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Winds of Change: A Century of Agroclimate Research

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Winds of Change: A Century of Agroclimate Research

Jean L. Steiner* and Jerry L. Hatfield

ABSTRACT

Climate has been of primary concern from the beginning of agricultural research. Early in the 20th century, climatology and agronomy evolved separately, focusing primarily on production agriculture and crop adaptation. Concepts developed include thermal units and water use efficiency. The integrated discipline of agroclimatology developed in the mid-20th century. As theoretical understanding evolved, numerous papers related to agroclimatology were named Citation Classics. Spectral properties of plants and soils were identified that underpin today's remote sensing technologies. Commercialization of instrumentation enhanced our ability to efficiently collect data using standardized methods. Private and public-sector partnerships advanced research capacity. Later in the 20th century, research focus shifted toward integrating knowledge into crop growth and agronomic models. Remote sensing provided capacity to gain theoretical and practical understanding of regional scale processes. In the early 21st century, recognition of earth as a system along with inter-related human systems is driving research and political agendas. There is a pressing need to change our data-rich to an information-rich environment. The emerging cyberinformatics field along with natural resource and agricultural system models allow us to apply climate information to assessments and decision support related to water supply, production, environmental management, and other issues. Solutions to today's problems require interdisciplinary and multi-sectoral teams. While needs have never been greater, fewer universities maintain critical mass required to offer advance degrees in agroclimatology. It will be increasingly important that agrclimatology attract top students and provide training and practical experience in conducting integrated systems research, communications, and team skills.

From the earliest writings about agriculture, climate and weather have been a major focus. In 29 B.C., Virgil wrote a lengthy poem about farming, "The Georgics," which included considerable discussions of soils and what we now call agronomy and agroclimatology (Virgil, 29 B.C.E.).

> "…An unknown surface, heed we to forelearn
> The winds and varying temper of the sky,
> The lineal tilth and habits of the spot,
> What every region yields, and what denies…"
> Virgil, The Georgics, 29 B.C.E.

Certainly, "the winds and varying temper of the sky,…the habits of the spot, what every region yields, and what denies…" captures the essence of agroclimatological characterization. Virgil also clearly highlighted the vulnerability of agricultural to seasonal weather patterns.

> "…And he, who having plowed the fallow plain
> And heaved its furrowy ridges, turns once more
> Cross-wise his shattering share, with stroke on stroke
> The earth assails, and makes the field his thrall.
> Pray for wet summers and for winters fine…"
> Virgil, The Georgics, 29 B.C.E.

From ancient times to the foreseeable future, the farmer is always vulnerable to vagaries of the weather, be it wet summers and fine winters providing for a bounteous harvest, or dry summers and harsh winters leading to hard times.

Since the development of agricultural and natural resources research, climate and weather have been of primary concern because of their impact on food, feed, and fiber production. Interactions between weather or climate and agriculture are complex because of the spatial and temporal variation in the physical environment and the biological response. Agroclimatology spans a wide range of spatial and temporal scales. Figure 1 presents the general spatial and temporal scales of agroclimatology and related fields of study; the arrows (Fig. 1) indicate that the boundaries between the scales are fuzzy and each level extends into larger or smaller scales. Weather is experienced on a relatively local to regional scale for periods up to 1 or 2 wk. While weather is absolutely critical to agriculture and there are many important advances in the development and application of knowledge about weather to management of agricultural systems, that is not the pri-

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Abbreviations: CWSI, crop water stress index; ENSO, El Niño–Southern Oscillation; ET, evapotranspiration; FACE, free air CO_2 enrichment; FAO, United Nations Food and Agriculture Organization; GIS, geographic information systems; SDD, stress degree day; SOI, Southern Oscillation Index; WDI, water deficit index; WUE, water use efficiency.

mary focus of this article. Climate is realized at seasonal to decadal scales and generally is discussed at county to regional scales. Agricultural meteorology and micrometeorology focus on short time scales and small spatial scales up to field scale. The term *environmental physics* is sometimes applied to studies of soil–plant–animal–atmosphere continuum that include but extend beyond meteorological processes. Agroclimatology addresses issues from field to roughly county scale and generally at weekly to seasonal scales. The purpose of this article is to review the progress in and status of the science of agricultural meteorology and agroclimatology. However, these will be discussed in the context of the broader regional climate, and particularly in terms of the implications of climate change. Climate change is generally focused on subcontinental to global spatial scales and decadal to millennial time scales. However, adaptation to and mitigation of climate change often must be addressed at local and regional scales that are relevant to agroclimatology.

During the first half of the 20th century, climatology and agronomy evolved primarily as separate disciplines. In the middle of the 20th century, the integrated discipline of agroclimatology developed rapidly, along with the related area of agricultural meteorology. Many key scientific advances in micrometeorology were made by agricultural meteorology researchers because of the simplifying assumptions that could be made within more uniform agricultural plant canopies and generally flatter topography, compared with more heterogeneous and complex canopies and topographies found in most natural ecosystems. Concurrent with the development of scientific and educational programs in agroclimatology and agricultural meteorology was the establishment of the American Society of Agronomy (ASA) "Meteorology and Climatology Division" in 1964. The current name, adopted in 1979, "Agroclimatology and Agronomic Modeling" represents the development of quantitative modeling to quantify, synthesize, and extend the research results.

This paper was developed to highlight the history, contributions, and future directions of the field of agroclimatology. Key themes are presented in this article as follows:

- U.S. weather and climate infrastructure for agriculture
- Agroclimatological characterization
- Energy balance
- Soil–plant–atmosphere interactions
- Flux measurement and mass balance
- Incorporating climate information into decision making

For each of these thematic areas, a historical overview of scientific advances, highlights of seminal work, discussion of changes in research focus and application over time, and research focus for the coming decade are presented.

Table 1 summarizes progress in the agroclimatology field through four major periods over the past century, along with key issues facing science during each period, the scientific focus in agroclimatology, and advances in methods and concepts. As the discipline of agroclimatology and agricultural meteorology developed, numerous papers extending the knowledge base (Table 2) were named as *Citation Classics* (http://garfield.library.upenn.edu/classics.html; verified 11 Dec. 2007). Each of these citation classic papers contributed to conceptual advances made during the given time period and a large portion of them were written by early career scientists. Another contribution to the agroclimatology field was publication of several books authored by ASA members. Books such as *Principles of Environmental Physics* (Monteith, 1973, later revised as Monteith and Unsworth, 1990), *Microclimate: The Biological Environment* (Rosenberg, 1974, later revised as Rosenberg et al., 1983), Hillel, (1971); and Brutsaert (1982) served as textbooks or key references for multiple generations of students.

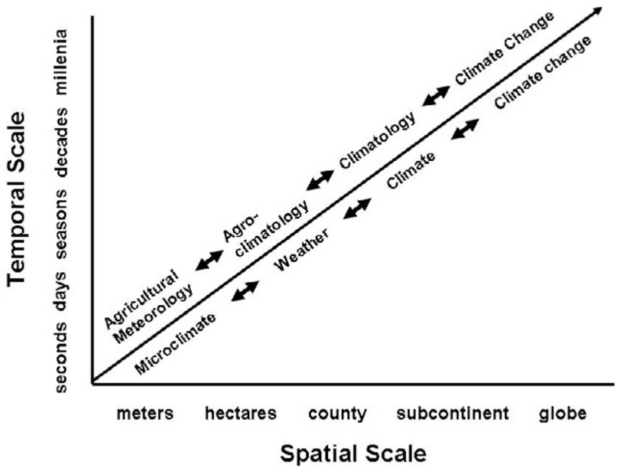

Fig. 1. Generalized temporal and spatial scaling of agricultural meteorology, agroclimatology, climatology, and climate change.

It is not possible to review of all of the literature over the past 100 yr. Livingston (1908) summarized the published literature on evaporation at the beginning the 20th century. Readers are referred to American Society of Agronomy publications by Taylor et al. (1983), *Limitations to Efficient Water Use in Crop Production*, and Hatfield and Baker (2005), *Micrometeorology in Agricultural Systems*, two major publications of ASA that reviewed and synthesized current knowledge at the time and fostered advances in the application of science to critical problems.

HISTORICAL OVERVIEW AND DISCUSSION

U.S. Weather and Climate Infrastructure for Agriculture

Federal Infrastructure

The first weather measurements supported by the U.S. government were under the direction of the Surgeon General in the early 19th century. In the mid-19th century, the Smithsonian Institution established a volunteer weather observer network. In 1890, the Cooperative Weather Observer Network was established and in 1891, the weather service was transferred to the Department of Agriculture where it remained until 1940. The National Oceanic and Atmospheric Administration and National Weather Service now reside within the Department of Commerce, but there continues to be a multi-agency, Joint Agricultural Weather Facility housed at the USDA, World Agricultural Outlook Board. The evolution of the U.S. weather monitoring infra-

Table 1. Summary of key issues, scientific focus and advances in agroclimatology.

Period	Key issues	Agroclimatology scientific focus	Methodological advances	Conceptual advances
Early 20th century Pre-1950	Crop adaptation Nutrient management Water stress	Agronomy and climatology were primarily separate fields.	Lysimetry Rain shelters	WUE concepts Thermal units
Mid 20th century 1950–1975	Production focus Development of industrial model of agriculture Development of hybrids	Evolution of agroclimatology Energy and water balance Evapotranspiration Soil plant water continuum Irrigation scheduling	Pressure plates Pressure bomb Porometry Leaf water potential Radiometers Water balance models	Combination equation Environmental physics Soil plant water relations Spectral properties of plants
Late 20th century 1975–2000	Environmental legislation Sustainability Globalization Global change	Field scale fluxes and budgets of N, C, trace gases Environmental mitigation	Field data acquisition Commercialization of research instrumentation Crop models Remote sensing Infrared thermometry Personal computers GIS technology Internet Plant temperature as a germplasm screening tool	Crop water stress index Land-atmosphere interface (mesoscale) Sustainability concepts Multi-objective decision making
Early 21st century 2001–present	Global change (Population, CO_2, temperature, and precipitation patterns) Global markets Limited natural resources and competition for land and water Bioenergy	Mesoscale focus Quantitative budgets and fluxes Verification Decision support	Climate forecasts Water supply forecast Environmental markets Cyberinformatics	4-D analyses Uncertainty and risk analyses Tradeoff analysis (energy, water, production, environment)

structure is comparable with similar developments in other nations and was paralleled by development of meteorological and agronomic societies and organizations (Table 3).

