

Chapter 13H

Agrometeorology and Wheat Production

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I. Introduction

From the earliest days of human civilization, wheat has played a significant role in nearly all societies. It was one of the first plants to be domesticated and cultivated by humans, possibly between 18,000 and 12,000 B.C. The domestication of wheat has been critical in the transition from hunter-gatherer groups into stabilized societies with an agrarian foundation. Initial wheat production flourished in the “fertile crescent” region of the Tigris and Euphrates rivers. Since domestication, wheat production has dramatically expanded, so that wheat ranks as one of the most important crops worldwide and has the widest geographical distribution of any crop. Its unique gluten content and associated bread-making properties, along with use in many food products, assure its continued role in society.

Classification of Wheat:

Wheat belongs to the genus *Triticum* and groupings within this genus are based on number of chromosome sets. Only three *Triticum* species have commercial significance: common bread wheat (*T. aestivum*), durum wheat mainly for pasta (*T. durum*), and club wheat primarily for pastry and household flour (*T. compactum*). Most wheat grown throughout the world is the hexaploid *T. aestivum*.

A number of derived species have been produced using *Triticum*. A cross of *Triticum* with rye (*Secale*) has produced *Triticale*; crossing with *Agropyron* has produced *Agrotricum* (Morris and Sears, 1967); and with *Haynaldia* has produced *Haynaltricum*. Some of this material has provided valuable genetic information or has contributed disease and insect resistance. The successful development of such wide crosses may be useful to the development of a perennial wheat and to gene diversity of cultivated wheat, but many are not useful at present.

Wheat is often characterized as being a “winter wheat” or “spring wheat”, with the normally recognized distinction being that spring wheat does not require a cold period (called vernalization) for the formation of flower primordia. Cultivars vary greatly in their vernalization requirement, and some “spring wheat” cultivars

have a short vernalization requirement. Given the vernalization requirement of winter wheat, often it is planted in the fall and receives the vernalizing temperatures in late fall and early winter. However two problems can occur: 1) winter kill can occur at high latitudes, and 2) late frosts in the spring can significantly reduce yields by damage to developing flowers. Winter cereals are preferred over spring cereals wherever it is possible for them to survive the winter period as they tend to be higher yielding (Hunt, 1980a,b; Salmon, 1917).

Considerable research has gone into developing greater cold tolerance and altering management via fertilizer (especially P at planting), tillage/residue cover (influencing snow catch), and planting date to reduce winter kill. As plant breeders succeed in producing cultivars with greater winter hardiness, and as cultural practices provide greater protection against winter injury, then the limits to winter wheat production will move into more extreme areas and may displace spring wheat. In North America, for example, increased winter hardiness has allowed winter barley to become more firmly established around the Great Lakes region (Hunt, 1980a). Except in favored areas of the northern Great Plains region of North America, winter wheat production is unlikely to expand unless winter survival becomes more reliable. In the past, quantum jumps in winter hardiness have not occurred because of the multiplicity of genetic factors involved in winter survival.

A key advancement in wheat production has been the introduction of semidwarfing genes, and indeed this was fundamental to the Green Revolution by allowing higher fertilizer inputs without the associated yield loss due to lodging (i.e., tall stems falling over). The introduction of semidwarfing genes has changed the partitioning between the canopy and roots and the harvest index (the ratio of the seed weight to the aboveground weight), among other traits (e.g., Baenziger et al., 2004; Miralles and Slafer, 1995).

A notable development of the last decade has been the explosion of information being derived from molecular biology and genome mapping, allowing characterization of genes and genomes beyond just their phenotypic effects. Positional cloning of important wheat genes is rapidly advancing. For instance,

in wheat three vernalization genes (*VRN1*, Yan et al., 2003; *VRN2*, Yan et al., 2004 and *VRN3*, Yan et al., 2006) have been cloned, as well as the *Ppd-H1* gene for photoperiod response in barley (Turner et al., 2005) and the *Ma3* maturity locus related to phytochrome B synthesis in sorghum (Childs et al., 1997). Gene networks controlling flowering are quickly emerging for crop plants such as barley (Laurie et al., 2004).

