CHAPTER 13E: A REVIEW OF AGROMETEOROLOGY AND POTATO PRODUCTION

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I Importance of the crop in various climates

The potato (*Solanum tuberosum* L.) is a member of the nightshade family (*Solanaceae*) and is a major world food crop and by far the most important vegetable crop in terms of quantities produced and consumed worldwide (FAO, 2005). Potato is exceeded only by wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and maize (*Zea mays* L.) in world production for human consumption (Bowen, 2003). Potato tubers give an exceptionally high yield per acre and are used in a wide variety of table, processed, livestock feed, and industrial uses (Feustel, 1987; Talburt, 1987). Potato provides nutritious food in a diversity of environments. Potato can be an important food for the increasing world population, and has the potential for increased vitamin C and protein content.

The mainly limiting factors for potato production are heat and water stresses. The effects of these factors on physiology, yield and grade of potato crop are thoroughly discussed in the current contribution. The meteorological elements governing growth, development, production, and quality of potato tubers at a given site are basically air and soil temperatures, solar radiation, photoperiod, soil moisture, and crop water use or evapotranspiration.

Potato originated from tropical areas of high altitude in the Andes. The crop is grown throughout the world but is of particular importance in temperate climates. Present world production is 329 10^6 Mg fresh tubers from 19.1 million ha (FAO, 2005). The major world producers, in order of production, are China, Russian Federation, India, United States, Ukraine, Poland, Germany, Belarus, Netherlands, United Kingdom, Canada, Turkey, and Romania (FAO, 2005).

The aboveground stems of potato plants are erect in early stages of development but later become spreading and prostrate or semi-prostrate. The tuber is an enlarged underground stem. The tubers have buds or eyes, from which sprouts arise under certain conditions. Tubers are harvested for both food and seed. The flowers and fruits are only important to potato breeders.

Potato has a relatively shallow, fibrous root system with the majority of the roots in the surface 0.3 m (Lesczynski and Tanner, 1976; Tanner et al. 1982). The root system develops rapidly during early growth and achieves maximum development by mid season. Thereafter, root length, density, and root mass decrease as the plant matures. Rooting depths of 1.2 m or more have been reported for potato under favorable soil conditions (Durrant et al. 1973; Fulton 1970). Potato extracted less water from the soil than barley (*Hordeum vulgare* L.) and sugarbeet (*Beta vulgaris* L.) and the differences were accentuated below 0.6 m depth (Durrant et al. 1973).

The origin of potato in cool climates with equatorial day lengths, and the shallow potato root systems have consequences for the agrometeorological responses of the crop.

Knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under site-specific atmospheric conditions. Crop weather models can be used to provide estimates of potato yield as a function of climatic factors at a particular locality. The SUBSTOR-Potato model, for instance, takes into consideration daily data of temperature, photoperiod, intercepted solar radiation, soil water and nitrogen supply. The model simulated fresh tuber yields ranging from 4 Mg ha^{-1} to 56 Mg ha^{-1} due to differences in climate, soils, cultivars and management practices (Bowen, 2003).

According to the Agriculture, Food and Rural Development Department (2005), potato plant has five growth stages: sprout development (I), plant establishment (II), tuber initiation (III), tuber bulking (IV), and tuber maturation (V). Timing and duration of these growth stages depend upon environmental factors, such as elevation and temperature, soil, moisture availability, cultivar and geographic location.

At growth stage I, sprouts develop from eyes on seed tubers and grow upward to emerge from the soil, roots begin to develop at the base of emerging sprouts, and the seed piece is the sole energy source for growth during this stage. At stage II, leaves and branches develop on emerged sprouts; roots and stolons develop below ground, and photosynthesis begins. Potato development in stages I and II lasts from 30 to 70 days, depending on planting date, physiological age of the seed tubers, cultivar, soil temperature, and other environmental factors. At stage III, tubers form at stolon tips but are not yet appreciably enlarged and in most cultivars the end of this stage coincides with early flowering with an average duration of roughly two weeks. At stage IV, tuber cells expand with the accumulation of water, nutrients, and carbohydrates. During tuber bulking stage, tubers become the dominant site for carbohydrate and inorganic nutrient storage. Tuber bulking can continue up to three months as a function of the cultivar and environmental conditions. During stage V photosynthesis gradually decreases, leaves turn yellow, tuber growth rate slows, and the vines die. Maturation may not occur in the field when a long season variety like Russet Burbank is grown in a short season production area.

II Agroclimatology of the crop (and some management aspects)

Kooman et al. (1996) reports three phenological phases in the allocation of daily-accumulated dry matter. Initially, dry matter is divided between stems and leaves (growth stage II). In the second phase, which starts at tuber initiation, an increasing amount of accumulated dry matter is allocated to the tubers and a decreasing fraction to the leaves (growth stages III and IV). In the third phase all assimilates are allocated to the tubers (growth stage V). Leaf growth stops and photosynthesis eventually stops because of leaf senescence. Climatic factors influence all three phenological phases. The duration of the first phase, comprising the development period between emergence and tuber initiation, is shortened by short days and temperatures less than 20°C. Tuber initiation is slower at temperatures over 20°C. The duration of the second phase is affected by temperature with an optimum between 16 and 18°C (van Heemst, 1986) or 14 and 22°C (Ingram and McCloud, 1984) and by solar radiation. Crop senescence is shortened by high temperatures, especially greater than 30°C (Midmore, 1990). The effects of agroclimatological factors on physiological parameters of potato, especially on tuber yield, grade, and internal quality, will be discussed below.

Air Temperature, Solar Radiation and Photoperiod

Due to the interactive effects of air temperature, photoperiod (day-length), solar radiation, and cultivar on the tuberization stimulus, these meteorological variables will be discussed together with emphasis on physiological responses to one or another climatic element consistent with the specific objectives of each research project.

The review by Haverkort (1990) points out that potato is best adapted to cool climates such as tropical highlands with mean daily temperatures between 15 and 18^{o}C as encountered in its center of origin. Higher temperatures favor foliar development and retard tuberization. In addition, heat stress leads to a higher number of smaller tubers per plant, lower tuber specific gravity with reduced dry matter content, and usually to a paler skin color of the tubers.