The first U.S. weather satellite was launched by NASA in 1960. Today, satellite technologies are essential to providing data for weather and climate monitoring and forecasting as well as meteorology and climatology research. Understanding of the global atmospheric system is rapidly expanding, presenting promise of increasing "forecast-ability" of weather and climate that could have tremendous benefit to agriculture through early warning and improved decision-making and risk management.

Public–Private Partnerships

Research progress and efficiency have been greatly advanced in agroclimatology, as well as other disciplines, by partnerships between the private and public sectors. Through the middle of 20th century, relatively simple equipment was used for agroclimatology research. In the era following World War II, many seminal studies were undertaken, often with specialized equipment designed and constructed by researchers and technical support staff. As the science and technology matured, key advances in measurement technology were led from the private sector, frequently in partnership with a public sector scientist. An early example was the establishment of Soilmoisture Equipment to commercially produce pressure membrane and ceramic plate extractors developed by P.E. Skaling at the USDA Salinity Laboratory in Riverside, CA (www.soilmoisture.com/about.html; verified 11 Dec. 2007). Availability of these standardized extractor plates greatly advanced the study of soil physics and soil–plant–water relations. In the early 1970s, LiCor Bioscience was established by W. Biggs, who had developed a silicon sensor for photosynthetically active radiation while on the faculty at University of Nebraska (www.licor.com/corp/history.jsp; verified 11 Dec. 2007). Since that time, LiCor has developed or commercialized a wide range of scientific instruments for agroclimatology and soil–plant–water relations research. The Heinz Walz GmbH company (http://walz.com; verified 18 Dec. 2007) was established in 1972 and have developed a range of scientific instrumentation in close collaboration with Dr. A.E. Hall, Dr. O.L. Lange, Dr. E.D. Schulze, and other prominent scientists. Campbell Scientific, established in 1974, provided some of the earliest rugged, battery powered data loggers that greatly expanded the capacity to conduct environmental research in remote locations. G. Campbell, formerly with Washington State University, has provided scientific input to the product development throughout the history of the company (www.campbellsci.com/history; verified 11 Dec. 2007). Dr. M.A. Dixon, University of Guelph, and Dr. I. Grierson, University of Adelaide, have served as research partners to ICT International (www.ictinternational.com.au; verified 11 Dec. 2007), which has provided monitoring solutions for soil, plant, and environmental research since 1982. Additional examples are commercialization of sapflow measurement devices by M. and C.H.M. van Bavel (Dynamax) and J. Kucera (EMS Brno); of net radiometers and other instrumentation by L. and C. Fritschen, of close system canopy chambers for gas-exchange measurements (Steduto et al. (2002), www.tecno-el.it; verified 11 Dec. 2007), and many others.

Table 2. Citation classics that advanced the field of agroclimatolgy and soil–plant–water relations. Essays by each the authors of these papers are available at http://garfield.library.upenn.edu/classics.html (verified 10 Dec. 2007).

Year	Author	Title	Citation	Early career†
1950	P.E. Weatherley	Studies in the water relation of the cotton plant: I. The field measurement of water deficits in leaves.	New Phytol. 49:81–97	
1960	W.R. Gardner	Dynamic aspects of water availability to plants.	Soil Sci. 89:63–73.	
1962	H. Brix	The effect of water stress on the rates of photosynthesis and respiration in tomato plants and loblolly pine seedlings.	Physiol. Plant. 15:10–20.	Y
1962	O.T. Denmead, R.H. Shaw	Availability of soil water to plants as affected by soil moisture content and meteorological conditions.	Agron. J. 54:385–390.	Y
1965	M. El-Sharkawy, J. Hesketh	Photosynthesis among species in relation to characteristics of leaf anatomy and CO_2 diffusion resistances.	Crop Sci. 5:517–521.	Y
1965	D.M. Gates, H.J. Keegan, J.C. Schleter, V.R. Weidner	Spectral properties of plants.	Appl. Optics 4:11–20.	
1965	C. Itai, Y. Vaadia	Kinetin-like activity in root exudate of water-stressed sunflower plants.	Physiol. Plant. 18:941–944.	Y
1965	J.L. Monteith	Light distribution and photosynthesis in field crops.	Ann. Bot. NS 29:17–37.	
1965	C.H.M. van Bavel, F.S. Nakayama, W.L. Ehrler	Measuring transpiration resistance of leaves.	Plant Physiol. 40:535–540.	
1967	W.G. Duncan, R.S. Loomis, W.A. Williams, R. Hanau	A model for simulating photosynthesis in plant communities.	Hilgardia 38:181–205.	
1967	S. Manabe, R.T. Wetherald	Thermal equilibrium of the atmosphere with a given distribution of relative humidity.	J. Atmos. Sci. 24:241–259.	Y
1967	P.J. Radford	Growth analysis formulae—their use and abuse.	Crop Sci. 7:171–175.	Y
1968	R.A. Fischer, T.C. Hsiao	Stomatal opening in isolated epidermal strips of Vicia faba: II Responses of KCl concentration and the role of potassium absorption.	Plant Physiol. 43:1953–1958	Y
1969	E.T. Kanemasu, G.W. Thurtell, C.B. Tanner	Design, calibration, and field use of a stomatal diffusion porometer.	Plant Physiol. 44:881–885.	Y
1969	D. Shimshi	A rapid field method for measuring photosynthesis with labelled CO_2.	J. Exp. Bot. 20:3821–401.	
1975	G.A. Ritchie, T.M. Hinckley	The pressure chamber as an Instrument for ecological research.	Adv. Ecol. Res. 9:165–253.	Y
1976	J.E. Begg, N.C. Turner	Crop water deficits.	Adv. Agron. 28:161–217.	

† Work conducted as graduate student, post-doctoral researcher, or in early career.

Such public–private partnerships have greatly contributed to the advancement of science through standardization of measurement technologies, reduced cost, improved reliability, and expanded functionality of instrumentation. Additional information about widely used measurement technologies and methodologies is provided by Pearcy et al. (1989).

Agroclimatological Characterization

As climate monitoring networks were established, research during the early part of the 20th century focused on describing basic climate characteristics such as mean and extreme values of temperature and precipitation on a monthly and annual basis, delineating frost-free periods, quantifying solar radiation, or sunshine hours. The first worldwide climate classification system (Köppen and Geiger, 1928) remains in use today. The important role of water to agriculture and human activities has led to development of several indices related to precipitation patterns. The aridity index, defined as the ratio of annual precipitation to annual potential evaporation, was defined in UNESCO (1977). Dregne (1982) described four key precipitation patterns, winter, summer, continental, and bimodal, which are critical determinants of ecological and

Table 3. Advances in organizations and infrastructure through key periods of the development of agroclimatology.

Time period		Seminal advances
Before 1907	1850	Establishment of British (later Royal) Meteorology Society
	1873	Establishment of International Meteorological Organization (IMO), predecessor of WMO
	1890	Cooperative Weather Observer network established in United States
	1891	Weather Service transferred to U.S. Department of Agriculture
1907–1950	1907	Establishment of American Society of Agronomy
	1908	First issue of *Agronomy Journal* published
	1908	Establishment of Bureau of Meteorology, Australia
	1913	Establishment of IMO Commission for Agricultural Meteorology
	1937	Simpson Report established research within Australian Bureau of Meteorology
	1940	National Weather Service transferred from U.S. Department of Agriculture to U.S. Department of Commerce
1950–1975	1950	Establishment of World Meteorological Organization
	1953	First meeting of the WMO Commission for Agricultural Meteorology (CAgM)
	1956	Dedication of Mauna Loa Summit Observatory
	1958	Establishment of National Aeronautics and Space Administration
	1960	First NASA weather satellite launched
1975–2000	1987	Canadian Society for Agricultural Meteorology established. (now Canadian Society for Agricultural and Forest Meteorology)
	1988	Establishment of International Panel on Climate Change
	1990	European Society for Agronomy established, including a Division for Agroclimatology and Agronomic Modeling
2000–2007	2001	International Society for Agricultural Meteorology established (a web-based communication network)
	2001	First international chair of Agroclimatology and Agronomic Modeling Division, American Society of Agronomy
	2006	First agroclimatologist elected president of American Society of Agronomy

agricultural potential. Mediterranean, monsoonal, and continental precipitation and evaporation patterns are illustrated in Steiner et al. (1988). Precipitation indices have been particularly important for agroclimatic analyses of dryland regions of the world (Hatfield, 1990; Stewart and Steiner, 1990).

Extensions in the later portion of the 20th century include development of ecoregion maps that blend climatological characteristics with other biophysical characteristics (Omernik, 1987, 2004). The development of geographic information systems (GIS) as a discipline has dramatically transformed agroclimatic and many other types of natural resource analyses. Wratt et al. (2006) provide an excellent description of GIS-based climatic mapping techniques to develop locally applicable information to help farmers and others identify opportunities and risks associated with new land uses.

Many methods have been developed to characterize agroclimatic 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. In agriculture, it is also essential to work at a finer scale of microclimate to understand the environment as it affects a particular organism or community of organisms.