Adaptation of Wheat:

Wheat is among the world's most widely cultivated crop, occupying over 22% of the area devoted to crop grain production (FAO, 2007). It is harvested every month of the year somewhere in the world, from as far south as Argentina and as far north as Finland, and is grown over a substantial area in almost every country of North and South America, Europe, and Asia (Table 1). Wheat, a C₃ crop, is considered a cool-season grass. Therefore it is concentrated in areas between 30° and 60° N latitude and 25° and 40° S latitude (Briggle and Curtis, 1987), although continued development of photoperiod-insensitive wheat cultivars developed by CIMMYT (and other breeding efforts) can thrive within 20° of the equator or lower at higher elevations. Production, in terms of harvested area, remains remarkably consistent among countries as rankings of countries changed little between 2004 and 2005 (Table 1).

Table 1. The Top15 Countries Ranked by Production in 2004 and 2005 Plus Additional Countries

COUNTRY	2005				2004			
	Production	Rank	Area Harvested	Yield	Production	Rank	Area Harvested	Yield
	1000 metric tons		1000 ha	t/ha	1000 metric tons		1000 ha	t/ha
China	97,445.25	(1)	44,793.46	2.18	91,952.24	(1)	19,005.36	4.84
India	72,000.00	(2)	26,493.06	2.72	72,060.00	(2)	26,616.63	2.71
United States	57,280.27	(3)	20,274.35	2.83	58,737.80	(3)	20,226.13	2.90
Russian Federation	47,697.52	(4)	24,619.09	1.94	45,412.71	(4)	22,804.13	1.99
France	36,840.81	(5)	5,272.50	6.99	39,692.94	(5)	5,230.87	7.59
Canada	26,775.00	(6)	9,828.05	2.72	25,860.40	(6)	9,866.73	2.62
Australia	25,090.00	(7)	12,625.50	1.99	21,905.11	(8)	13,400.18	1.63
Germany	23,692.70	(8)	3,174.02	7.46	25,427.21	(7)	3,111.50	8.17

Pakistan	21,612.30	(9)	8,357.97	2.59	19,499.80	(10)	8,216.14	2.37
Turkey	21,000.00	(10)	9,300.01	2.26	21,000.00	(9)	9,300.06	2.26
Ukraine	18,699.20	(11)	11,216.49	1.67	17,520.20	(11)	5,531.64	3.17
United Kingdom	14,877.00	(12)	1,868.90	7.96	15,473.00	(13)	1,989.87	7.78
Iran	14,500.00	(13)	6,499.25	2.23	14,000.00	(14)	6,798.82	2.06
Argentina	12,579.15	(14)	12,854.36	0.98	15,959.58	(12)	6,069.33	2.63
Kazakhstan	11,066.00	(15)	8,324.63	1.33	9,936.93	(15)	12,388.43	0.80
Egypt	8,185.00	(17)	1,261.98	6.49	7,177.86	(19)	1,094.74	6.56
Hungary	5,088.22	(21)	1,132.24	4.49	6,006.82	(21)	1,168.66	5.14
Denmark	4,887.20	(22)	675.71	7.23	4,758.50	(26)	666.39	7.14
Czech Republic	4,145.04	(25)	820.44	5.05	5,042.52	(25)	863.14	5.84
Mexico	3,015.18	(29)	634.55	4.75	2,321.20	(34)	518.3	4.48
Saudi Arabia	2,648.47	(31)	490.07	5.40	2,775.68	(29)	524.34	5.29
Sweden	2,246.80	(34)	366.97	6.12	2,412.30	(33)	403.24	5.98
Belgium	1,768.41	(39)	213.75	8.27	1,913.18	(38)	213.04	8.98
Netherlands	1,174.69	(47)	137	8.57	1,223.90	(47)	137.29	8.92
Ireland	798.1	(53)	94.7	8.43	1,019.20	(49)	102.7	9.92
New Zealand	277	(63)	39.0	7.10	271	(66)	39.07	6.94

Source: FAO, 2007

Wheat is the cereal crop that accounts for the greatest volume of international trade, yet is subject to political and economic factors in addition to its environmental adaptation. Producers are guided in their decision making process by the net returns to be obtained from wheat as compared to other farm products, in which biofuels and animal product prices may be a deciding factor. Net returns for wheat are influenced greatly by prevailing national policies, with the result that world production patterns are strongly influenced by a number of factors other than agronomic considerations. The recent interest in biofuels has impacted the price of wheat pushing prices to historic highs on global commodities markets.