Temmerman et al. (2002) examined the effect of latitude, seasonal mean air temperature (ranging from 13.8 to 19.9^{o}C), global solar radiation (ranging from 12.0 to 21.3 MJ m^{-2} d^{-1}), air humidity, soil moisture, and atmospheric CO_2 concentrations on tuber yield in European experiments. Ignoring CO_2 enrichment, the yield of potato (cv. ‘Bintje’) increased from south to north Europe. Marketable tuber yields increased at higher latitudes. The authors ascribed this result to lower temperatures, lower vapor pressure deficits, and longer day lengths at higher latitudes, which in turn resulted in longer effective growing seasons.

Climatic conditions, as affected not only by the latitude but also by altitude, influence potato plant growth and development. Moreno (1985) found that plants grown at low (coastal) altitudes have low yield of tubers per plant as compared with those grown in the Andean highlands. Tubers harvested from coastally grown plants had lower free amid acid and amide contents and a higher content of tuber protein than those from the Andean highland. Coastal tubers also had less total sugar content than Andean tubers.

Haverkort (1990) reports that an inconvenience of the short day sensitivity of the potato is that cultivars that make use of the whole growing season and produce well in northern Europe (5-6 month growing season), may mature too early and senesce between 60 and 70 days after planting in the equatorial highlands and consequently yield less. Cultivars that perform well at low latitudes in a 3 to 4 month growing season start tuberizing late and mature too late at 50^{o}N.

Photoperiodic responses are mediated by endogenous plant hormones. Relatively high gibberellic acid (GA) levels reduce or stop tuber growth and relatively high abscisic acid (ABA) levels promote tuber growth. In some potato cultivars and species, long photoperiods produce high GA levels that prevent tuber growth. This can be a problem for temperate regions, which have long photoperiods during their usual crop season. Fortunately, many of the American cultivars are “day neutral” and presumably have lost the GA-photoperiod response (Dwelle, 1985).

Carbon dioxide concentration can also exert a strong influence on potato productivity. The influence of carbon dioxide depends on solar irradiance (Wheeler et al., 1991). Potato (cultivars ‘Norland’, Russet Burbank, and ‘Denali’) were grown at CO_2 levels of 350 or 1000 μmol mol^{-1}, irradiance of 400 or 800 μE m^{-2} s^{-1} photosynthetic photon flux (PPF), and photoperiod of 12 or 24 hours-light. Increased CO_2 provided greater tuber yield at low PPF but decreased tuber yields at high PPF. Increasing the PPF increased the tuber yield for Denali but decreased the yield for Russet Burbank. When averaged across all irradiance treatments, Denali showed the greatest gain in tuber and total weight (21 and 18%, respectively) in response to increased CO_2 enrichment for the three cultivars tested. Norland showed the least (9 and 9%, respectively), while Russet Burbank showed an intermediate response, with gains nearly as great as for Denali under a 12 h-photoperiod (18%) but less than Denali under a 24 h-photoperiod. A pattern of greater potato plant growth was observed from CO_2 enrichment under lower PPF and a short photoperiod.

Crop growing systems for space travel are needed to generate oxygen, purify water, remove carbon dioxide, produce food, and recycle waste materials. Total irradiance has been suggested to be the largest limitation to crop productivity in these systems. Potato yield improvements might be obtained by increasing the net daily photosynthetically active radiation (PAR) through higher irradiance or longer photoperiod (Stuttle et al., 1996). The photoperiod duration doubles from December to June at 50^{o}N, while PAR increases eightfold from 211 to 1701 MJ m^{-2} d^{-1} due to higher elevation of the sun above the horizon with lengthening days. Gross carbohydrate production on standard clear days increases from 108 to 529 kg ha^{-1} d^{-1} at 50^{o}N, whereas it remains at about 420 kg ha^{-1} d^{-1} year-round near the equator. Low solar irradiance is a yield constraint at 30 to 40°N in winter when potatoes are grown to escape the summer heat (Haverkort, 1990).

Stuttle et al. (1996) studied the effect of photoperiod (12, 18, and 24 h-light) on net carbon assimilation rate (A_{net}) and starch accumulation in newly mature canopy leaves of Norland potato under low and high PPF, 263 and 412 μE m^{-2} s^{-1}, respectively. Whenever the photoperiod was increased from 12 to 18 hours, there was a marked decline in A_{net} of 16.1%, and declines were most pronounced under high PPF. The maximum starch concentrations were obtained under high PPF treatments at a shorter photoperiod than under low light treatments. An apparent feedback mechanism exists for regulating A_{net} under high PPF, high CO_2, and long photoperiod, but there was no correlation between A_{net} and starch concentration in individual leaves. This suggests that maximum A_{net} cannot be sustained with elevated CO_2 enrichments under long photoperiod and high PPF conditions for Norland. Therefore, if a physiological limit exists for the fixation and transport of carbon, increasing photoperiod and light intensity under high CO_2 enrichment may not maximize potato yield.

Since the onset and early phases of tuber growth are important for the further development of potato, Dam et al. (1996) conducted a factorial experiment with two photoperiods (12 or 18 h) and four 12-h day/night temperatures (18/12, 22/16, 26/20, and 30/24°C) to analyze photoperiod and temperature effects on early tuber growth, dry-matter partitioning, and tuber number for cultivars 'Spunta' and 'Desiree'. They concluded that low mean temperatures (15-19°C) with a short photoperiod (12 h) were most suitable for early tuber growth. Under these conditions, onset of growth and onset of bulking were early, and absolute tuber growth rates and dry matter partitioning were high. Slight increases in temperature strongly reduced partitioning rates, whereas further increases had a large impact on the onset of tuber growth and absolute growth rates. Differences between treatments in numbers of tubers initiated were inconsistent. The absolute growth rate under long photoperiod was higher for Spunta than for Desiree. Different genotype responses to temperature and photoperiod on tuber growth were also found by Snyder and Ewing (1989) using potato cuttings.