Changing water supply because of climate variation will continue to challenge agriculture in both rainfed and irrigation regions. Variation in rainfall patterns and drought cycles, as well as decreased fresh water supply for irrigation, will increase the demand for a better understanding of soil–plant–water relationships and how this information can be incorporated into crop selection and management decisions. In an era of global climate change, climatologists and agroclimatologists need to develop a system to periodically re-evaluate climate means, extremes, and probability distributions and revise maps of agroecological zones.

Energy Balance

Quantifying energy exchanges in the soil–plant–atmosphere continuum has been the subject of research throughout the past century. Net radiation is the total energy input into the system that is partitioned at the earth's surface into sensible, latent, and soil heat fluxes. Study of this partitioning is termed the *energy balance*, and it has been the subject of many investigations. Geiger (1973) in the fourth printing of his original 1927 work described the "heat budget' of the earth's surface as the basis for micrometeorology.

A basic description of the energy balance that underpins a large body of research and practice is:

$$R_n + G + LE + H = 0 \quad [1]$$

where R_n is net radiation, G is soil heat flux, LE is latent heat flux, and H is sensible heat flux, all in the same units (e.g., W m^{-2}) and with fluxes toward the soil–atmosphere surface being positive and fluxes away from the surface being negative. The energy balance varies with time, space, and type of surface. Additional terms can be included in the energy balance (Eq. [1]) to account for advected energy, physical storage of energy within the canopy, and biochemical energy storage in the photosynthetic process of vegetation. However, these terms are generally minor and are usually considered in special circumstances where understanding these component fractions is required to understand the dynamics of the vegetative layer. In the remainder of this section the components of the energy balance will be discussed to show the advances and challenges in quantifying these components.

Net Radiation

The driving force for energy input is the solar and longwave radiation from the atmosphere. Net radiation can be directly measured or estimated through physical relationships governed by sun angle, atmospheric depletion of sunlight, and emission of thermal radiation from the atmosphere and the surface. Many early researchers (e.g., Szeicz et al., 1964; Gates et al., 1965; Stanhill et al., 1966; Linacre, 1968; McKree, 1972, 1973; Idso, 1981; and many others) contributed to a quantitative understanding of radiation in agricultural environments. Net radiometers were developed in the 1960s and 1970s (Fritschen, 1962; Idso, 1970; and others) and remain a widely used type of instrument. However, with the beginning of large multi-institutional field energy and C balance campaigns in the mid 1980s, problems with design, calibration, and operational procedures became obvious when substantial differences were observed in net radiation measurements by different researchers (Fritschen, 1992; Kustas et al., 1998). Research continues to address calibration (e.g., Fritschen and Fritschen, 2007), design (e.g., Cobos and Baker, 2003), and cross comparison of net radiometers (e.g., Kohsiek et al., 2007).

Soil Heat Flux

The partitioning of energy into the soil, *G*, is a relatively small fraction of the energy balance but it is critical in terms of quantifying changes in soil temperature throughout the year (e.g., relative to modifications in the soil surface through mulches and tillage). The soil heat flux can be calculated using the temperature gradient method (Kimball et al., 1976a) or measured directly using soil heat flux plates, but they have the potential for large errors (Kimball et al., 1976b). To obtain good measurements, depth of measurement and accounting for heat storage above the plate must be considered (Ochsner et al., 2006, 2007). Soil heat flux is sometimes estimated as a fraction of net radiation, but this may introduce excessive error into the energy balance during periods of soil drying (Idso et al., 1975), when weather fronts cause major air temperature changes, or for daily or shorter time periods.

Sensible Heat Flux

The sensible heat component (*H*) is the energy that is available to heat the air surrounding the earth's surface. Sensible heat flux can be measured using aerodynamic methods (discussed below) or may be determined as a residual of the energy balance equations when all other terms are measured (e.g., when using weighing lysimeters to directly measure latent heat flux). Begg et al. (1964) reported some of the early diurnal energy budgets for high radiation environments that showed the sensible heat flux term can be quite large in the absence of adequate water to meet the evaporative demand. Raschke (1960) reviewed the literature on heat transfer between the plant and the environment. Tolk et al. (2006) reported sensible heat flux into the canopy accounted for 45% of LE for irrigated alfalfa (*Medicago sativa* L.) grown in a semiarid climate for selected days with high ET, high vapor pressure deficit, and high windspeed.

Latent Heat Flux

Latent heat flux is more generally known as evaporation or evapotranspiration (ET). Water loss via the soil and crop surfaces to the atmosphere has been one of the most studied areas in agroclimatology. The amplification of the original model of Penman (1948) by Monteith (1964) led to one of the most widely used ET equations which describes fluxes from a number of vegetative surfaces. The Penman–Monteith equation is currently used as a worldwide standard for reference ET by the Food and Agricultural Organization (FAO) as described by Allen et al. (1998). Several forms of the energy balance equation that range in complexity are used for ET estimation. Some early ET models that focused on limited requirements for input data (Thornthwaite, 1948; Blaney and Criddle, 1950; Priestley and Taylor, 1972) are still used today. Estimating ET under water-limiting conditions is more difficult than under well-watered conditions, and limitations that must be considered when using ET models are discussed by Hatfield and Allen (1996). The ET models are currently used at scales ranging from fields to large regions. As data availability and computational capacity become less limiting, there is increasing interest and progress in integration of remote sensing observations into surface energy balance models to produce regional (e.g., Anderson et al., 2007) and global estimates of water use and to provide feedback to global circulation models.

Partitioning of energy at the earth's surface and separation of ET into soil (E) and plant (T) components were the focus of studies by Ritchie (1971) and Ritchie and Burnett (1971) that improved understanding of linkages between crop development, precipitation patterns, and soil on the components of ET. These concepts are used today and are critical to understanding of impacts of soil management on E and the development of cropping systems with increased WUE.

Significant advances and application of evapotranspiration theory has been made in engineering disciplines, particularly to improve irrigation scheduling (Jensen et al., 1970). Significant publications in the engineering literature include *Advances in Evapotranspiration* (American Society of Agricultural Engineers, 1985), *Lysimeters for Evapotranspiration and Environmental Measurement*

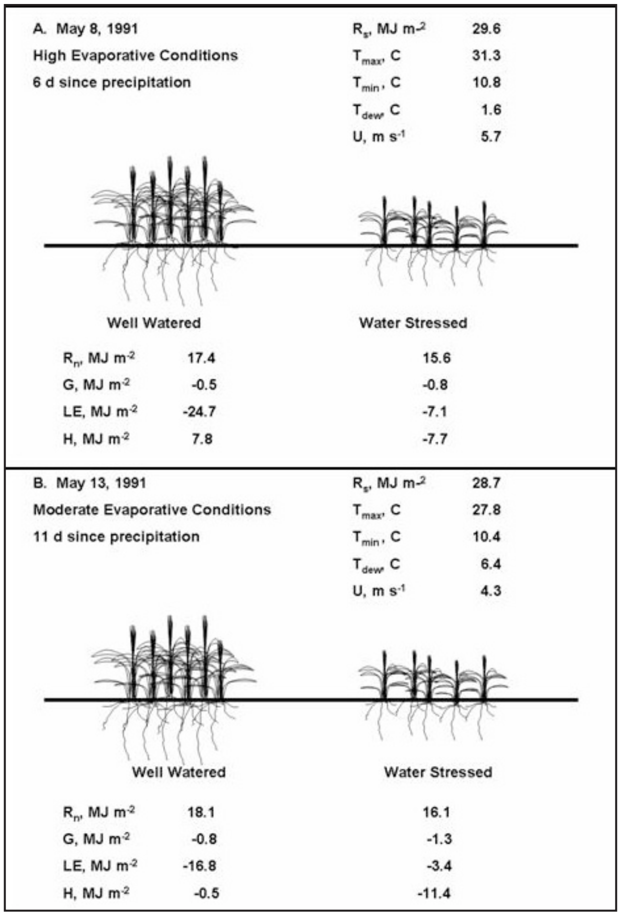

Fig. 2. Energy balance of well-watered and water-stressed winter wheat under (A) high and (B) moderate evaporative demand at Bushland Texas. Evaporation (LE) was measured by weighing lysimeters, R_n by net radiometer, *G* by heat flux plates corrected for heat storage above the plates, and sensible heat (*H*) by solution of Eq. [1]. Last rainfall of 12.2 mm (29.9 MJ m^{-2} equivalent) was May 2. Data source: Collaborative research of J.L. Steiner, T.A. Howell, A.D. Schneider, S.R. Evett, and J.A. Tolk, USDA-ARS, Bushland, TX.

(Allen et al., 1991) and *The ASCE Standardized Reference Evapotranspiration Equation* (Allen et al., 2005).

In moist systems, latent energy dominates the energy balance, while in drier systems, sensible heat accounts for a large portion of available energy. Figure 2 illustrates some of the interactive effects between the plant and atmosphere by contrasting the daily energy balance components for irrigated and rainfed wheat (*Triticum aestivum* L.) under high and moderate evaporative conditions. First, the lower net radiation in the stressed wheat compared to the well-watered wheat illustrates the impact of the surface conditions on outgoing radiation. Both the reflected shortwave and outgoing longwave radiation can be affected by the crop canopy condition in which a water stressed canopy may be brighter, rougher, and warmer than the well watered canopy. On the day with extremely high evaporative conditions (very low dewpoint temperature and high windspeed compared to the more moderate day), the LE in the well-watered crop exceeded the net radiation by 40% with the additional energy coming into the canopy in the form of sensible heat. The impact of soil water availability on LE of the water stressed crop is illustrated by the LE component, which was 44% of R_n at 6 d after precipitation, compared with 21% of R_n at 11 d after precipitation.