II. Influences of agroclimatological variables on wheat

As with all crops, climatological factors such as temperature, precipitation, solar radiation (intensity, photoperiod, and quality), and wind are important in influencing wheat production. While these and many other factors influence yield, the close association between yearly/seasonal weather and yield has often been noted. Therefore, weather (particularly temperature and precipitation) would likely be the first factor to explore in explaining differences observed in the Republic of

China and Ukraine yields by over 100% between 2004 and 2005 (Table 1). As the climate continues to change in the 21st Century, whether hotter and drier or cooler and wetter in different regions, wheat production should be impacted.

Breeding has resulted in considerable diversity of genotypes (i.e., cultivars) that respond differently to the interaction of these environmental variables, and indeed, the genotype by environment interaction is important in selecting cultivars for specific environments. The ever-expanding genetic diversity is allowing for the expansion of wheat into new production regions. However, selection of wheat cultivars is still strongly influenced by the vernalization (low temperature period required to initiate flower formation) and photoperiod requirements, disease and pest resistance, and drought-tolerance of the cultivar. Also, consideration of extreme environmental conditions such as late spring frosts during flower formation and hot, dry weather at anthesis and early grain growth are important. As mentioned earlier, winter wheat production may be limited by winter kill at high latitudes, and spring wheat by high temperatures during the grain filling period.

Better understanding of the variable responses of wheat to the environment is gained by considering the development and growth of the wheat plant. This is necessary because wheat has great plasticity (i.e., there are many ways that final yield can be reached), and both the environment and management influence the path taken to final yield. The important yield components of wheat are number of plants per hectare and tiller number per plant (resulting in number of spikes/heads/ears per unit area), number of spikelets per spike and kernels per spikelet (resulting in number of kernels per spike), and kernel weight. In many production environments, particularly semi-arid environments, number of spikes per unit area is the most important yield component, followed by number of kernels per spike, and least important is kernel size (e.g., Fischer et al., 1977; McMaster, 1997; Shanahan et al., 1984). Final yield is the result of development creating the yield potential (the number of spikes and kernels present in the plant) and the ability of the plant interacting with the environment to realize that potential by filling the grain (i.e., kernel size).

Many reviews of important developmental and growth processes exist (e.g., Kirby and Appleyard, 1984; McMaster, 1997; Simmons, 1987) and will not be repeated in detail here. However, several points merit mentioning. First is that developmental events creating the yield potential are occurring throughout the life cycle of the plant. It begins with seed production in the previous year, where seed viability and size are important in successful seedling emergence. Tillering begins about when the third leaf appears and continues until the growth stage of jointing (when the plant grows from the prostrate rosette form to upright form because of stem growth). Tiller abortion generally begins at jointing, and the tillers remaining at anthesis determine the number of shoots that produce spikes. Flower primordia begin to form prior to jointing, and subsequent flower differentiation and abortion continues until anthesis. Grain set at anthesis (i.e., the successful fertilization and survival of florets) determines the number of kernels per spike. After grain set, the ability of the plant to supply carbohydrates and nutrients to the grain (which is a function of both the canopy and root system) determines the final yield and quality.

The second point is that development is orderly and predictable (Hay and Kirby, 1991; McMaster, 2005; Rickman and Klepper, 1995). The genetics determines the order and sequence of events, and the environment (primarily temperature and photoperiod) is used to predict this sequence.

The last point is characterizing the environment, and plant responses to environmental factors, depends on the timing, degree, and history of the environmental factor being considered. For instance, gradual changes in the factors allowing acclimatization usually are not as stressful to the plant as sudden significant changes, or the timing and intensity of the stress may result in greater plant responses at certain growth stages.

Temperature:

Temperature is important in all plant processes and is the dominant factor controlling wheat development (McMaster, 1997). In most discussions of temperature, the reference is to air temperature just above the canopy with the

assumption that tissue or whole plant temperature is equal, or very closely related, to air temperature. The assumption of a close relationship between air and plant/tissue temperature is normally reasonable when the plant is not under water deficits or the tissue is not belowground (i.e., the roots or the crown where the shoot apex is located until the growth stage of jointing when the apex is elevated from the crown into the canopy and ultimately above the canopy at heading/anthesis). Recognition that the relationship is not always consistent led to interest in the 1990's and early 2000's in measuring or estimating soil temperature at the depth of the crown for use in plant temperature response curves when the shoot apex was located in the crown. However, it appears that for a variety of reasons using soil temperature is not necessarily more accurate than using air temperature (McMaster et al., 2003b).