Midmore and Prange (1992) examined the effects of day/night temperature (33/25°C or 20/10°C), and 12-h high irradiance (430-450 μE m^{-2} s^{-1} PAR) or 12-h low irradiance (250-280 µE m^{-2} s^{-1} PAR) both with a 6-h photoperiod extension at 6 µE m^{-2} s^{-1} on relative growth rate, net assimilation rate, and dry matter production of *Solanum goniocalyx* cv. 'Garhuash Huayro' and DTO-33, a heat tolerant clone of *S. tuberosum* x *S. phureja*. The highest relative growth rate was obtained at low temperature and low irradiance. At high temperature, low irradiance had the opposite effect, producing the lowest net assimilation and relative growth rates. Both tuber number and weight were markedly reduced by high temperature. Low irradiance in combination with high temperature produced virtually no tubers. These data, consistent with field observations that reduced potato growth at high temperatures, can be aggravated by lower irradiance. Both leaf area and net assimilation rate are reduced.

Manrique and Bartholomew (1991) carried out a potato genotype x environment experiment on Mt. Haleakala, Maui, Hawaii, at three elevations from 91 to 1097 m, to assess the performance of four standard temperate cultivars and three heat-tolerant clones in warm to cool temperatures at photoperiods prevailing in the tropics. Dry weight of plant components and total dry weight per plant were measured at tuber initiation, 20 days after tuber initiation, and 40 days after tuber initiation. Warm temperatures at 91 m hastened development such that, at tuber initiation, total dry weight per plant was 2 to 4 times greater than at 1097 m in 1985 and 1986 Tuber dry weight increased significantly at the second two sampling dates with lower temperature at higher elevation. Dry matter partitioning to tubers generally was highly and significantly correlated with temperature, with the optimum of 15 to 20°C for tuber growth. Potato plants lost their ability to allocate dry matter to tubers at higher temperatures.

Sarquis et al. (1996) stated that the magnitude of the effect of elevated temperatures on potato growth and final yield is determined by an intricate interaction between soil temperature, air temperature, solar radiation and photoperiod duration. Their data extended previous observations of reduction in photosynthesis rate under elevated temperatures. Under field conditions they concluded that reduced carbon assimilation rate could not explain the yield reduction observed; the temperature effect on assimilation was not as dramatic as it was on growth or yield. Other workers have reported a severe reduction in the rate of assimilation at air temperatures above 30°C under controlled experimental conditions. In such cases, the reduction in carbon assimilation rate was shown to correlate well with reductions in growth and yield (Ku et al., 1977; Midmore and Prange, 1992). These contrasting results reveal the complexity of plant responses to the combined effects of water and temperature stress, which inevitably occur in association under field conditions.

Thornton et al. (1996) examined the effect of two day/night air temperature regimes (low 25/12^{o}C, and high 35/25^{o}C) on dry matter production of three potato clones (Russet Burbank, Desiree, and 'DTO-28') for five weeks, beginning two weeks after tuberization, under controlled environmental conditions. Tuber growth rate was more affected by high temperature than was whole plant growth. All clones exhibited a decline in tuber dry matter production at high compared to low temperatures; however, Russet Burbank exhibited the largest decline. Potato clones varied in partitioning of dry matter to tubers at high temperatures. In addition to carbon assimilation, heat stress reduced tuber yields by affecting several plant processes such as dark respiration.

Although high temperature stress is a major uncontrolled factor affecting growth, development and productivity of plants, relatively little is known about genetic diversity for heat tolerance in potatoes. Tolerance to heat stress may involve many complex relationships. An adapted genotype must have a diverse and complex combination of genes for tolerance to high temperatures and for superior performance in the field (Tai et al., 1994).

Potato cultivars and clones vary significantly in their ability to tuberize at elevated air temperatures and continuous irradiance. Tibbitts et al. (1992) carried out two experiments under controlled environments to determine the capability of 24 highly productive potato genotypes to tolerate continuous light and high temperature. Six cultivars grew well under continuous light while three cultivars were superior to the others at high temperature. Two cultivars were well adapted to continuous light and high temperature. These evaluations were made after only 56 days of growth and further assessments should be made in longer-term productivity studies.

For some crop plants, leaf angle can be important for maximizing solar radiation interception. With potato cultivars that are intercepting as much as 95% of incident solar radiation at a LAI of 4, one must question whether alterations in leaf angle would significantly improve light interception. Individual leaves can utilize only 50-60% of incident radiation on a clear day. Following tuber initiation, the photosynthetic apparatus saturates by about 1200 $\mu E\ m^{-2}\ s^{-1}$, or about 60% of full light. Ideally, the top leaves of a potato canopy should absorb no more than 1200 $\mu E\ m^{-2}\ s^{-1}$ and should allow the remaining light to pass to the lower canopy (Dwelle, 1985). Opportunities remain to modify potato plant architecture to increase productivity (Hawkins, 1982).

Gawronska and Dwelle (1989) studied the effect of high light levels (maxima between 500 and 1200 $\mu E\ m^{-2}s^{-1}$) and shaded low light levels (approximately one-quarter of the high light) on potato plant growth, biomass accumulation and its distribution. They observed that plants under low light did not produce auxillary shoots, while those under high light did. Tubers of plants under low light were very small and irregular in shape. The most evident plant response to low light was greater stem elongation as well as a reduction in total biomass accumulation and in tuber weights. The reduction in total biomass under low light was 34 to 45%. Reduction in tuber dry weights under low light ranged from 39 to 57%, depending on the growth stage and harvest time. In addition, at all growth stages, the percentage of biomass partitioned to the tubers was higher under high light than under low light conditions.

According to Gawronska et al. (1990), potato plants grown under low light generally had lower rates of photosynthesis (when compared with those grown under high light), reaching saturation for maximum photosynthesis at about 500 $\mu E\ m^{-2}\ s^{-1}$. Some clones maintained the higher rates of photosynthesis than Russet Burbank at nearly all-light levels, demonstrating the potential to breed for cultivars that maintain higher rates of photosynthesis and potentially higher tuber yields.