Derivations of the Energy Balance Equation

Exchange processes, governed by properties of the surface, have been expressed in many forms by agricultural meteorologists. It is instructive to examine different forms because they represent changes over time in our understanding about dynamics of the energy balance. One of the most well-known techniques and often cited method is the Bowen ratio (Bowen, 1926). This method is built on the ratio of sensible and latent heat fluxes from the surface (β) and is given as:

$$\mathrm{LE} = (R_n + G)/(1 + \beta) \qquad [2]$$

where R_n and G are positive toward the surface and

$$\beta = \gamma(h_h/h_v)[(T_z - T_0)/(e_z - e_0)] \qquad [3]$$

where γ is the psychrometric constant, h_h and h_v are transfer coefficients for heat and vapor, respectively (h_h/h_v is assumed to be equal to 1), T_z and T_0 are temperature at height z and at the surface, respectively, and e_z and e_0 are vapor pressure at height z and at the surface, respectively. Bowen's (1926) method continues to underpin flux measurements in a wide range of research.

A seminal paper by Penman (1948) described the equation given below:

$$\mathrm{LE} = [\Delta/(\Delta+\gamma)]\{(R_n+G)+[(\rho Cp/\Delta)h(e^*_z - e_z)]\} \quad [4]$$

where Δ is the slope of the saturation vapor curve, ρCp is the volumetric heat capacity, h is a transfer coefficient, e^*_z is the saturation vapor pressure at height z and e_z is the vapor pressure at height z. This equation combined energy and atmospheric terms and is often called the combination equation. Penman derived an empirical term for the aerodynamic portion of the equation that included the vapor pressure deficit and a linear windspeed function. This equation and later extensions have been used widely to calculate "potential evaporation" or "potential evapotranspiration" and sometimes is referred to a "big leaf" model because it treats the evaporation process of a grass surface as similar to transpiration from a single leaf.

The Penman combination equation was developed for daily evaporation estimates for a short grass surface that was not limited by water supply. Tanner (1960) presented a more detailed energy balance approach to describing ET from a cropped surface and proposed micrometeorological methods that would permit measurement of fluxes at intervals of less than 1 h, important in advancing understanding of the processes. In this study, Tanner began to describe the problems of obtaining energy fluxes over small areas and the need for larger areas (later termed *fetch*) to account for the dynamics of the vertical energy exchanges.

Monteith (1964) advanced our understanding of coupling of the plant with the atmosphere, expressed in the expanded form of the energy balance below:

$$R_n - G = \rho Cp[(T_s - T_a)/r] + \rho Cp/\gamma \{[e_s(T_s) - e_a]/(r_a + r_c)\} \quad [5]$$

where T_s and T_a are the surface and air temperatures (°C), respectively, r_a is the aerodynamic resistance (s m^{-1}) and r_c is the canopy resistance (s m^{-1}), $e_s(T_s)$ is the saturation vapor pressure at the T_s (kPa), e_a the actual vapor pressure, and γ the psychometric constant (kPa °C^{-1}). This expression of the energy balance has permitted a more rigorous description of the coupling of surface characteristics (surface or canopy resistance) with surface temperature as part of the energy balance and it has been explored by numerous research groups in attempts to quantify the changing response of plants to available soil water.

It is not possible to mention all of the researchers who have worked in this area over the past century; however, their contributions have advanced our understanding of the complexity and dynamics of the microclimate in which we manage agricultural ecosystems. A recent product from the American Society of Agronomy, *Micrometeorology in Agricultural Systems* (Hatfield and Baker, 2005), reviews in detail the current state of knowledge on the exchange processes in the soil–plant–atmosphere continuum and measurement of the components required to understand the dynamics of this region of the earth's surface.

Soil–Plant–Atmosphere Interactions

Radiation

Radiation has many effects beyond the energy balance. Light interception by plants, as well as the spectral characteristics of the light impinging on plants, must be known to understand plant physiological responses. The utilization of Beer's law to describe the absorption of solar radiation as it penetrated into a plant canopy was first described by Monsi and Saeki (1953). This simple relationship opened the path for many studies that described how the extinction coefficient is affected by leaf angle, leaf area distribution, and plant spacing. A review by Lemeur and Blad (1975) assembled the current information on light models according to whether they treated the foliage as a geometrical or statistical problem. A summary of processes involved with understanding radiative transfer in plant communities was provided by Ross (1975).

Monteith (1965) related light distribution within crop canopies to photosynthesis rates. In that same time period, a linear relationship between accumulated biomass and the accumulated amount of intercepted solar radiation was demonstrated for maize (*Zea mays* L.) (Williams et al., 1965) and soybean [*Glycine max* (L.) Merr.] (Shibles and Weber, 1966). Radiative transfer in plant communities is routinely used in crop growth simulation models to estimate the photosynthetic rate and overall plant growth, and agricultural meteorologists have contributed significantly to the refinement of these models. Research on plant responses to light has been conducted at the interface of plant physiology and agricultural meteorology, with much of the work reported in the plant physiology literature.

Leaves, as objects, reflect, absorb, or transmit light. The reflectance properties of leaves have been used throughout the past century to evaluate plant responses to stress and for a variety of predictive purposes. Gates et al. (1965) were the first to describe the spectral properties of plants, setting the basis for later development of remote sensing technologies that are widely used today. Their work provided a foundation for a number of research studies that began to define the spectral differences among species and changes in the spectral components in response to age, nutrient stress, or disease (Gausman and Hart, 1974; Gausman et al., 1975, 1976; Pinter et al., 1979). Asrar et al. (1984) developed a method to estimate absorbed photosynthetically active radiation and leaf area index from spectral reflectance. Goel and Norman (1990) provided information about optical and thermal infrared approaches to study vegetation canopies that summarizes the utility of different waveband combinations for agronomic assessment. Details about the advances in the use of remote sensing for agronomic applications are described in Hatfield et al. (2008).

Temperature

Temperature responses of biological systems can be characterized by the minimum and maximum temperatures at which biological activity stops. This range and the optimum temperature are species specific and characterize the role of temperature in many biological processes, for example, vernalization, breaking dormancy of seeds, changing from vegetative to reproductive growth. For many responses, the temperature of a particular plant part (root, tuber, bud) is critical to obtain the desired response. In some cases, there is a thermoperiod response in which alternating day and night temperatures are required to trigger a process, for example, breaking dormancy in potatoes (*Solanum tuberosum* L.) requires cool night temperature.

Temperature is one of the most easily observed parameters in the lower atmosphere. The development of observational networks for air temperature created a database that has been extensively used for agriculture. The simple observation that air temperature was related to phenological development of plants provided one of the early tools for managing crops (Madariaga and Knott, 1951; Katz, 1952; Lana and Haber, 1952). These initial observations prompted a series of studies that continue today to use temperature-phenological relationships in crop development models. Many different thermal models have been developed and several were compared by Aspiazu and Shaw (1972). There have been amplifications of thermal models to include daylength to account for photoperiod in photoperiod sensitive plants (Coligado and Brown, 1975) and vernalization requirements for winter wheat (Streck et al., 2003). Insect and disease models have used either air or soil temperature as driving variables for insect or disease development. An example of this type of model to predict insect emergence is given by Rummel and Hatfield (1989). Thermal models are routinely used in integrated pest management models for a variety of crops and reported in the entomological literature. Nocturnal temperature and the relationship to relative humidity and dew formation are important aspects of the temperature complex, particularly for pest management and for many horticultural crops.

Water Stress

A key concept developed from energy balance studies was that of potential evaporation as described by van Bavel (1966). This spurred a range of studies to evaluate ET in context of what a full-canopy could potentially transpire under given weather conditions; these concepts remain at the core of much research and are embedded in many current plant growth models. The energy balance model shown in Eq. [5] has been used for evaluation of water use by plant canopies and has quantified reductions of LE associated with inadequate soil water.

Understanding water stress onset, intensity, and impact has probably been the largest area of agroclimatic research. The development of the porometer for field measurement of stomatal resistance by Kanemasu et al. (1969) launched a series of studies that began to develop an improved understanding of crop water relations. Another advance at this time was the "pressure bomb" or Scholander chamber by Scholander et al. (1965). Both of these instruments provided a method for quantifying plant water relations under field conditions and required measurements on individual leaves. Application on individual leaves was considered a limitation for some purposes. For example, a comparison of eight different methods on rice (*Oryza sativa* L.) showed that more rapid measurement methods, e.g., canopy temperature methods, were most useful in screening large number of plants (O'Toole et al., 1984). However, the insights provided through application of the pressure bomb and porometry have been invaluable in advancing understanding of plant physiology and soil–plant–water relations. For example, Evenson and Rose (1976) quantified the seasonal variation in stomatal resistance in cotton (*Gossypium hirsutum* L.) and identified changes associated with factors in addition to water stress.

Development of sap flow measurement devices (Cěrmaìk et al., 1973; Cěrmaìk and Kucìera, 1981; Dixon and Tyree, 1984; Granier, 1985; Baker and van Bavel, 1987; Baker and Nieber, 1989) provided greater insight into root water uptake, translocation of water to the leaves, and photosynthesis. The role of roots in soil has long been an area where quantitative understanding is sparse and ability to predict growth and function is limited. As we gain understanding in limitations posed by the soil environment to roots, it may be possible to identify plants with root systems that better sustain plant growth and productivity. An example of this that has shown promise is selection of plants with aerenchymous root systems for use in soils that have limited aeration due to compacted layers or high soil water content during some seasons (Huang et al., 1997a, 1997b).