Temperature response curves for various wheat physiological processes normally follow a curvilinear response (e.g., Cao and Moss, 1989; Friend et al., 1962; Streck et al., 2003; Yan and Hunt, 1999) with a frequent simplification of a linear segmented model approach often sufficient for many purposes (e.g., Jamieson et al., 2007; Porter, 1993). Regardless of the function assumed, a minimum temperature exists (T_{base}), below which the rate of the process is zero. A linear development or process rate from T_{base} to a lower optimum temperature (T_{optl}) is often observed, and from T_{optl} to an upper optimum temperature (T_{optu}) the development or process rate is maximum, and the rate declines from T_{optu} to an upper maximum temperature (T_{max} , the temperature above which again the rate of the process is assumed to be zero). While these cardinal temperatures are difficult to precisely determine, vary among cultivars, and possibly change with growth stage, generally T_{base} is about 0°C, the optimum temperature range is about 18 to 24°C, and T_{max} is above 35°C for wheat.

Regardless of the temperature response function used, temperature effects on development and many other processes are usually quantified by some measure of thermal time which is used as an indicator of the internal biological clock. Many equations are used in calculating thermal time, which is the time integral of a temperature response function that is accumulated over

time. Often it is expressed as growing degree-days and uses daily maximum and minimum air temperatures as estimates of daily mean temperature.

In most instances, the mean monthly air temperatures are gradually changing during wheat development and growth. For example, up to jointing, temperatures are normally within the optimum range from 0°C to 25°C, but temperatures for later growth stages such as anthesis and grain filling can be above the optimal range. Therefore, a lack of yield response to temperature in many of the earlier parts of the life cycle are not observed, but often are observed for later phases (e.g., Johnson and Kanemasu, 1983; Warrington et al., 1977). Of particular note for yield, temperature is very important for grain set and grain filling. High temperatures decrease grain set, increase the grain filling rate, and decrease the duration of grain filling with the usual result being lower yield under high temperatures (e.g., Herzog, 1986; Wardlaw et al., 1980; Wiegand and Cuellar, 1981). High temperatures during grain filling also often have a negative effect on grain quality (Asseng et al., 2002; Martre et al., 2003, 2006).

Discussions of wheat and temperature must include two aspects of low temperatures: vernalization and freezing temperatures/frosts. Vernalization has been well documented to vary among cultivars, and as mentioned previously is commonly used to distinguish among winter and spring wheat types. Generally a linear segmented model is used for the temperature response function, where temperatures from about 4 to 8°C are most effective in for vernalizing, with linear decreases for temperatures below 4°C and above 8°C (Porter, 1993; Ritchie, 1991).

Both spring and winter wheat seedlings will withstand reasonably low temperatures without adverse effects. Frost from just prior to jointing (when flowers are being formed) can severely damage the reproductive organs and result in sterile florets. A late-season frost may cause kernel discoloration, hinder development, and lower grade and quality.

Freezing temperatures during the winter period can induce winter kill as a result of mechanical injury, desiccation of the protoplasm, chemical effects, or suspension of metabolism (Salmon, 1917), and Fowler and Gusta (1982) showed

the importance of phosphorus in improving winter hardiness. As our understanding of the mechanisms increases and predictions improve (Fowler et al., 1999), breeding efforts may result in extending the geographic region where winter wheat may be reliably grown. Whether plants are injured by low temperatures depends on a number of factors.

Site and structure of ice crystals in the cell wall. Hardy winter wheat plants contain soluble polysaccharides which hinder ice-crystal formation in the cell wall and intercellular spaces. Ice-crystal formation can penetrate the cytoplasm and disrupt cell structure. Cells damaged by low temperatures have a typical water-soaked appearance, because membranes have been ruptured, allowing cell contents to flow out. Such cells become dehydrated and wilt when exposed to the sun.

Moisture content. Winter wheat seedlings can become conditioned to survive low-temperature stress conditions through an acclimatization process associated with cell differentiation. Acclimatization involves complex biochemical changes triggered by environmental signals such as low temperatures (0 to 5°C) and shortened day-lengths. The biochemistry of the plant cell is changed from promoting active growth to promoting high stress tolerance, involving gums and resins to resist freezing damage. The potential winter hardiness of any cultivar depends on the success of these various biochemical changes or the degree of acclimatization or cell differentiation.