Soil Temperature and Soil Temperature Management

The rate of development of sprouts from planted seed pieces depends on soil temperature. Very little sprout elongation occurs at 6°C. Elongation is slow at 9°C and is maximized at about 18°C. The time between planting and emergence depends on soil temperature. Phytotron and field experiments carried out by Sale (1979) showed that emergence was linearly related to mean soil temperature and relatively independent of diurnal fluctuations up to an optimum of 22-24°C. Up to this optimum emergence could be considered as a degree-day requirement calculated either from soil temperature at tuber depth or air temperature. At temperatures above the optimum, emergence was inhibited.

Sattelmacher et al. (1990) studied the effect of 20°C and 30°C root-zone temperatures on root growth and root morphology of six potato clones. Significant genotypical differences in the responses of potato roots to 30°C were observed, indicating the potential for selecting heat tolerant potato clones. In both heat tolerant and heat sensitive clones, the size of the root system was reduced by a 30°C root-zone temperature explained by a reduction in the cell division followed by cessation of root elongation.

Tuberization stimulus favors both tuber initiation and tuber enlargement. Through artificially prolonged exposure to short days and cool temperatures, it is possible to attain such a high level of stimulus that induction is irreversible, even if potato plants are subsequently exposed to long days for weeks or months. The optimum soil temperature for initiating tubers ranges from 16 to 19°C (Western Potato Council, 2003).

Reynolds and Ewing (1989) examined the influence of four air and soil day-night temperature treatments on root, tuber, and shoot growth in growth chambers: (cool air (19/17°C), with cool or heated soil (20/18°C or 32/31°C); and hot air (34/30°C), with hot or cooled soil (32/27°C or 19/17°C)). Cooling the soil at high air temperatures neither relieved visible symptoms of heat stress on shoot growth nor increased the degree of induction tuberization by the leaves. Heating the soil at cool air temperatures had no apparent detrimental effect on shoot growth or induction of tuberization by the leaves. Under high soil temperatures, stolonization was substantially compromised and there was no underground tuber development. In one experiment, stolons grew up out of the hot soil and formed aerial tubers above the soil surface in the cool air. The induction of tuberization by the leaves was affected mainly by air rather than soil temperature, but the signal to tuberize might be blocked by high soil temperatures. According to Mares et al. (1985), it is expected that the effect of high soil temperature on growing tubers would be similar to that of exogenously applied gibberellin, inhibiting tuberization.

Tuber development declines as soil temperatures rise above 20°C and tuber growth practically stops at soil temperatures above 30°C. The number of tubers set per plant is greater at lower temperatures than at higher temperatures, whereas higher temperatures favor development of large tubers (Western Potato Council, 2003).

Little research is available on the effect of soil temperature during tuber growth on potato grade and quality. Kincaid et al. (1993), assessing the influence of the interaction between water management and soil temperature on potato quality in the Pacific Northwest, observed that the critical period for tuber quality appears to be from mid-June to mid-July, based on measured soil temperature differences, frequent sprinkler irrigation reduced soil temperatures, along with the incidence of sugar-end tubers. Yamaguchi et al. (1964) found that yield, specific gravity and starch content of Russet Burbank and 'White Rose' tubers were higher, and the sugar content lower when grown at soil temperatures between 15 and 24°C, than when grown at higher temperatures.

Ewing (1981) reports that in many areas the sequence of temperatures that most often brings economic damage to potato crops is warm temperatures early in the season, followed by cool temperatures that induce strong tuberization, followed in turn by another period of high temperatures. Such temperature oscillations lead to heat sprouts, chain tubers, and secondary growth of tubers. Apparently the fluctuations in tuberization stimulus cause tuber formation to alternate with more stolon-like growth.

Management practices, such as planting population density, use of mulch and irrigation might substantially modify the soil temperature regime within the root zone in such a way as to affect stolonization, tuber initiation and bulking, and tuber enlargement at a given site, particularly where solar irradiance availability is shown to be a non-limiting factor for potato production. Increase of plant population through a reduction of between-row spacing was effective in raising tuber yields in the hot tropics, largely through the increase in amounts of intercepted solar radiation, which brought about a significant decline on soil temperatures during the tuber growth. Since the proportion of marketable tubers was scarcely affected by planting densities, Midmore (1988) reasoned that potato plant population in hot climates should be as high as possible without limiting the amount of soil available for hilling-up.

In order to quantify the effects of organic mulch on soil temperature and soil moisture regimes during the growth of potato, Midmore et al. (1986a) conducted seven experiments at three contrasting hot tropical sites (latitude varying from 5 to 12°S, and altitude ranging from 180 to 800 m). Mulch retained more heat in the soil at night when combined with agronomic practices that themselves increased soil heat retention at night (i.e. on the flat potato beds). The magnitude of soil cooling by mulch during the day and heat retention within the soil at night was dependent on solar irradiance levels and soil moisture content. Mulch was more effective in cooling dry soils, especially at high irradiance. Heat retention at night following days of low irradiance was greater in mulched plots, whereas at high irradiance heat retention of mulched plots was intermediate between those of moist and drier control plots.

Midmore et al. (1986b) showed that mulch increased tuber yield by 20% during the summer in Lima, Peru. Manrique and Meyer (1984), studying the impact of mulches on potato production during winter and summer seasons at the same site, found no effect on yields during the winter, but yield increases of 58% and improvements in soil moisture retention were obtained in the summer with surface mulch.

Mahmood et al. (2002) reported that mulch at Islamabad, Pakistan, decreased daily maximum soil temperature at a 15 cm-depth by 1.5 to 4.5°C, resulting in faster emergence, earlier canopy development, and higher tuber yields. Many other recent studies conducted in Asia point out the beneficial effects of mulch in potato production systems as an efficient alternative to obviate heat and water stresses in order to maximize crop yield (Jaiswal, 1995; Ruiz et al., 1999; and Sarma et al., 1999).

Atmospheric Humidity and Wind, Wind Management

There are very few recent studies dealing with the direct effects of relative humidity (RH) on potato growth, tuber yield and grade. Most of the contributions related to the influence of RH on potato refer to potato storage where RH is an important factor in tuber weight loss and the occurrence and severity of diseases and pests. The same scarcity of research exists with regard to the wind regimes at a particular location as an agrometeorological factor affecting potato production systems.