Canopy resistance and aerodynamic resistance are critical terms in Eq. [5]. Canopy resistance is an extension of stomatal resistance and is related to crop water stress. A study on alfalfa (*Medicago sativa* L.) showed that ET proceeded at the potential rate and canopy resistance remained below 20 s m^{-1} when soil water was adequate, but that canopy resistance began to rapidly increase and ET to decrease when soil water became limited (van Bavel, 1967). Hatfield (1985) showed that canopy resistance could be calculated from application of the energy balance (Eq. [5]) for wheat crops and quantified a linear relationship of canopy resistance and soil water content. This method was extended to potatoes by Amer and Hatfield (2004) to evaluate irrigation management.

Water stress is a common occurrence in agronomic crops, and at some time during the growing season, water deficits impact crop growth or yield in almost all climates. Crop stress has been quantified using the thermal portion of the radiative spectrum. One of the first definitive reports describing the relationship among plant water stress, solar radiation, air temperature, and leaf temperature was by Wiegand and Namken (1966). Their research built on the finding by Tanner (1963) that plant temperature varied from air temperature and could be measured with thermocouples attached to the leaves. Wiegand and Namken (1966) and Ehler et al. (1978) found that leaf temperature was related to plant moisture status. Later, leaf thermocouples were replaced by infrared thermometers and the quantification of crop stress and estimates of water use have been based on observations of canopy temperature. *Stress degree day*, *crop water stress index*, *non-water stressed baselines*, *thermal kinetic windows*, *crop specific temperatures*, and *water deficit index* are terms that have been used to describe plant stress and that have been developed for a number of different agronomic crops to evaluate crop water stress.

The canopy resistance approach provided the foundation for development of the crop water stress index (CWSI) by Jackson et al. (1981), who used infrared measurements of canopy temperature as a measure of crop water status in wheat. A linear relationship was developed for red kidney bean (*Phaseolus vulgaris* L.) between crop water use and the accumulation of stress degree days (SDDs, defined as canopy–air temperature) during the growing season (Walker and Hatfield, 1979). Patel et al. (2001) expanded these original studies to demonstrate that water use in pigeonpea [*Cajanus cajan* (L.) Millsp.] decreased with increasing SDD and seed yield decreased exponentially with increasing SDD. As additional crop and climate factors were shown to affect the canopy–air temperature difference ($T_c - T_a$), Idso et al. (1981) derived an empirical model for canopy stress that was based on observations of $T_c - T_a$ for the crop of interest combined with $T_c - T_a$ for well-watered and completely stressed plots of the same crop and same atmospheric conditions.

The theoretical approach developed by Jackson et al. (1981) shows the utility of the energy balance model (Eq. [5]) to derive other relationship as follows:

$$\mathrm{CWSI} = 1 - \frac{E}{E_p} = \frac{\gamma\left(1 + \frac{r_c}{r_a}\right) - \gamma\left(1 + \frac{r_{cp}}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad [6]$$

where the quantity r_c/r_a is expressed as:

$$\frac{r_c}{r_a} = \frac{\frac{r_a R}{\rho c_p} - \left(T_c - T_a\right)\left(\Delta + \gamma\right) - \left(e_a^* - e_a\right)}{\left[\gamma\left(T_c - T_a\right) - \frac{r_a R_n}{\rho c_p}\right]} \qquad [7]$$

and E is actual evaporation, E_p potential evaporation, r_{cp} the canopy resistance of a well-watered canopy, r_c the actual canopy resistance, r_a the aerodynamic resistance to sensible heat transfer, e^*_a the saturation vapor pressure, and e_a the actual vapor pressure of the air. Jackson et al. (1981) derived the theoretical shape of Eq. [6] from the assumptions about a well-watered and a completely stressed or nontranspiring canopy. The CWSI has become one of the more widely used methods for quantifying crop stress. Gardner et al. (1992a, 1992b) summarized the theory underlying the CWSI and the potential measurement problems in obtaining accurate values for parameters needed to estimate CWSI. Wanjura and Upchurch (2000) compared the empirical (Idso et al., 1981) and theoretical (Jackson et al., 1981) forms of CWSI for corn and cotton on the High Plains of Texas and found the empirical approach was more accurate than the theoretical approach because of the bounds of 0 to 1.0 placed by the empirical method on stress levels.

One problem in the application of infrared temperature measurements in crops has been incomplete ground cover where the infrared temperature reflects a mixture of crop and soil temperature. Heilman et al. (1981) demonstrated that incomplete groundcover caused a significant bias in estimating the plant canopy temperature. Moran et al. (1994) developed a relationship to extend the CWSI theory to partial vegetative cover using a spectral approach. They developed the water deficit index (WDI) that covers the range of well-watered to completely stressed vegetation for a range of canopy sizes based on the ratio of actual to potential evaporation, the same foundation as the CWSI in Eq. [6]. The WDI approach offers potential as a method for quantifying water stress under conditions of partial cover.

Canopy temperatures have been incorporated directly into the forms of the energy balance to estimate evaporation as:

$$\mathrm{LE} = R_\mathrm{n} - G - \rho c_\mathrm{p} \frac{(T_\mathrm{c} - T_\mathrm{a})}{r_\mathrm{a}} \qquad [8]$$

Hatfield et al. (1984) showed this model provided a sound approach for measuring crop water requirements by comparing direct measurements of LE from lysimeters to LE from Eq. [8] for number of locations and crops.

Evapotranspiration is a critical energy balance component in crop growth models and being able to estimate LE over large areas would help in regional plant growth or crop yield estimation. Bausch and Neale (1989) showed that crop coefficients, required for many ET models, could be obtained from remotely sensed data. This is an indirect approach that uses a vegetative index to derive a crop coefficient that would allow the use of standard meteorological data with less frequent remotely sensed observations of the canopy to provide regional estimates of evaporation. Zhang et al. (1995) developed regional estimates of LE using Eq. [8] and found the model produced acceptable agreement to area averages determined by ground-based measurement.

The extension of point measurements collected over fields into regional scale estimates is one of the current challenges facing agroclimatologists. Regional scale models require integration of remote sensing and ground-based observations. One problem facing regional scale studies is that vegetation is not distributed uniformly. The nonrandom effects of vegetative cover on the regional scale energy exchanges have been studied using a scaling method called DisALEXI (Disaggregation Atmosphere–Land Exchange Inverse) that disaggregates 5-km regional output to the Landsat TM resolution (Anderson et al., 2005). Anderson et al. (2007) further developed a multiscale approach that uses thermal, visible, and near-infrared imagery from multiple satellites to partition the fluxes between the soil and canopy. Their approach produced fluxes at a range of scales from 1 m to 10 km with the potential of being able to assess the representativeness of sensor placement across complex landscapes. Further refinement in the use remote sensing as an assessment tool coupled with ground-based observations will advance our understanding of the linkages among the scales shown in Fig. 1.

Canopy temperatures have proven useful to quantify crop stress in agronomic crops and there is expanding interest in the coupling of thermal measurements with spectral reflectance to provide a robust method of quantifying crop stress and development. The approaches developed by Hatfield (1983) and Moran et al. (1994) are examples of integrating measures of radiative emission and reflection from canopies to estimate crop growth and yield. The development of simple two-source models by Norman et al. (1995) and the Dual Temperature Difference method developed by Norman et al. (2000) to consider explicit contributions of the soil and vegetation to the radiometric temperature and energy exchanges have great potential to improve evapotranspiration predictions from crop canopies.

Water Use Efficiency

Water availability for agricultural systems is critical for optimum production. Throughout the past century there have been a wide range of studies conducted on water stress, water use rates by crops, water balance in different cropping systems, and methods to assess each of these using a variety of techniques. In the early 20th century Briggs and Shantz (1912, 1914), introduced the concept of water use efficiency (WUE), defined as the ratio of plant biomass produced relative to the quantity of water consumed. They derived WUE values for numerous crop species using pot lysimetry, where water use was determined by measuring the water added through the growing season. Denmead and Shaw (1960, 1962) advanced our understanding of interactive effects of soil water content and meteorological factors in availability of water to plants and impacts of water stress on productivity. The concept of WUE remains central to evaluation of agricultural systems.

The impact of atmospheric humidity on WUE was elucidated by Tanner and Sinclair (1983), who suggested that agroclimatologists and agronomists reconsider the role that WUE has in crop production efficiency. They proposed that for full cover crops, atmospheric vapor pressure deficit was a key determinant of dry matter (yield) produced per unit of transpiration (water use). Monteith (1994) suggested that WUE should be linked to broader resource capture efficiency and argued that capture and efficient use of CO_2, water, light, and nutrients be linked as part of the analyses of crop growth. He summarized the development of these concepts from their basis in two key assumptions about plant growth proposed by Blackman (1919). First, the rate at which leaves capture light energy is proportional to the total biomass and second, the rate of biomass accumulation is proportional to the rate of capture. Although WUE receives the most attention as a measure of crop response to water, linkage with other limiting resources is critical to understand the dynamics of plant response to the environment.

Soil Microclimate

Soil provides the environment for plant roots and a diverse array of organisms and important nutrient cycling processes. Soil microclimate is predominately determined by the radiation and water balances, soil properties (texture, structure), and the physical site (slope, aspect), but management practices can influence soil microclimate to produce conditions more favorable for processes of interest. In cold areas, it might be beneficial to apply practices to increase soil temperature to extend the growing seasons for crops. In dry areas, it would be beneficial to apply practices to conserve soil water content. In windy areas, it is beneficial to modify the wind regime near the soil surface to reduce soil erosion and plant damage from moving soil particles. Early soil microclimate research focused on seedling establishment and nutrient cycling from a production perspective. Today, such studies are equally focused on environmental and ecological aspects of agricultural systems. The root environment and soil–root interactions remains one of the least understood aspects of plant physiology and remains a focus of active research. Soil and climate are discussed in detail in Steiner (2002).