External moisture content may influence freezing susceptibility. Following a midwinter thaw, winter wheat and barley plants were more susceptible to low-temperature injury because of high moisture content in the crown (Metcalf et al., 1970).

Thawing conditions may also reduce the effect of acclimatization. Cold tolerance in winter wheat and rye was reduced an average of 5°C after two thawing and freezing cycles (Gusta and Fowler, 1977). Reductions in hardiness, however, were variable.

Rate of freezing and thawing. A sudden drop in temperature before acclimatization has occurred or a sudden rise in temperature of frozen tissue

will have a more detrimental effect than a slow drop or rise in temperature. The shoot apex is the most vulnerable plant part to freezing injury. The shoot apex contains the meristematic tissue that produces new leaves, tillers, and inflorescence parts. The crown, containing the shoot apex until internode elongation begins, is a diverse part of the plant, and different patterns of freezing occur simultaneously in its various tissues (Everson and Olien, 1975). A protective snow cover may prevent plant cells from experiencing rapid and wide temperature fluctuations. A light snowfall lodged in the crown of winter cereals can provide some protection against damage by low temperatures.

Duration of freezing. The longer the tissue is exposed to sublethal temperatures, the more severe the freezing stress becomes. McKersie (1981) reported that at -12°C the ability for plants to survive began to decline after 12 hours, and at -16°C after only one hour.

Precipitation:

Successful cultivation of wheat involves the interplay of stored soil water and precipitation. Stored soil water at planting will be a function of prior precipitation, pre-plant tillage and residue cover management, and prior land use (i.e., fallow, previous crop and when harvested, etc.). Wheat is normally grown where annual precipitation averages 25 to 175 cm, but about three-quarters of the land area in wheat averages from 38 to 88 cm, and often wheat is grown in semi-arid regions with highly variable precipitation (both among and within years) with water deficits common.

Because yield components are developing and growing over the entire life cycle of the plant, water deficits at any time likely will reduce final yield. Obviously a critical period of undesirable water stress is seed germination and emergence. If soil moisture in the seedbed zone is below optimal, germination and seedling emergence rates will be reduced, leading to slower and delayed emergence which has many negative ramifications for the remainder of the growing season and final yield (McMaster et al., 2002).

The period from anthesis to maturity (and therefore grain filling duration)

is also critical in wheat yield and quality. Water deficits (and particularly if coupled with high temperatures) cause significant deterioration in pollen viability and grain set (i.e., fertilization). Water deficits during grain filling not only reduces carbon assimilation rates, but increases canopy temperature via reduced transpiration rates (see temperature effects above) and canopy senescence via accelerated leaf senescence. The result is significantly lowered yield under water deficit conditions. Even irrigation or high rainfall during this period can be insufficient to completely meet the plant demands for water. The importance of the grain filling period in yield has resulted in extensive breeding efforts selecting for drought tolerance and selection of cultivars with the ability to store and retranslocate stem reserves prior to anthesis as a means of counteracting reduced assimilation rates during grain filling (Blum et al., 1994; Haley and Quick, 1993; Nicolas and Turner, 1993).

The effects of water deficits on wheat phenology are fairly clear now (McMaster and Wilhelm, 2003; McMaster et al., 2005). Generally, water deficits must be moderately severe to result in a significant change in wheat phenology for early growth stages up through about flag leaf appearance. However for later growth stages such as heading, anthesis, and physiological maturity, water deficits will result in earlier occurrence of these stages by as much as 16 days.

Not only water deficits can affect wheat yield, but high rainfall conditions can as well, especially if accompanied by moderate to high temperatures. Some reasons for this are because it intensifies disease and insect attacks, causes harvesting difficulties, induces undesirable seed sprouting in the field, and is usually associated with a lower protein content and reduced bread-making quality. For soft wheat production, adequate rainfall during growth and development promotes high yield and low protein, the latter a desirable factor for pastry making.