Wheeler et al. (1989) studied the effect of two RH levels, 50% and 85%, on the physiological responses of three cultivars of potato (Russet Burbank, Norland, and Denali) in controlled-environment rooms under continuous light intensity at 20°C. No significant differences in total plant dry weight were measured between the atmospheric humidity treatments, but plants grown under 85% RH produced higher tuber yields. Leaf areas were greater under 50% RH and leaves tended to be larger and darker green under drier than at more humid atmospheric conditions. The elevated humidity appeared to shift the allocation pattern of photosynthates to favor allocation to the tubers over leaves and stems.

Gordon et al. (1999) estimated sap flow from solar radiation and vapor pressure deficit data for three field-grown potato cultivars (‘Atlantic’, ‘Monona’ and ‘Norchip’) at Nova Scotia, Canada, under non-limiting soil water conditions. Sap flow rates for all cultivars were closely linked with solar radiation under conditions where soil water was not limiting. The vapor pressure deficit (VPD), a function of relative humidity and air temperature, had less effect on sap flow, although the magnitude of the VPD during the growing season was generally < 2 kPa. All cultivars maintained actual daily transpiration near the potential energy limiting rate under well-watered conditions. When the soil was drier (percent available soil water < 30%), Monona potato plants had a much more rapid decline in transpiration than the other two cultivars.

Another physiological parameter closely related to yield is water use efficiency. Bowen (2003) reported that potato farming in coastal Peru occurs during the winter, when the cool humid conditions favor growth and promote a more efficient use of irrigation water. During the winter, less soil water evaporation caused by a smaller VPD enhances water use efficiency when compared with that observed during the summer. Sinclair (1984) also showed that generally more humid environments provide greater water use efficiency because of a lower VPD.

Stomatal resistance governs photosynthesis and transpiration. Two major feedback loops are reported by Raschke (1979) as the direct controllers of stomatal resistance (r_{st}). The first involves photosynthesis where a reduction in intercellular carbon dioxide (CO_2) occurs as the photosynthetic active radiation (PAR) increases, the stomata open and r_{st} decreases. The second involves an increase in r_{st} whenever leaf water potential reaches a critical threshold as a result of transpiration intensity.

Stomatal resistance is affected by many factors including PAR, the ratio of leaf to air water potential, leaf age, air temperature and the ambient CO_2 concentration (Kim and Verma, 1991). Gordon et al. (1997) studied the stomatal resistance of three field grown potato cultivars (Atlantic, Monona and Norchip) in response to photosynthetic photon flux density, leaf to air vapor pressure difference and root zone available water. Under the climatic conditions of their field experiment in Eastern Canada, stomatal activity in potato was primarily driven by light intensity. However, as soil water became limiting the soil/plant water status became increasingly more important. The absence of very high VPD values throughout the growing season is the probable main reason for the lack of potato r_{st} response to air vapor pressure differences. Significant differences were observed among cultivars in the response of stomata to changes in available soil water. Crop weather modeling needs to incorporate these differences into model systems because they might have a significant effect on eventual model performance at a given site.

Wind has important effects on potato. Pavlista (2002) reported that leaves injured by lower wind speeds show bronzed areas, brown with a shiny surface, due to the rubbing of leaves against each other. The bronzed areas tend to brittle from drying. When pressed the bronzed areas crack, forming a sharp-edged rip through the affected tissue. Under higher wind speeds, leaves not only bronze but also tatter. Tattered leaves typically have a 6 to 25 mm sized tears with irregular brownish borders. Stems may also be affected by winds. When exposed to a mild wind, stems may just be flopped around causing a slight weakness of the tissues. Under strong winds, vines might actually get twisted, bringing about a break or hinge-like weakness in the stems. If exposed to strong winds for several hours, the vine may twist all the way around and cause the stem to collapse, cutting off nutrient flow through the phloem between the vine and the tubers.

Wind also affects transpiration rates and, therefore, photosynthetic activity and crop yield. At sites where winds are frequently strong throughout the year, increased stomatal resistance can cause reduction in potato yield (Pavlista, 2002; Sun and Dickinson, 1997). At such sites, guidelines for the sustainable management of potato cropping systems need an emphasis on windbreak development including height, porosity, and orientation.

Sun and Dickinson (1997) studied the benefit of two 30-month-old windbreaks (one with two rows of trees and one with three rows of trees) for potato in tropical northeastern Australia. Two *Eucalyptus* species (*E. microcorys* and *E. torelliana*) were found to be highly suitable for windbreaks since they showed rapid development in height and branch growth while retaining low branches. The porosity of three row and two row windbreaks were 37.2 and 60%, respectively. The optimum range of porosity for windbreaks is between 40 and 50% (Marshal, 1967). Windbreaks increased potato plant growth in height and leaf number, however, had limited effects on leaf length and width. Potato plants grown close to windbreaks yielded more than those grown at the furthest positions, with the highest production removed 3 times the windbreak height. Windbreaks increased potato yield by up to 7.7%, whereas Sturrock (1981) found windbreaks increased yield by 35%.

Wright and Brooks (2002) examined the effect of windbreaks on growth and yield of potatoes over a 4-year period in Australia, measuring the amount and severity of wind damage to leaves, plant height, and leaf numbers from potato located at various distances from the windbreak in both sheltered and unsheltered positions. Windbreaks increased tuber yield between 4.8 and 9.3% for the sheltered portion of the field in seasons with higher than average wind speeds and caused a reduction in wind damage to leaves on protected potato plants. In seasons where wind speed was above average, windbreaks increased yield at distances away from the windbreak between 3 and 18 times the height of the windbreak. Cleugh (2003) reported that potato crop yields were significantly higher in the sheltered zone from 2 to 18 times the height of the windbreak compared to yields obtained in unprotected areas.

Crop Evapotranspiration and Irrigation Requirements

Crop consumptive water use is the amount of water transpired by the plants plus the water evaporated from the soil plus the fraction of water held by the plant tissues. The amount of water retained by plant metabolic activity is about 1% of the overall water taken up by the plants. Thus, in practical terms crop water consumption corresponds to crop evapotranspiration (ET_c). Potato ET_c can be estimated using weather data and is the amount of water to be replenished during the growing season in order to assure potential tuber yields at a given site. Potato ET_c is important to consider in irrigation planning and its use in irrigation scheduling is a well-developed strategy to improve the effectiveness of irrigation.