Over the past few decades, conservation tillage systems have been developed and implemented worldwide to provide soil and water conservation in cropping systems. The impacts of retaining more residues on the soil surface through reduced tillage are complex and interactive (Steiner, 1994). Improved measurement systems such as time domain reflectometry (TDR) and heat pulse methods allow precise measurements in space and time that can provide for better understanding of heat and water flow processes and of the environment encountered by organisms in different parts of the soil. Evett (1999) summarized key processes that can be manipulated to improve agronomic management outcomes.

In many models, effects of microclimate on nutrient cycling, seed germination, root elongation, and other processes are calculated. However, few models address impacts that organisms may have in shaping their own environment, e.g., modification of total soil porosity, pore size distribution, and pore continuity. Improved understanding of interactions of soil organisms with their microclimate will be essential to understand contributions of agriculture and natural ecosystems to net emissions of greenhouse gases such as nitrous oxides and methane.

Flux Measurement and Mass Balance

Movement of oxygen, CO_2, and water vapor to and from the soil and plants is essential to sustain biological and ecological functioning. Water vapor concentration would accumulate and suppress ongoing evaporation if the vapor were not moved from near the evaporating surfaces to other parts of the atmosphere. Similarly, as plants photosynthesize and deplete the air around them of CO_2, photosynthesis would decrease if the supply of CO_2 were not replenished from other parts of the atmosphere. Continual movement in the atmosphere is driven by energy from the sun that causes heating, changes in air density, and movement from regions of higher to lower pressure. A number of methods developed over the past 50 yr to quantify atmospheric fluxes remain viable for research today.

Aerodynamic Fluxes

Fluxes of energy, momentum, or gases in the lower atmosphere have been described by the flux gradient adaptation of Fick's Law of Diffusion (Fick, 1855). Flux gradient equations for momentum, heat, and water vapor are:

$$\tau = \rho_a k_m \frac{\partial u}{\partial z} \quad [9]$$

$$H = \rho_a C_p k_h \frac{\partial \theta}{\partial z} \quad [10]$$

$$E = \rho_a k_q \frac{\partial q}{\partial z} \quad [11]$$

where τ is the surface shear stress (kg m^{-1} s^{-2}), H is the sensible heat flux (W m^{-2}), E is the water vapor flux (W m^{-2}), ρ_a is air density (kg m^{-3}), C_p is specific heat of air (J kg^{-1} K^{-1}), and k_m, k_h, and k_q are eddy diffusivities for momentum, heat, and water vapor, respectively. The assumption that $k_m = k_h = k_q$ has been the foundation for the development various forms of the energy exchanges. Monin and Obukhov (1954) described some of the basic relationships of turbulent mixing in the lower atmosphere that are still being used today. Businger et al. (1971) further refined the understanding of the impacts of stable and unstable atmospheric conditions on the eddy diffusivity terms. Quantification of the roughness height and displacement lengths for crop canopies was a critical theoretical advance to which the worldwide community of agricultural meteorologists contributed (Inoue, 1963). Early studies often used strip chart recorders to obtain data from field studies; use of digital recorders has dramatically increased the magnitude of data collection for atmospheric flux analyses.

The eddy covariance method was proposed by Swinbank (1951) as a direct measure of flux based on correlation between variation in an entity of interest to variation in the vertical vector of wind flux in fully turbulent systems. This method requires very rapid response and very precise instrumentation, and application of the method expanded rapidly in the latter portion of the 20th century. The eddy covariance method was adopted as the standard flux measurement method by FLUXNET, a global network, and the measurements and analyses from this network have contributed greatly to understanding of the C cycle and earth–atmosphere processes (Baldocchi et al., 2001; Law et al., 2002).

Challenges remain in application of all aerodynamic methods. Baker (2003) identified surface-flux exchange measurement as one of the "recalcitrant problems in environmental measurement," in particular difficulties in closing the energy balance and in achieving the assumptions of stationarity and surface homogeneity required for the eddy covariance method. Flux relationships for different surfaces were recently reviewed by Prueger and Kustas (2005), who summarized the current use of these approaches in soil–plant–atmosphere studies.

Carbon Dioxide Fluxes

One of the first studies combining CO_2 measurements with aerodynamic flux measurement was reported by Lemon (1960). This study, combining wind velocity gradients with CO_2 gradients over a corn canopy, was one of several studies conducted in Ellis Hollow, New York, that quantified exchanges above and within the canopy (Wright and Lemon, 1966). These studies set the pathway for subsequent research over the course of the next decades. In a recent overview, Welles and McDermitt (2005) traced the history of CO_2 measurements including the development of the fast response CO_2 sensors that are being used today as part of several large-scale C exchange studies. The combination of the fast response CO_2 and H_2O vapor sensors have begun to provide new insights into the dynamics of crop surfaces that are being used to estimate regional scale fluxes of water and C.

Carbon dioxide fluxes from agricultural systems have been studied intensively as part of the Ameriflux program and the North American Carbon Program. These programs have attempted to document C fluxes in different systems. Verma et al. (2005) provide an example of comprehensive flux measurement for irrigated and rainfed agricultural systems. Baker and Griffis (2005) illustrate how eddy covariance and mass balance techniques can be linked to provide an analysis of the energy and C exchanges for corn and soybean canopies. Meyers and Hollinger (2004) showed it was possible to combine energy and C flux measurement to document storage terms within plant canopies. Such studies show that once elusive parameters in the expanded energy balance can be quantified through the use of the newer techniques.

Evaluation of the potential impact of increasing atmospheric CO_2 on plants has been addressed in free air CO_2 enrichment (FACE) experiments. The FACE methodology was developed to extend understanding of impacts of elevated CO_2 on plants from controlled environments to more natural field environments through complete growing seasons (Hendrey et al., 1993; Hendrey and Kimball, 1994). Kimball (1983) summarized the information available from small chamber studies and suggested that doubling of CO_2 from 330 to 660 μmol mol^{-1}) would increase C-3 plant yield by 33% and C-4 plants by 10% without any other limitations to plant growth. In a later summary of responses under free-air enrichment, Kimball et al. (2002) concluded that plant responses may not be as large as previously predicted. Leakey et al. (2006) recently reported a 50% increase in CO_2 levels (from 376 to 542 μmol mol^{-1}) produced no significant response in a well-watered maize crop. Allen et al. (2003) showed for soybean that doubling of CO_2 increased the water use efficiency. Further application of the FACE technology coupled with crop simulation models will continue to provide information about how crops and other ecosystems may respond to climate change scenarios. Long et al. (2004) and Ainsworth and Long (2005) synthesized findings from numerous FACE experiments over the last two decades and found that crop yields increased less than had been anticipated based on earlier controlled environment studies.

Remote Sensing

Remote sensing has provided a method to quantify spatial and temporal dynamics of crops and the response of crops to various management scenarios. Development of remote sensing methods over the last century is detailed by Hatfield et al. (2008) as part of this series of papers. The applications of remote sensing technology to agroclimatological problems have focused on methods that quantify biomass (living or dead) or leaf area present on the soil surface for input into energy balance models, direct estimation of ET for regional scale water use models, or the quantification of crop stress or water requirements. A review of these approaches for dryland crops was prepared by Hatfield et al. (2004) and a special issue of *Photogrammetic Engineering and Remote Sensing*, Volume 69 (Hatfield and Hart, 2003) evaluates progress in applying remote sensing techniques to various agronomic and natural resource problems.

Remote sensing technologies are providing better spatial resolution that is allowing researchers to develop relationships of spectral signals to specific land areas, rather than an average signal across multiple land uses. Similarly, technologies are being developed and applied within fields that allow managers to address factors that are spatially distributed within the field that affect plant growth and yield. Some of the limiting factors being identified and managed include soil micro-climate, including variability of soil texture and the soil water balance or spatial patterns of soil compaction and associated problems with poor aeration. Integration of multiple platforms to provide a more comprehensive "view" of the agricultural system and linkage of this information into assessment tools offers potential for improved efficiency of agricultural production. While most agricultural remote sensing research has focused on use of broad band or hyperspectral reflectance data, inclusion of fluorescence might provide more information about vegetation and plant stress (Corp et al., 2003; Campbell et al., 2007).

Emerging Techniques

Advances continue in the development of techniques to quantify the energy and gas exchanges in the soil–plant–atmosphere continuum. Methods such as relaxed eddy accumulation, scalar fluxes, inverse Lagrangian fluxes, or surface renewal have begun to appear in the literature. These are summarized in recent reviews by Denmead et al. (2005), McInnes and Heilman (2005), Meyers and Baldocchi (2005), and Paw U et al. (2005). Zhang et al. (2006) combined continuous stable isotope measurements with micrometeorological measures to partition net CO_2 exchange into photosynthesis and respiration components.

Development and application of Light Detection and Ranging (lidar) systems with expanded spatial and temporal resolution have allowed more detailed characterization of the vertical and horizontal structure of the atmosphere. Cooper et al. (2006) determined the mass exchange in the stable boundary layer using a high resolution Raman lidar to measure water vapor fluxes in the lower 75 m of the atmosphere. Lidar has been combined with eddy covariance and footprint models to evaluate three-dimensional fields of moisture movement in the lower atmosphere (Cooper et al., 2003). Eichinger and Cooper (2007) utilized lidar measurements to calculate spatially resolved LE, *H*, and virtual potential heat flux over agricultural fields. The ability to quantify the fluxes of water and heat in three dimensions above a surface will continue to provide new insights into the dynamics of the coupling between the surface and the atmosphere. As emerging methods increase our ability to quantify energy and mass exchanges at the earth's surface, the challenge for agronomists will be to link with plant physiologists, agricultural meteorologists, and others to effectively apply these and other approaches to understanding complex interactions of plants with the soil and atmosphere.

