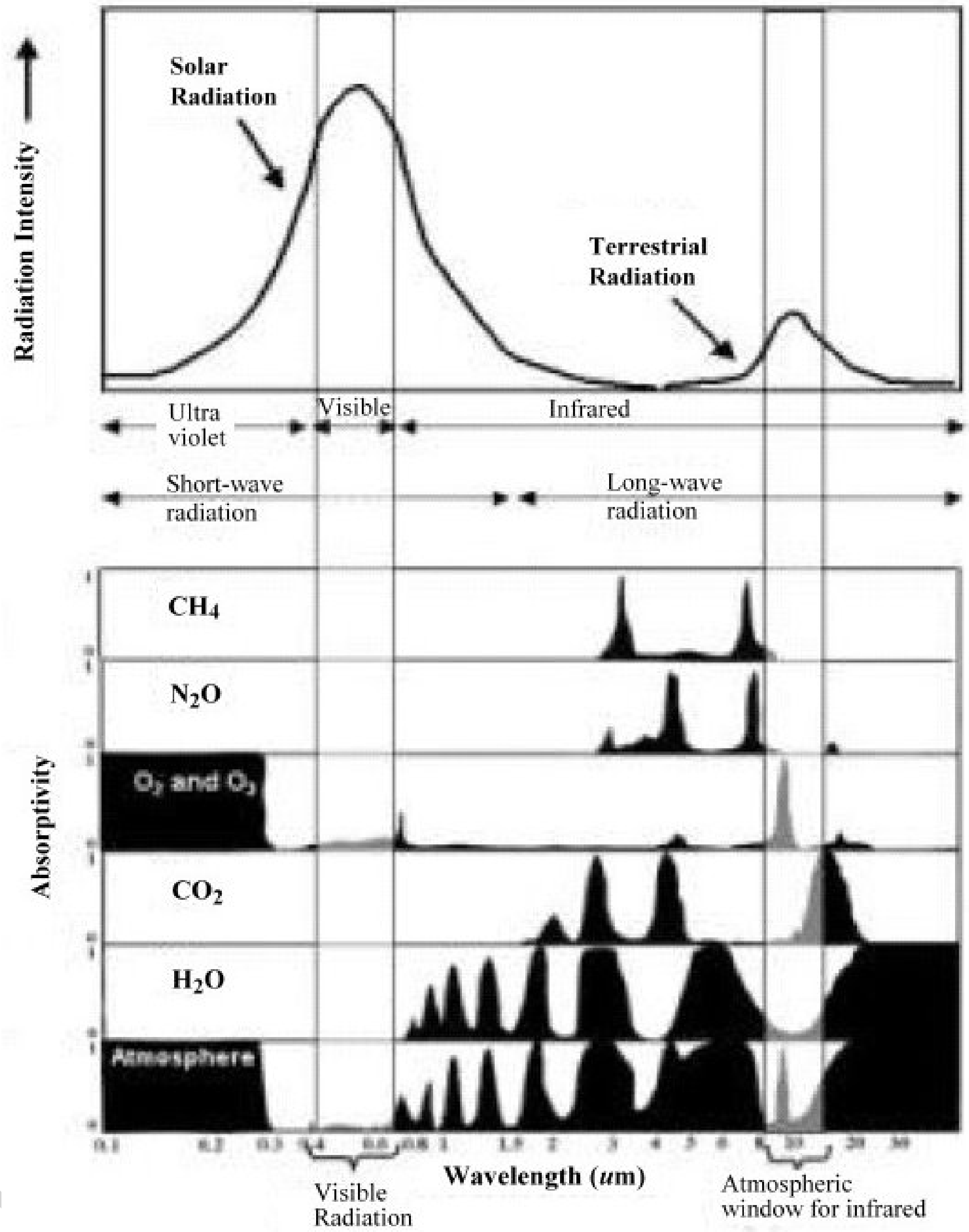

Figure 2. The emission spectrum for a body 6000 °K (sun) and 300 °K (earth) and the absorptivity of atmospheric constituents that affect the earth's radiation balance and spectral distribution of radiation at the earth's surface. (Source: Lutgens and Tarbuck, 1995, using data from R. G. Fleagle and J. A. Businger, An Introduction to Atmospheric Physics. 1963. Academic Press).

2.2 Radiation balance

Energy available at the earth's surface is determined by the balance of incoming (⇓) and outgoing (⇑) radiation in the short- (S) and long-wave (L) spectra, termed net radiation, R_n and is determined as:

$$R_n = (S\Downarrow - S\Uparrow) + (L\Downarrow - L\Uparrow)$$

The incoming shortwave radiation is solar radiation, both direct beam and diffuse. The net long wave radiation is the balance between long wave radiation that is emitted by atmospheric molecules, particles and clouds, counter balanced by radiation emitted by the earth. Since the temperature of the sky is cooler than that of the earth, there is a net loss of energy from the earth to the atmosphere by longwave radiation.

In ecological and agricultural sciences, it is of great importance to know the portion of incoming radiation that is intercepted by plants, because radiation intercepted by plants in the visible waveband determines potential photosynthesis. Additionally, interception of light across the entire spectrum determines the energy that drives potential transpiration. The fraction of radiation that is not intercepted by plants or other bodies and reaches the soil surface determines the energy that drives evaporation of water from soils and heating and cooling of the soil.