Photoperiodism and Solar Radiation:

Three aspects of solar radiation are important for plant processes: intensity, duration (i.e., photoperiod or day length), and quality. Intensity is most

involved in influencing growth by altering the size of organs by influencing photosynthesis. Photosynthesis is responsive to photosynthetically active radiation (PAR) ranging from about 380 to 680 nm, with the most effective wavelengths being in the blue (around 400 nm) and red (around 640 nm) wavelengths. Numerous shading studies (e.g., Fischer and Stockman, 1980; Kemp and Whingwiri, 1980; McMaster et al., 1987) have demonstrated the positive relationship between radiation and yield. Both photoperiod and quality are primarily involved in developmental events such as leaf appearance rates (e.g., Baker et al., 1980) and phenology (e.g., Nuttonson, 1948), although duration of day length is positively related to amount of daily radiation that can be important in total assimilation. Light quality in the red and far-red spectrum and photoperiod are particularly important in the phytochrome system. Photoperiod is primarily influential in controlling the phenological stages of flower formation (signaling the switch at the shoot apex from producing primarily vegetative primordia to reproductive primordia) and timing of flag leaf appearance.

Wind:

Wind has many impacts on wheat production. It influences the energy balance of the canopy and soil surface, altering both evaporation and transpiration, so that it influences water and temperature conditions of the plant (Grant et al., 1995; McMaster et al., 2000). As mentioned previously, wind can significantly reduce grain set, and therefore yield, if hot and dry winds occur during the period of pollination. This is a common problem in many semi-arid wheat production regions.

Wind can also result in harvest losses due to lodging (stems falling over due to wind). This problem is most common for standard tall cultivars grown under high N conditions as the stems tend to grow tall and are more easily knocked down by wind or other disturbances. For this reason, cultivars with semidwarfing genes are commonly used because of the reduced stem height under high N conditions and reducing lodging potential.

III. Management aspects of wheat production in various climates

Planting Date, Seeding Rate, and Plant Density:

A positive relationship between spike density and yield is often found up to fairly high densities with a slight negative relationship at very high densities (e.g., Briggs and Aytenu, 1979; Ciha, 1983; Darwinkel, 1978, 1980; Holliday, 1960; Laloux et al., 1980; Shanahan et al., 1984). Spike density is a function of planting rate, seedling emergence, and tillers that produce spikes, and all environmental factors discussed above influence these processes. However, planting date also influences seedling emergence and tillering in several ways. As planting date is delayed in the fall, temperatures are usually lower which delays seedling emergence. Delayed emergence further shows canopy development as fewer leaves are produced in the fall. Since the appearance of tillers is related to the appearance of main stem leaves, delaying leaf appearance results in delayed appearance of fall tillers (Klepper et al., 1982, 1984). Delaying tiller appearance decreases the likelihood of tillers surviving to produce a spike, with tillers appearing in the spring more likely than fall-appearing tillers to abort before producing a spike. In general, if a tiller can survive to anthesis, it will produce a spike with reasonable yield (McMaster et al., 1994; Power and Alessi, 1978). Other factors influencing tiller appearance and survival include plant density, environmental conditions, and cultivar differences. As a result, managing final spike number must account for the complex interplay of planting rate and date, seedling emergence, environmental conditions, time of tiller appearance, and survival of tillers to produce a spike. As planting date is delayed, generally planting rates should increase to offset less tillers appearing and surviving to produce a spike.

The preceding discussion gives some qualitative guidelines for seeding rate. Fortunately, seeding rates can vary greatly without modifying final grain yield, and it is often best to plant at higher rates given that seed cost is relatively

minimal when compared to reducing the risk of having too few plants.

Soil Fertilization and Plant Nutrition:

Nitrogen, phosphorus, potassium, and a variety of micro-nutrients are essential in wheat production. Interaction of these nutrients with the climate, soil, and management (previous crops, tillage, residue cover, fertilizer, etc.) determine the availability of nutrients needed for development and growth. Soil pH is important in determining the availability of nutrients to the plant. Numerous studies have shown that growth and yield increases with fertilizer application up to some level, and then generally has no further positive influence until at very high levels yield reductions can occur (e.g., Halvorson et al., 1987 provides a review). While it is difficult to over-fertilize the wheat plant from the perspective of reducing growth and yield, doing so has many negative environmental and economic implications. This has spurred a great deal of research on how to apply the optimal amount (and when) of fertilizer for the specific production environment (e.g., Fischer et al., 1977). Under more uniform conditions of irrigation or high rainfall evenly spread out throughout the growing season, fertilizer recommendations are more easily made, whereas under rainfed semi-arid production regions with highly variable precipitation, *a priori* estimates of optimal rates are very difficult. This has promoted the concept of split fertilizer applications where a portion is added at planting and a later application at about the jointing growth stage is “matched” to the weather to date and best guess (usually the average) for the remainder of the growing season to meet a yield goal. Split applications reduce the likelihood of over-application of fertilizer at planting, thereby saving on fertilizer expenses and reducing the negative environmental impacts of excessive nutrient application. For winter wheat, applying nitrogen in early spring can stimulate leaf, tiller, and root growth, but excessive nitrogen can result in abundant vegetative growth, increased incidence of disease, and crop lodging.