Incorporating Climate Information into Decision Making

Agronomic Models

The WUE approaches pioneered by Briggs and Shantz (1912, 1914) evolved into regression approaches to crop yield forecasting. By the 1960s the knowledge base within agricultural meteorology and plant physiology were maturing along with the evolution of computer technologies. This led to development of mathematical descriptions of plant growth (Radford, 1967; Duncan et al., 1967; France and Thornley, 1984) that were later incorporated into process-oriented crop growth models.

A soil water balance model that partitioned energy into transpiration and soil evaporation based on leaf area index of the crop (Ritchie, 1972) was incorporated into several early crop models developed at the USDA and Texas Agricultural Experiment Station in Temple, TX, and that approach remains a key component of many crop, range, and natural resource models used today. Another major center of crop model development was at Wageningen University (de Wit and Penning de Vries, 1985; Penning de Vries, 1982). A comprehensive overview of models developed to support a wide range of production, management, and economic analyses and decision-support applications is beyond the scope of this article and readers are referred to Ahuja et al. (2002) for further information.

As the focus of agricultural research and agroclimatology broadened from a production focus to incorporate a range of environmental concerns, modelers incorporated functions for nutrient cycling, soil C dynamics, tillage systems, and other management practices. Under the Decision Support System for Agrotechnology Transfer framework (www.mic.hawaii.edu/dev_tech/software/dssat.html; verified 11 Dec. 2007), a suite of models along with default data bases were compiled allowing new users to efficiently begin crop modeling efforts (Jones et al., 2003). Formal and informal networks of modelers (e.g., International Consortium for Agricultural Systems Applications, www.icasa.net; verified 11 Dec. 2007) result in rapid exchange of new modules and exchange of development and validation data sets.

Weather Generators

Development of synthetic weather generators (e.g., Nicks and Harp, 1980; Richardson, 1981) in parallel with development of diverse crop and natural resource models, was an important advance that facilitated scenario analysis (Semenov, 2006). Garbrecht and Zhang (2003) showed that because of inherent characteristics of random number generators, screening the generated precipitation to ensure representation of the climate of interest allows for shorter simulation duration and greater ability to simulate subtle changes in precipitation such as those associated with seasonal forecasts. Carlini et al. (2006) developed a library to generate synthetic precipitation data for future crop modeling applications.

Seasonal Climate Forecasts

While knowing the next season's climate has long been a dream of agriculturalists, today there is reason for optimism that our ability to predict future seasonal climates is improving. The El Niño phenomenon was observed in the 19th century, and the Southern Oscillation Index (SOI) was quantified in the late 19th century. Sivakumar (2006) provided an overview of early studies of climate anomalies and development of climate forecasting, particularly for developing regions of the world.

Operational forecasts are being made by various groups around the world. The International Research Institute for Climate and Society produces widely used seasonal climate forecasts (http://iri.columbia.edu/climate; verified 11 Dec. 2007). The Queensland Department of Primary Industry and the Commonwealth Bureau of Meteorology produces seasonal climate forecasts based on ENSO and SOI signals for Australia (www.bom.gov.au/climate/ahead; verified 11 Dec. 2007), or worldwide (www.longpaddock.qld.gov.au/index.html; verified 11 Dec. 2007). The U.S. National Oceanic and Atmospheric Administration's Climate Prediction Center (www.noaa.gov/climate.html; verified 11 Dec. 2007) releases seasonal climate forecasts covering the coming year for the United States and are developing North American forecast products.

Because forecasts are a relatively new product, and the forecasts are being released to user groups outside the traditional meteorology community, new methods for evaluation are needed. Schneider and Garbrecht (2003a, 2003b) developed indices to evaluate seasonal forecasts for agricultural applications. Their recent analyses of forecasts from the U.S. National Weather Service (Schneider and Garbrecht, 2006) indicate the results depend on forecast variable, direction of forecast (wetter/drier, warmer/cooler), season, and forecast lead time. Overall, in the Desert Southwest, southern and eastern Texas, the Gulf Coast, Florida, and parts of the Pacific Northwest, temperature forecasts have relatively high effectiveness, primarily in November through July and precipitation forecasts have moderate effectiveness in October through February, for lead times up to about half a year. For the rest of the United States, only temperature forecasts show some effectiveness at longer lead times. Lack of skill in seasonal climate forecasts was also identified as a limitation for DEMETER forecasts for Europe and New Zealand (Semenov and Doblas-Reyes, 2007) and for many developing countries (Sivakumar, 2006).

For the regions with high "effectiveness," seasonal climate forecasts may have considerable water resource and agricultural implications, but questions remains of how to downscale and interpret the impact of forecasts for applications at a local level (Steiner et al., 2004). Hansen (2002) discussed many challenges in matching appropriate forecast information to climate sensitive responses that are important to particular decision makers. Applications involving crop models are impeded by divergence in the spatial and temporal scales of the forecasts relative to the input requirements of models, as well as the nonlinear response of plants to climate (Hansen et al., 2006a).

Applications of Seasonal Climate Forecasts

Research conducted in the 1970s by J.I. Stewart and others (Stewart and Hash, 1982; Stewart and Kashasha, 1984; Stewart and Faught, 1984; Stewart, 1988) pioneered the concept of response farming. Response farming was based on identification of correlations between date of onset of the rainy season with length of the growing season and total seasonal precipitation. Such relationships gave an early indication of the type of season to be expected. With early onset, and in anticipation of a good rainy season, longer growing season crops could be planted and higher level of inputs could be purchased. With late onset indicating higher probability of low rainfall, a conservative management system could be followed to ensure food security and minimize economic risks. Response farming is generally most applicable to Mediterranean and monsoonal climates, where virtually all of the annual precipitation comes in the rainy season; it is less applicable to continental climates.

Stewart's work provided the basis for later research by Sadras et al. (2003), who developed systems for the southeast Australia Mallee region to adjust seasonal management based on April precipitation. Phillips and McIntyre (2000) identified significant correlations of ENSO to rainfall variability in unimodal and bimodal regions of east Africa, particularly relating to length of season. Phillips et al. (2002) later analyzed national records of planted area for grain in Zimbabwe, and found that farmers, in aggregate, reduced planted area during an El Niño year when a poor season was forecasted, compared with increased planted area during a La Niña year when a favorable season was forecasted.

Comprehensive summaries of research and applications related to seasonal climate forecasts with application to agriculture and natural resource management were reported in Muchow and Bellamy (1991) and Hammer et al. (2000). Hammer et al. (1996) reported that tactical management based on five phases of the SOI increased profit and reduced risk compared with fixed management in Australian wheat regions. Another approach uses analog climate years, based on a climate indicator. For instance, the Queensland Center for Climate Applications contrasted scenarios for the five phases of the SOI index (Stone et al., 1996) by selecting all years in the historical record that match the current phase of the SOI as analogs for the probable climate for the upcoming season.

Operational climate forecasts offer potential to guide production decisions, such as crop species or cultivar selection, fertility management, area to be planted, pest management, intensity and timing of grazing and purchase, sale, or movement of animals. Management decisions related to marketing, labor, and diversification, and regional decisions relating to input supply, markets, transportation, storage, community health (e.g., Bi et al., 1998) or drought preparedness (Dilley, 2000; Finan and Nelson, 2001) could also be guided by climate forecasts. To move forward, continued improvement and evaluation of forecasts skill are needed. Forecasting tools for regions that gain little from current forecasts and forecasts of extreme events should be a focus for further work in the climatology and agroclimatology communities. Uncertainty analysis for scenario simulation will be required as we develop tools to assess tradeoffs among multiple objectives and as we scale up to whole farm or landscape context. A key limitation that must be addressed is methods to communicate probabilistic outcomes and engaging farmers or other end users as partners in development of tools to support decision-making.

Because soil water depletion is a major component of crop water use and soil water is highly variable at planting time in many regions, opportunities to integrate measurement of soil water content at planting with use of climate forecasts should be investigated. Robinson and Butler (2002) found that preplant soil water content provided the best forecast of dryland crop yields in the northern Australian grainbelt, but relatively few farmers accurately measured soil water content before planting. Before turning to seasonal climate forecast to reduce risks, there usually will be greater return to first analyzing risks associated with the current management system, adopting good agronomic practices, and implementing relatively straightforward monitoring (such as soil water or soil nutrient contents) into decision-making processes. Carberry et al. (2002) have worked with Australian farmers who have had some successes in using of seasonal climate forecasts in farm level decision-making, FARMSCAPE. Their system combined soil monitoring and crop simulation with the climate forecasts, and involved farmers, advisors, and researchers working together closely.

FUTURE DIRECTIONS

Driving Forces

As our understanding increases and societal priorities change, our knowledge of agroclimatology is being applied to new issues. There is rapidly increasing knowledge of and attention to the science of climatology and increasing pressure to redefine the science of agronomy to provide a balance of production, economic, environmental, and social criteria for evaluation at the field and farm scales as well as for the agricultural sector as a whole. Although the trend over past decades has been toward large-scale production of standardized commodities, many of today's consumers are demanding more information about their food products and expressing preferences for particular production practices within the marketplace as well as the regulatory environment. With vast and growing human populations on the earth, there is increased pressure on water resources, food, energy, and environmental services. The recent rapid development of biofuels as a political, economic, and social priority, along with the rapid increase in prices of petroleum and other fossil fuels, has intensified the debate about tradeoffs between food, feed, fuel, fiber, and environmental function of agricultural systems.