An adequate water supply is required from tuber initiation up until near maturity for high yield and good quality. Applying water in excess of plant needs compromises the environment, may harm the crop, and is expensive for growers. Excessive irrigation of potatoes results in water loss and significantly increases of runoff and soil erosion from production fields to rivers, streams, and reservoirs. Leaching can lead to contamination of the groundwater due to lixiviation of fertilizers and other chemical products (Al-Jamal et al., 2001; Feibert et al., 1998; Shock et al., 2001; Waddell et al., 2000). Irrigation in excess of crop needs increases production costs, can reduce yield by affecting soil aeration and root system respiration, and favors the occurrence and severity of diseases and pests. Deficient irrigation promotes a reduction of tuber quality and lower yield due to reduced leaf area and/or reduced photosynthesis per unit leaf area (van Loon, 1981).

Local atmospheric conditions, surface soil wetness, stage of growth, and the amount of crop cover are the factors that govern the daily fluctuations of potato ET_c (Wright and Stark, 1990). They observed that ET_c increased as the leaf area and transpiration increased and reached near-maximum levels just before effective full cover. The leaf area index (LAI) reached 3.5 by effective full cover coincident with the highest daily ET_c of 8.5 mm. Seasonal total ET_c corresponded to 604 mm in southern Idaho.

Potato ET_c varies greatly from region to region. Seasonal potato ET_c in the humid Wisconsin area for June through August ranged from 293 to 405 mm during 3 years of study (Tanner, 1981). At Mesa, AZ, ET_c for February through June, averaged 617 mm (Erie et al., 1965). The mid season daily potato ET_c was 6 mm near Calgary, Alberta, Canada (Nkemdirim, 1976.), while the daily water consumption was 3 mm under the climatic conditions of Botucatu, State of São Paulo, Brazil, during the winter where seasonal ET_c was only 283 mm (Pereira et al., 1995a). Wright and Stark (1990) reported that seasonal water use in irrigated areas of Oregon and Washington, USA, ranged from 640 to 700 mm. For high yields at a given site, the seasonal water requirements of a potato crop with a phenological cycle varying from 120 to 150 days ranged from 500 to 700 mm, depending on climate (Doorenbos and Kassam, 1979).

The maximum daily potato ET_c measured by a weighing lysimeter in a sub-humid region in India was found to be 4.24 mm d^{-1} (Kashyap and Panda, 2001). Under a hot and dry climate in northeastern Portugal, peak ET_c rates reached 12-13 mm d^{-1} on the days immediately following irrigation, but crop water use declined logarithmically with time to about 3 mm d^{-1} within 5 days (Ferreira and Carr, 2002).

Wright (1982) developed improved crop coefficients for various irrigated crops in the Pacific Northwest, including potato, using alfalfa to measure reference evapotranspiration (ET_o) and weighing lysimeters at an experimental field near Kimberly, Idaho. Growth-stage specific crop coefficients (K_c) and the water balance method provided a valuable tool in scheduling overhead irrigation of Russet Burbank potatoes in the Columbia Basin of Oregon (Hane and Pumphrey, 1984). Simonne et al. (2002) reported that K_c values ranged from 0.3 at emergence to 0.8 during maximum leaf area, and declined as the crop matured. ET_c is usually calculated by the product of K_c and ET_o, or as a function of a number of climatic elements to provide the atmospheric potential demand.

Apart from the crop coefficient approach, potato evapotranspiration can also be estimated by means of multiple regression equations that take into consideration the leaf area index (LAI) of potato crop and atmospheric evaporative demand depicted by ET_o or pan evaporation (Pereira et al., 1995b).

Potato can be sensitive to irrigation less than ET_c that result in soil water deficits. A study in three successive years on silt loam soil in eastern Oregon investigated the effect of water deficit on yield and quality of four potato cultivars grown under four season-long sprinkler irrigation treatments (Shock et al., 1998b). The results suggest that irrigation water applied at rates less than ET_c in the Treasure Valley of Oregon would not be a viable management tool to economize water, because the small financial benefit would not offset the high risk of reduced tuber yield and profit from the reduced water application.

Potato cultivars may respond differently not only to deficit irrigation but also to total seasonal crop evapotranspiration under non-limiting soil water supply. Wolfe et al. (1983) reported that total seasonal actual crop water use at Davis, California, on a deep Yolo loam soil ranged from 316 to 610 mm for the ‘Kennebec’ cultivar and from 331 to 630 mm for ‘White Rose’, as a function of six levels of irrigation water supply established throughout the growing season. Shock et al. (2003a), comparing the performance of two new potato cultivars (‘Umatilla Russet’ and ‘Russet Legend’) with four other cultivars grown in the Treasure Valley of Oregon (‘Russet Burbank’, ‘Shephody’, ‘Frontier Russet’, and ‘Ranger Russet’), observed that Umatilla Russet showed a higher yield potential at ideal water application rates, while Russet Legend was the only cultivar tolerant to deficit irrigation treatments.

ET_c is an essential agrometerological index, which can be used to determine both the amount of water to be applied and the irrigation frequency for a particular crop and site. Stockle and Hiller (1994) compared a canopy temperature-based method, the neutron probe method, and the computer-assisted method based on evapotranspiration and K_c values to schedule irrigation for potato in central Washington State. A soil water depletion of 70% was allowed before starting irrigation. They concluded that the most practical method was the computer-assisted method using estimates of ET_o and K_c values.

Soil Moisture Requirements and Irrigation Management

Soil moisture status is expressed by percent available soil water (ASW) content or by soil water tension (SWT). Available soil water content is defined as being the amount of water that plants can extract from a given volume of soil, from the crop effective rooting zone. Available soil water is usually expressed as a percent between “field capacity” (100%) and “permanent wilting point” (0%). Soil water tension is the force necessary for roots to extract water from the soil.