In plant canopies consisting of randomly distributed leaves, light transmission can be described as an exponential function of the leaf area index, LAI, as given below:

$$I/I_0 = e^{-kLAI}$$

where k is an extinction coefficient. Although most crop canopies do not have randomly oriented leaves, they can still be adequately described by the above equation, with k varying with canopy characteristics such as plant height and general plant shape; leaf size, shape, and orientation; and plant spacing, and row direction. For most crops and many other plant communities, light interception approaches the maximum when the leaf area index, the area of leaf per unit area of soil, reaches about 3.

2.3 Biological responses to light

Light has many impacts on organisms, including photosynthesis, respiration, photo-morphogenesis, and germination for plants. Many plant physiological functions such as fruiting can be affected by spectral qualities of light. Humans also respond to light quality and quantity with depression being more prevalent in high latitudes during winter months

3. Soil heat flux and soil temperature

Soil provides the environment for plant roots and a diverse array of organisms. Nutrients are stored and cycled in the soil and are released in forms available to organisms through chemical and biological processes. Since temperature is an important controlling factor in biological and chemical function, it is important to understand how heat flows into and out of the soil, and the patterns of soil temperature that prevail. Flow of heat in the soil is primarily by conduction. In some circumstances, heat flux by convection is important. An example would be when water of an appreciably different temperature from the soil infiltrates, and the soil temperature changes as water fills soil pores.

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Bibliography

Brutsaert, W. 1982. Evaporation into the atmosphere. Kluwer Academic Publishers. [gives a detailed discussion of basic processes in the energy balance, soil heat flux and soil temperature as well as soil water balance.]

Buchan, Graeme D. 1996. Ode to H_2O. J. Soil and Water Conservation. 51:467-470. [gives an informative description of unique properties of water and impacts of water in critical earth and life processes.]

Evett, S. R.. 1999. Energy and water balances at soil-plant-atmosphere interfaces. Pp. A-129 to A.-185, In Sumner, Malcolm E. (ed.) CRC Handbook of Soil Science, CRC Press, Boca Raton, FL. [quantitative treatment of the processes, with particular detail on net radiation and soil heat flux.]

Hillel. D. 1971. Soil and Water. Physical principles and processes. Academic Press. New York. [soil physics text book covers key principles]

Klute, A. 1986. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. (2^{nd} Edition). No. 9, Agronomy Monograph Series, American Society of Agronomy, Inc. and Soil Sci. Society of America, Inc., Madison, Wisconsin, USA. [descriptions of instrumentation and methods to measure soil physical properties that affect heat and vapor flow in soils].

Lutgens, F. K. and E. J. Tarbuck. 1995. The Atmosphere. 6^{th} Edition. Prentice Hall, Englewood Cliffs, New Jersey. [describes basic meteorologic climatic processes that determine microclimate].

Monteith, J.L. and M.H. Unsworth. 1990. Principles of Environmental Physics, 2^{nd} Ed. Edward Arnold Limited, London. [gives an excellent discussion of basic physical principles and how they apply to practical environmental physics problems of a wide variety.]

Pearcy, R.W., J. Ehleringer, H.A. Mooney and P.W. Rundel. 1989. Plant physiological ecology. Chapman & Hall, London. [gives a good overview of instrumentation and field measurement principles applicable to a wide range of ecological and agricultural studies.]

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate, the biological environment. John Wiley & Sons, New York. [gives basic principles about micrometeorolgy].

Steiner, J. L. 1994. Crop residue effects on water conservation. pp. 41-76 *In* Unger, P. W. [ed.]. Managing Agricultural Residues. Lewis Publ., Boca Raton, Florida. [describes crop residue effects on soil microclimatic processes and implications for water conservation].

Website for additional information:

http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGL/agll/aez.htm [describes the Food and Agriculture Organization's approach to Agro-ecological zoning using information about soils, climate, topography, and other factors]

Biographical Sketch

Jean L. Steiner is a Research Leader at the U.S. Department of Agriculture, Agricultural Research Service, Grazinglands Research Laboratory in El Reno, Oklahoma, leading research programs related to climate, water, and natural resource management. She is a Kansas native and received a B.A. (1974) from Cornell College, Mt. Vernon, Iowa, and M.S. (1979) and Ph.D. (1983) degrees from Kansas State University. Following a short post-doctoral research assignment with CSIRO Irrigation Research Centre in Australia, she joined ARS in 1983 at Bushland, Texas, where her research focused on dryland agriculture. From 1994 to 2001, she was Center Director at Watkinsville, Georgia, focusing on integrated agricultural systems and agricultural impacts on water quality. In 2002, she worked with CSIRO Land and Water Division as an OECD Fellow, focusing on sustainability research. She is a member of American Society of Agronomy, Soil Science Society of America, Soil and Water Conservation Society, American Association for the Advancement of Science, and International Union of Soil Science . She has served these Societies in numerous offices and committees and was named Fellow of Soil Science Society of America in 1996 and of American Society of Agronomy in 1998.