Increasingly agronomy must be able to address multiple objectives and tradeoffs at farm to global scales (Hatfield, 2005). Stigter (2007) set forth a framework that spans from basic agrometeorological sciences to agrometeorological services to support decision making. He emphasized the need for better dispersion of knowledge to the farm level and applications that use existing information better through improved determination of the decision-maker needs, training of agrometeorological extensionists, evaluation of the policy environment needed to foster success, and explicit evaluation of the agrometeorological knowledge base for technologies and areas of scientific knowledge that need to be moved to operational status. Reynolds et al. (2007) identified key lessons in developing a new framework for science for dryland development that are equally relevant to advancing the field of agroclimatology. Researchers and practitioners must: (i) adopt an integrated approach, (ii) be aware of slowly evolving conditions, (iii) recognize nonlinear processes, (iv) anticipate cross-scale interactions, and (v) value local knowledge.

One of America's early environmentalists, George Perkins Marsh, wrote *Man and Nature* (originally in 1864), a sobering account of the multitude of unintended consequences of man's actions on nature, including the impacts of agriculture.

> The felling of the woods has been attended with momentous consequences to the drainage of the soil, to the external configuration of its surface, and probably, also, to local climate; …
>
> George Perkins Marsh, 1865, *Man and Nature*

A significant effort for future agroclimatologist will be on development of strategies and technologies to restore nature's function impaired by past practices, mitigate unintended consequences of current practices, and develop methods to better evaluate the range of likely outcomes associated with proposed alternative technologies and practices.

Research Challenges

Adapting to and Mitigating Climate Change

The Mauna Loa observation of increasing CO_2 in the atmosphere was first published in 1976 (Keeling et al., 1976). Although the possible linkage between atmospheric CO_2 concentration and the energy balance (now called the *greenhouse effect*) was raised by Arrhenius (1903), the Mauna Loa data were the first to raise widespread scientific and public awareness of increasing concentrations of CO_2 in the atmosphere. Keeling et al.'s work triggered concerns about the greenhouse effect and potential global climate change, leading to a tremendous research focus on the earth–ocean–atmosphere system from the 1970s to the present. The recent reports from the International Panel on Climate Change have indicated that the evidence for climate change is strong and that anthropogenic sources are a likely causal factor (IPCC, 2007a), that likely impacts on temperature and precipitation will have significant impacts on agriculture, including the most negative impacts on the poorest populations (reduced food security, inadequate potable water, increased health risks) (IPCC, 2007b), and that agriculture can play a significant role in mitigating climate change, particularly through reduced emissions of methane and nitrous oxide gases (IPCC, 2007c). Unlike prior IPCC reports, which focused on C sequestration in forestry, increased soil C sequestration was identified as a viable mitigation strategy.

Many adaptation strategies proposed for agriculture also have potential to contribute to mitigation of greenhouse gas emissions (Olesen, 2006). Additionally, many of the promising mitigation strategies for agriculture would provide important cobenefits such as increased water and nutrient holding capacity and enhanced soil biodiversity with increased soil C levels, reduced risk of erosion with increased crop residues, and improved N use efficiency and reduced nutrient contamination with improved N management (Rice, 2006). Bonan (2002) described in detail the processes at multiple scales by which landscapes affect and are affected by climate. Understanding these processes provides the scientific basis for adaptation and mitigation strategies.

The potential for managing agriculture, forestry, and ecosystems to "sequester" C from the atmosphere has greatly influenced agronomic research and will continue to be a focus of scientific, policy, and private sector attention. The practicality of C sequestration in the soil remains controversial because of the difficulty in compiling quantitative inventories and monitoring changes in soil C. The role of soil processes in the state and flux of other greenhouse gases is even less understood. Lokupitiya and Paustian (2006) reviewed national inventory methods for soil greenhouse gas emissions and discussed challenges and complexities that must be a high priority research area in coming years.

While a great deal of attention has been given through the years to effects of soil microclimate on N transformations in the soil, particularly nitrification and denitrification, far less attention has been paid to soil organisms and processes that produce methane and nitrous oxide. Because of the importance of these gases in the global atmospheric processes, they will continue to receive increased attention (Duxbury, 1994, Kroeze et al., 1999). Comprehensive studies that address the spatial and temporal interactions in the C and N cycles for major land uses, including cropping systems, range and pastures, and forests will be one of the challenges ahead for agroclimatologists and their collaborators.

Climate change impacts on agricultural production have serious implications for food security on a global basis (Parry et al., 1999). Increasing CO_2 levels have been shown to impact competitiveness of invasive species (Ziska, 2003), weed response to glyphosate (Ziska et al., 1999), and many other processes. Changing CO_2 concentration also impacts species composition and forage quality in rangelands (Morgan et al., 2004; 2007). Such studies represent some of the many challenges that agroclimatologists should address as part of future scenarios analyses.

Enhancing Resilience to Extreme Events

Numerous scientists have documented changes in annual and seasonal mean precipitation and temperature during the 20th century, and also in precipitation and temperature extremes (Easterling et al., 2000; Frei et al., 1999; Groisman et al., 2001; Karl and Knight, 1998; Kunkel et al., 1999). The SWCS (2003, 2007) convened panels who determined that the historic record exhibits increased frequency of intense precipitation at the end of the 20th century and determined that the magnitude was such that changes in agricultural conservation planning and practice may be required to protect soil and water resources. The SWCS (2003) assessment summarized major observed climate changes for the contiguous United States to include many factors of great concern to agriculture and natural resource management, including higher minimum temperature, decreased spring snow cover in the West, increased mean precipitation, increased heavy rains, and increased high streamflow events in the eastern United States. Changes in extreme weather are likely related to interdecadal oscillations in the oceans (e.g., Greene et al., 2007) as well as by longer-term global change (IPCC, 2007a).

Most studies focus on changes of extreme precipitation events, but changes in temperature extremes also have serious implications for ecosystems, agriculture, and human well being. Warmer minimum temperatures may cause problems with vernalization of some crops. Absence of freezing temperatures in some mid-latitude regions may significantly change the insect and disease populations for agriculture as well as for human populations and natural ecosystems. Increased warm temperatures and heat waves will require adaptive practices to reduce wildfire risks in grassland and forest systems and will increase the need for more drought-tolerant crops. Warming temperatures and the related decline of glaciers in the many regions of the world that rely on snowmelt to meet year-round water requirements will leave these regions more vulnerable during persistent drought periods.

Monitoring and Assessing Agriculture in the Environment

Agriculture increasingly faces trade-offs among different food–fiber–fuel and ecosystem enterprises, but lacks the tools to comprehensively assess short-term and long-term costs and benefits of alternative strategies. Agriculturalists at all levels need to identify new production, marketing, and policy approaches to simultaneously sustain the resource base and support economic viability of rural households and communities. In the policy arena at international, national, state, and local levels, market mechanisms are being explored to address short- and long-term environmental concerns including water quantity and quality, greenhouse gas mitigation, air quality, farmland protection and green space preservation, wildlife habitat and species protection, and others. In developing and implementing such market based instruments, great challenges exist in inventory of existing condition, monitoring of change in condition, and estimating desired benefits provided by particular management practices.

Remote sensing technologies and a wide range of agricultural, ecological, and hydrologic models have an important role to play in development and implementation of environmental markets as they evolve over the next decades. A special issue of Agricultural Systems (Perez et al., 2007) focused on how agroclimatology researchers and crop modelers need to interact with social scientists to address challenges to help make C sequestration markets work for Africa's rural poor. Schlenker et al. (2007) quantified the impacts of water availability and degree days on agricultural land values in California. As pressure on water resources increases, analyses such as this can play a role in determining the value of water rights that might be transferred from agriculture to other sectors through rental, lease, or sale.

Informing Agricultural Decision Making

Since the 1970s and 1980s, support of agricultural decision making through the application of crop models has been a goal of researchers. McCown et al. (2002) developed a special issue of *Agricultural Systems* that probed the enigma of lack of adoption of crop models by farmers and other agricultural decision makers. Many of the papers in that issue identified the need for more focus on the interactions of social and technical issues and for participatory approaches where both the researcher and the decision maker are engaged in learning and exchange of information. In a special issue on applying climate prediction to agriculture (Hansen et al., 2006b), Sivakumar (2006) identified several areas that need attention to advance the use of climate information particularly to smallholder farmers. These include improved forecast accuracy, quantifying the evidence of forecast benefit, enhanced stakeholder participation, assessing adoption failures for lessons learned, exploring regional market and storage applications, and addressing institutional and policy issues. Vogel and O'Brien (2006) emphasized that application of climate information must consider the diverse multiple stressors that farmers face in addition to climate uncertainty and the resources and coping mechanisms available to respond. Cabrera et al. (2007) emphasized that the value of climate information is impacted by farm policy and the risk aversion or tolerance of individuals. In their assessment for peanut–cotton–corn systems in Florida, current farm policies in the United States decreased the value of climate forecasts because other policy-related considerations were driving decision making. For risk adverse farmers, the highest benefit of a climate forecast was realized because of taking better advantage of favorable forecast years.

The Discipline of Agroclimatology

There has never been a greater need for the development and application of agroclimatological information to solving diverse agricultural and environmental problems. The solutions to today's problems require that agroclimatologists work in collaboration with broad interdisciplinary and multisectoral teams. While the needs are large, the availability of training in agroclimatology is diminishing, as fewer and fewer universities maintain critical mass required to offer an advance degree program in agroclimatology. Programs that are offered may be located in soils, agronomy, geography, or other academic departments and are difficult to identify through graduate studies websites. The loss of critical mass in academic agroclimatology programs was raised by Decker (1994) and remains a concern. For the universities that maintain advanced agroclimatology and agricultural meteorology programs, it will be increasingly important to train students not only in mathematics and biophysical sciences, but also to provide training and practical experiences in conducting integrated systems research, communications, and team skills. Given the high level of creativity and productivity indicated by the high proportion of "citation classics" (Table 2) that were published by early career scientists, it is urgent that a continued stream of high caliber students be attracted into advanced studies in agroclimatology.

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