Curwen (1993) reviewed water management for potato and placed great emphasis on using the irrigation criterion of 65% ASW. At “field capacity” (100% ASW), the SWT is often between 20 and 33 kPa depending on soil type and the method of determination. Soil water is assumed to no longer be available at the “permanent wilting point”, generally assumed to be at a SWT of 1,500 kPa.

The ASW approach works well for irrigation scheduling in regions with extensive areas of homogeneous soil. It is often a practical impossibility for growers to know when the soil is at 65% ASW, even if they have soil water content sensors available. Usually the percent water content that a given field contains at “field capacity” is unknown for a given part of a specific field. Similarly the percent water content at the “permanent wilting point” for a given part of a specific field is also usually unknown. Both the “field capacity” and the “permanent wilting point” vary tremendously with soil type, vary from spot to spot within a field, vary with cultivation, and vary over time. With neither "field capacity" nor "permanent wilting point" known, 65% ASW cannot be known; the prescription of an irrigation criterion of 65% ASW can become much like telling a grower to irrigate at the "right moment" and leaving the decision to intuition and experience.

Growers need direct and unambiguous irrigation recommendations to deal with crops that have negative responses to small variations in irrigation management. In contrast to the ASW, SWT can be measured directly using tensiometers or granular matrix sensors (Shock, 2003). The SWT irrigation criterion needed to optimize potato yield and quality can be determined by production region and generalized soil type.

Measurements of SWT that optimize potato yield and grade have been determined for a number of locations, some of which are wetter than 65% ASW. Based on potato yield and grade responses to irrigation, ideal potato SWT irrigation criteria were found to be 50 kPa using furrow irrigation on loam in California (Timm and Flockner, 1966), 50 to 60 kPa using sprinklers on silt loam in Oregon (Eldredge et al., 1992, 1996), 25 kPa using sprinklers on silt loam in Maine (Epstein and Grant, 1973), 60 kPa and 30 kPa using furrow and drip irrigation, respectively, for silt loam in Oregon (Shock et al., 1993, 2002), and 20 kPa using sprinklers on sandy loam in Western Australia (Hegney and Hoffman, 1997).

Irrigation Scheduling

Irrigation of crops sensitive to water stress requires a systematic approach to irrigation scheduling. Information to answer irrigation scheduling questions may include atmospherically based, plant-based, or soil-based data (Heerman et al., 1990; Shae et al., 1999). Examples of atmospheric irrigation scheduling information include weather forecasts, estimates of crop evapotranspiration (ET_c) such as those provided by AgriMet (U.S. Bureau of Reclamation, Pacific Northwest agricultural meteorological stations), pan evaporation, and atmometers. AgriMet is an automated weather station network operating throughout the Pacific Northwest of the USA that uses site-specific climatic data, the current stage of growth of local crops, and models to estimate daily crop water use (Pereira and Shock, 2006). Access to daily weather data, crop water use charts, and related information is available at http://www.usbr.gov/pn/agrimet.

Plant data may include canopy temperature, xylem water potential, and visible wilting. Soil-based data may include soil water content and soil water tension (SWT). In practice, plant, soil, and atmospheric data are often used concurrently, especially when changes in irrigation schedules are required to adjust for changes in crop water use.

Growers should pay attention to crop appearance, soil water tension, the rate of crop evapotranspiration, precipitation, and the amount of water applied. With knowledge of these factors, irrigation can be well managed in order to obtain high yields of better quality tubers along with environmental protection (Pereira and Shock, 2006).

III Other background information on the crop (yield, quality)

Response to Irrigation Management

Potato tuber response to soil moisture conditions begins before tuber set. MacKerron and Jefferies (1986) have shown that increased duration of water stress before tuber initiation reduces tuber set per stem. Shock et al. (1992) demonstrated that reduced tuber set in the Treasure Valley was related to the duration of SWT drier than 60 kPa before and during the beginning of tuber set. Where *Verticillium* wilt is present, there are advantages to keeping soils a little dry early in the season before tuber initiation (Cappaert et al., 1994; Shock et al., 1992).

Jones and Johnson (1958) described the reduction in potato yield caused by water stress. Through the use of a line source sprinkler system, Hang and Miller (1986) showed how a moisture gradient affects plant top growth, tuber yield, and tuber grade. With sprinkler irrigation, water application had to remain near potential ET_c for maximum tuber yield and grade.

Potato varieties differ in their response to water stress (Shock et al., 2003a). Kleinkopf (1979) found that Russet Burbank was more sensitive than the ‘Butte’ variety in forming misshapen tubers under water stress.

Assuring Tuber Grade

Fluctuations in water that stress the potato plant during tuber development can result in greater proportions of misshapen tubers of lower market grade. Corey and Myers (1955) determined that the proportion of misshapen tubers was directly related to drier SWT. Eldredge et al. (1992) found that a single transient SWT stress drier than 50 kPa increased misshapen Russet Burbank tubers. Pereira and Villa Nova (2002) studied the effect of three irrigation treatments on tuber yield and grade at Botucatu, São Paulo, Brazil. Potatoes irrigated to fully replace ET_c had higher yields and better grade and fewer physiological defects.

Assuring Internal Tuber Quality

Tuber physiological disorders such as brown center, hollow heart, and translucent end, as well as secondary growth, growth cracks, bruise susceptibility, and heat necrosis have been associated with water stress and/or wide variations in soil moisture content (Eldredge et al., 1992, 1996; Hooker, 1981; Hiller, et al., 1985; MacKerron and Jefferies, 1985; Rex and Mazza, 1989; Shock et al., 1993).

The sugar-end disorder is also known as dark ends, translucent ends, or in more severe incidences when stem-end tissue breakdown occurs, jelly ends. Jelly ends can occur in the field or during storage. These physiological disorders are often considered a minor production problem. However, when above normal temperatures occur during the growing season, significant economic losses can result from excess reducing sugars (glucose and fructose) in the stem end of tubers. These reducing sugars react with free amino acids during frying to form brown or black colors. For processors dark-ends result in reduced processing efficiency and economics and in some cases, an unusable product (Valenti, 2002).