Tillage and Residue Cover Management:

Tillage practices, and resulting impacts on residue cover, have a great influence on the micro-environment of the wheat plant and are increasingly being considered as an integral component of soil and water conservation practices in semi-arid wheat production systems (e.g., Black and Unger, 1987; Farahani et al., 1998a,1998b; McMaster and Wilhelm, 1997; McMaster et al., 2000, 2002; Van Doren and Allmaras, 1978). Pre-plant tillage practices usually result in increased convective exchange of water vapor at the soil-atmosphere interface thereby reducing soil water in the seedbed zone and germination rates in semi-arid regions. Loss of standing residue cover by mechanical damage or burying of residue by tillage practices continues to affect the soil surface boundary layer for quite some time following seedling emergence. This will increase convective soil evaporative losses creating water deficits severely reducing yields and exposing the soil to water and wind erosion. Residue cover also influences soil temperature and albedo, further influencing both root and canopy development and growth processes. Last, residue cover in no-till systems increases snow catch which both adds soil moisture available to the growing crop and reduces winter kill.

Cropping Systems:

Cropping systems are increasingly being integrated with changes in tillage practices, particularly in semi-arid production regions. There are many reasons for a shift from the more traditional wheat-fallow system used in many regions. Of primary importance are the impacts of creating greater biodiversity in agricultural systems with the benefits of better weed, disease, and pest control and optimal use available water in the system. These, and other benefits, typically result in greater sustainability of wheat-based cropping systems and economic returns to farmers (Halvorson et al., 1994; Nielsen et al., 2002; Peterson et al., 1993).

Weed, Disease, and Pest Management:

Wheat production systems must deal with a variety of biotic factors that

influence final yield. Weeds, diseases, and various pests are common issues limiting wheat production. A complex interaction exists between the occurrence and degree of biotic factors with the weather (e.g., temperature, precipitation, and solar radiation), soils, and management practices (e.g., tillage and residue cover, cropping systems selected, fertilizer and irrigation applications). The relative importance of weeds, diseases, and pests can vary significantly within and among years and locations. For instance, Russian wheat aphid (*Diuraphis noxia*) infestations are highly variable in the Central Great Plains of the U.S. based on the temperature during the winter period, with colder winters reducing the infestation level. Weeds infestations vary greatly based on the tillage and chemical control practices, amount and timing of precipitation, and previous crops used in rotation (Canner et al., 2002). Often high wheat production regions such as the Pacific Northwest of the U.S. have much greater disease problems under no- or low-tillage practices than the semi-arid regions of the Central Great Plains.

Changing climates in the future will likely significantly influence weed, disease, and pest pressures on wheat production. As temperature and precipitation changes, pest populations will respond accordingly. A striking example of this is the introduction of the Russian wheat aphid into the United States in 1986. It was thought that winter temperatures in the Central Great Plains were too low for the Russian wheat aphid to survive. However, as winter temperatures in the Central Great Plains have been warmer than normal since introduction into the U.S., Russian wheat aphid has often reduced yields quite substantially in recent years. Future estimates of continued warming for this region will likely exacerbate the problem, as with many other weed, disease, and pest problems.

IV. User requirements for agrometeorological information.

There are increasing demands for timely and effective agrometeorological information for on-farm applications. Decision-makers are interested in monitoring the agricultural season to assist the farming community

during adverse years, managing risk, and to provide agroclimatological information for agricultural planning. Providing agroclimatological information requires the conversion of meteorological data associated with crop yields, presentation of weather data in formats suitable for agricultural decision making, and insulation of marginal farmers with small holdings from the adverse impact of the vagaries of weather. Meteorological data are also necessary in development and adoption of digital technology such as simulation models, decision support systems (DSS), and commodity forecasting. These digital technologies are rapidly emerging for use by scientists, producers, agricultural consultants, agribusiness, and policy makers, and rely on accurate, and hopefully readily available, agrometeorological data. The need for agrometeorological data will further increase with expected climate shifts.