When dark ends, as measured at harvest, exceed contract specifications, grower returns are reduced by contract penalty clauses. Research has shown that the incidence of sugar ends in tubers was reduced substantially when irrigation scheduling was based on SWT measurements (Eldredge et al. 1996: Shock et al., 1993). Dark-ends may become more severe after tubers have been stored (Eldredge et al., 1996). The timing of water stress is important; water stress before tuber initiation has no deleterious effect on tuber quality (Shock et al., 1992), while stress later during tuber bulking can cause dark stem-end fry color and reduced specific gravity (Eldredge et al., 1992, 1996; Shock et al., 1993).

Penman (1929) was one of the first authors to discuss the importance of translucent-end potatoes. Numerous authors have suggested that translucent-end potatoes are caused by early season moisture stress (Murphy, 1936; Nielson and Sparks, 1953; Kunkel, 1957; Kunkel and Gardner, 1958; and Lugt, 1960). Iritani and Weller (1973a, 1973b) and Iritani et al. (1973) produced translucent-end potatoes by subjecting plants grown in Washington to two weeks of moisture stress in late June.

Sugar-end tubers result in French fry “dark-ends” and are related to tubers with translucent-ends and jelly-ends. Owings et al. (1978) reproduced the results of Iritani and Weller (1973a) demonstrating that late June water stress could cause sugar ends. Shock et al. (1992) subjected potatoes to water stress in May and the beginning of June and found very early season stress did not result in sugar-ends. But short duration water stress any time during tuber bulking accompanied by heat stress resulted in sugar ends (Shock et al., 1993).

Increases in reducing sugars occurred more than two weeks after the end of transient water stress (Shock et al., 1993; Eldredge et al., 1996), which suggests that water stress causes enzymatic or membrane changes that eventually result in the loss of cellular control of sugar metabolism and the onset of sugar-ends and translucent ends. Sowokinos et al. (2000) demonstrated the importance of specific tuber starch and sugar enzymes in the development of sugar-ends.

Paradoxically, season-long uniform stress does not have the same negative effect on potato tubers. Painter et al. (1975) observed no fry color differences between potato irrigated at 25 ASW season-long and those irrigated at 65 ASW, which proved to be consistent with later findings where potato was stressed all season (Shock et al., 1998b, 2003). Kleinkopf (1979), Iritani and Weller (1977), Shock et al. (1993) and others have demonstrated that reducing sugar concentrations vary among varieties.

Kincaid et al. (1993) reviewed the role of temperature on tuber development and demonstrated that sugar ends are increased by increases in soil temperature. The relative roles of water stress and temperature stress on potato defects are poorly defined. Water stress is often associated with increased canopy temperature and soil heating in the field. In most field trials where water stress has been imposed and measured, canopy and soil temperatures have not been measured.

IV Other management aspects of the crop (irrigation and microclimate interaction with potato diseases and pests)

Irrigation management practices can affect disease severity. The increased humidity from irrigation will have greater effects where the macroclimate is humid or sub-humid and be of less importance where it is drier. For potato grown in hot areas, sprinkler irrigation can cool the environment, with possible reductions in physiological defects. However, different irrigation methods can contribute to the occurrence of diseases and pests on the crop depending on site-specific weather pattern.

Wet soil is conducive to most tuber-rotting pathogens. Excessive soil moisture following planting can promote seed piece decay and erratic plant. Excess soil moisture also encourages the incidence of blights, rots, and wilts, particularly prolonged excess soil water conditions.

Avoiding over-irrigation, or even keeping soils a little dry early in the season before tuber initiation may reduce the amount of root infection by *V. dahliae,* a major component in early die. On the other hand, avoiding excessive plant water stress during the tuber bulking growth stage, which usually coincides with the warmest part of the season, may help decrease the severity of early die (Cappaert et al., 1994).

Potato vines that remain wet for long periods create a microenvironment conducive to early blight (*Alternaria solani*), late blight (*Phytophthora infestans*), white mold (*Sclerotinia sclerotiorum*), and blackleg (*Rhizoctonia solani*) (Curwen, 1993). The timing of these diseases and associated crop losses vary regionally with yearly weather patterns, and can be affected by irrigation methods, which increase or decrease the duration of high humidity in the crop canopy.

Consistently rainy summer or fall weather promotes late blight. However, in the 1990's, epidemics of late blight developed in potato crops in arid production areas of the Pacific Northwest where late blight had not been a problem (Stevenson, 1993). Irrigation that tends to keep the foliage wet may contribute to this developing risk. Potatoes cultivated under center pivot irrigation can receive a relatively low volume of irrigation water for a long time near the pivot, favoring late blight occurrence. Johnson et al. (2003) showed that the incidence of late blight tuber rot significantly increased as the amount of irrigation water applied increased, and was significantly greater within 30 m of the pivot than at greater distances. Long duration sprinkler irrigation also favored late blight in Oregon and California (Shock et al. 2003b). Cohen et al. (2000) showed that under overhead sprinkler irrigation the proportion of potato leaflets containing late blight oospores and the number of oospores per leaflet were dependent on the soil water regime (rain plus sprinkler irrigation).

Long periods of leaf wetness or high relative humidity within the potato canopy favor infection by white mold (Powelson et al., 1993). Avoiding light, frequent irrigation of coarse-textured soils, and avoiding heavy, less frequent irrigation of fine-textured soils can diminish the risk of white mold.

Simons and Gilligan (1997) found irrigation to increase the incidence of stem canker, stolen canker, and black scurf to a limited extent although the effect of season tended to be more pronounced on these defects than any of the agronomic treatments tested.

While avoiding developing high humidity in the canopy, adequate soil moisture is essential not only for potato yield and quality but also for pest management strategies. Adequate soil moisture helps reduce the attack of cutworms (*Spodoptera litura*) and mites (*Tetranychus* spp and *Tenuipalpidaee* spp). Potato tubermoth (*Phthorimaea operculella*) and its larvae are repelled by soil moisture. Soil moisture also reduces formation of cracks in the soil, which allow the entry of potato tubermoth and its larvae (Grewal and Jaiswal, 1990). Irrigation scheduling based on ET_c and/or SWT can account for the local climate and keep the soil from becoming too dry.

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