A holocoenotic approach to agrometeorological data on a global basis would provide many benefits. Schwere and Kellogg (1982) discuss how this would aid in rapidly and reliably assessing global crop yields to match areas with surplus production to areas of demand, as well as aid monitoring production patterns that accompany climatic shifts. Another benefit would be to improve the judicious application of expensive inputs (e.g., fertilizers, irrigation, pesticide application) in terms of amount and timing.

Use of Agrometeorological Data in Simulation Models and Decision Support Systems (DSS):

Early success in crop forecasting as noted by Bauer (1979) has spurred research in the area of crop simulation modeling and decision support systems. A brief overview of some of these efforts is provided here as these digital technologies provide an important user demand for agrometeorological data.

Early modeling efforts were commonly based on regression, or statistical, approaches, but beginning in the mid-1970's more mechanistic, or process-based, simulation models began to appear. To date, more wheat simulation models exist than for any other crop (McMaster, 1993). Regardless of type of model, all normally require at least daily maximum and minimum temperature,

precipitation, and many require daily solar radiation and windrun data as inputs. A pre-cursor to crop simulation models was the daily canopy photosynthesis model of de Wit (1965), that was used at least in concept in many initial simulation models (and most even today). These models tend to be carbon- or energy-driven models that use canopy leaf area index to absorb solar radiation to produce carbon that is then distributed to different plant components such as leaf, stem, root, and seed tissue. Examples of these models include SUCROS (and earlier models of ELCROS and BACROS; van Keulen et al., 1982), CSM-Cropsim-CERES-Wheat (Hoogenboom et al., 2004; Hunt and Pararajasingham, 1995; Jones et al., 2003, Ritchie, 1991), and Sirius (Jamieson et al., 1998a, 1998b). Beginning in the 1980's, an alternative approach towards more development-driven models were created, such as ARCWHEAT1/AFRCWHEAT2 (Porter, 1984,1993; Weir et al., 1984), SHOOTGRO (McMaster et al., 1991, 1992a, 1992b; Wilhelm et al., 1993; Zalud et al., 2003), and MODWht3 (Rickman et al., 1996). Often a simulation model is incorporated with decision support systems. Two examples with extensive adoption include the Australian APSIM DSS (Asseng et al., 2002) and the United States GPFARM DSS (Ascough et al., 2007; McMaster et al., 2003a; Shaffer et al., 2004).

V. Examples of agrometeorological services related to wheat.

The technology for a holocoenotic approach to global crop-climate relationships has been aided by satellite monitoring and weather collection networks. Satellite technology allows for remote sensing of the reflected solar radiation to estimate the areas planted to specific crops and collection of some climatological data (Idso et al., 1977), and when combined with local weather network data, provides a powerful database with great potential.

One early illustration of how this can work is provided by work in the United States. Based on 8100 surface weather observations as well as information from satellites, United States scientists are able to compare deviations in current weather variables from the expected or long-term average (Richter, 1982). Survey data determine whether rainfall is lighter or heavier than

normal; how soil moisture levels compare to those of previous years; thermal time accumulated; and if weather occurrences in general are normal or represent departures from the expected for a given area. The area planted to a specific crop, the disease situation, the level of technology, and general agronomic practices can be used for yield determination and global crop estimates using various digital technology tools and other forecasting techniques. The success of this approach rests not only on weather information, but on the assembling of high-quality, historic databases for all the major regions of the world. Early efforts to use agrometeorological data in global crop forecasting showed great promise. For example, production estimates were within 10% of the measured estimates 90% of the time, and this level of accuracy was achieved 1.5 to 2 months before harvest (Bauer, 1979).

Since these early efforts, much agrometeorological information is now readily available, particularly in the western world, via weather networks, databases, and reported statistics. Indeed, the danger exists there of an information overload. Agrometeorological information is available from governments, businesses, and the scientific community, and range from local to global scales. Global climate change models have projected climate change for many regions across the globe. One caution to note on this information is that quality assurance and completeness is not always assured. Certainly many weather networks and databases have missing data, and occasionally the methods for estimating missing data are questionable. Other chapters in this guide provide excellent guidelines related to agrometeorological information collection and presentation to users. They also show that in developing countries much still remains to be done as to services to end users.

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