A MODEL OF CORN RESPONSE TO AVAILABLE MOISTURE AND AN ECONOMIC MODEL TO SCHEDULE IRRIGATIONS

by

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CHAPTER I

INTRODUCTION

Because of increased interest in the scheduling of irrigations, which has been largely due to the dwindling supplies of irrigation water and the increasing costs of pumping it, there have been numerous attempts to develop irrigation scheduling models. The degree of usefulness of those models vary widely, but generally they can be found to be lacking either in economic considerations or in their representation of the biological and physical processes involved in plant-water relationships.

Since there was a need for a model that would integrate the economic, biological, and physical aspects of irrigation scheduling in a realistic fashion, two models were developed and are presented here.

The first model, a crop response model, was developed to simulate corn grain yield response to soil moisture availability. It integrated the biological and physical aspects of irrigation scheduling. In developing that model pertinent literature was reviewed regarding corn growth both in relation to water availability and crop modeling. Data were collected and several agronomic functions were estimated. Those functions included two growth functions and a plant-soil moisture stress function. The model was then simulated using the test data.

The second model was an economic irrigation scheduling model. It combined the biological and physical relationships in the crop response model with economic aspects of irrigation scheduling. The economic criterion used was to maximize total revenue net of irrigation costs. The crop response model was combined with a water balance equation and the criterion function to make the model. Those components were cast into a dynamic programming framework which resulted in a multiperiod decision model. That model was then solved for two different levels of irrigation costs.

CHAPTER II

CORN DEVELOPMENT AND ITS RESPONSE TO SOIL MOISTURE STRESS

Growth and Development of the Corn Plant

The construction of the corn crop response model involved an understanding of the growth and development of the corn plant in relation to the whole range of water availabilities. The following subsections contain a brief review of the present understanding of corn growth as it relates to grain yield and water availability.

Two Phases of Corn Growth

The corn plant's "development can be divided into two phases, vegetative and ear development [43]." The corn plant can be divided into those two phases because most of the earlier growth occurs in the vegetative parts while most of the later growth takes place in the ear parts. For example, the leaves and tassel are fully developed two to three days before silking and the stalk has ceased to elongate by silking; therefore just prior to silking vegetative growth has practically ceased. Thereafter, most accumulations of dry matter in the vegetative parts will be in the form of labile carbohydrates which will later be translocated to the grain. In addition to vegetative growth ceasing just prior to silking, the ear development phase begins. The ear development phase commenses with the silks elongating, the cob growing and the ovules enlarging. From that point on, most of the dry matter accumulation in the plant occurs in the ear. The interval during which vegetative growth ceases and ear development commences is between tasseling and silking.

Vegetative Growth Phase

The vegetative growth phase begins with plant emergence and ends a few days after tasseling but a few days prior to silking at about stage 4.5.[1] During that time the plant produces practically all of its leaves, leaf sheaths, stalk, tassel, husks and ear shanks. The length of that period is variable [22] and dependent on fertility [22], temperature [43], [13], and available moisture [43].

From emergence (stage 0) to 35 days after emergence, DAE, (stage 2.5) most of the growth is in the leaves and leaf sheaths. During that period the leaf growth results in a growing number of leaves being exposed to sunlight, causing the rate of photosynthesis to increase. Therefore, during the first 35 DAE dry matter accumulates at an increasing rate.

The first two weeks after emergence are important because by the end of the first week (stage 0.5) the plant is feeding itself by photosynthesis and by the end of the second week (stage 1) the tassel has been initiated. Kiesselback [30] found that initiation of leaf primordia ceases with the initiation of the tassel. Hanway [22] also has observed that all the leaves and ear shoots are initiated by stage 1. "Thus, the number of leaves that will develop on the corn plant has been determined by this time (stage 1)." Therefore, environmental conditions need to be favorable for sufficient number of leaf initials and

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[1] The use of stages in this paper refer to Hanway's stages as reported in [22] and [23].

tassel initiation. The number of leaves initiated at that time is the first step in determining the plant's photosynthetic capacity.

During the third week the stalk elongates and by stage 1.5 (21 DAE) the growing point is at or above the soil surface. By the end of the fourth week (stage 2) the stalk has started rapid elongation. The stalk will continue to elongate until tasseling. Conditions favorable enough to allow sufficient development in the stalk are needed during that time. The diameter of the stalk will largely determine its strength, so as to avoid lodging, and its volumnmetric capacity for labile carbohydrates [13], which will later be stored and then transferred to the grain.

At stage 2 (28 DAE) the plant is in the middle of rapid leaf formation and by stage 3 (42 DAE) leaf enlargement is complete and maximum leaf area is attained.

One can not expect to increase the size of the leaves after that time. At stage 3 only about half of the leaves are fully exposed to sunlight and therefore only half are functional at that time. After stage 3 the leaves will continue to emerge from the whorl and become functional. As the leaves emerge from the whorl they develop green color and continue to increase in weight. Although by stage 3 a potential leaf area is determined, functional leaf area continues to develop. Claassen and Shaw [9] found that severe soil moisture stress can significantly affect the leaf area at stages 2, 2.5, and 3.

"By stage 3, enough leaves are exposed to sunlight so the dry matter accumulation is rapid [23]." That rapid rate continues nearly constant until near maturity [23], [22], [14]. Claassen and Shaw [9] reported reductions in total dry matter production as high as 17 per cent at stage 2.5 and 15 per cent at stage 3 for short severe periods of stress. Those same stages are also important to the development of the tassel and ear. At stage 2 the tassel begins to develop rapidly and by stage 2.5 it is developing rapidly. That rapid development continues through stage 3. At stage 3.5 the tassel is nearly full size. Severe stress st stages 2.5 or 3 "appear to have the most effect on tassel emergence [9]." Silking was found to be delayed from 2 to 5 days by a severe stress at 2.5, 3 or 3.5 [9].

The ear shoots are developing at stage 2.5. The ear shoots first develop the ear shank and husks. After all the husk initials are formed, the growing point of the ear shoot elongates to form the beginning of the ear [13]. At stage 3 the uppermost ears were beginning rapid development and "the potential number of ovules on the top (major) ear is determined at that time [23]." That rapid development continues at stage 3.5 when "the number of ovules which develop silks and thus the number of kernels is being determined [23]."

Claassen and Shaw [9] found that the first stress period for the cob coincided with stages 2.5 and 3. They also reported that water deficits had an adverse effect on husk weight at stages 2.5, 3, and 3.5. During that same period, stages 2.5 and 3, "the earliest significant stress effects on yield" were reported by those researchers [10]. They reported as much as a 12 to 15 per cent reduction in yields due to a short period of severe stress at either of those stages. They noted severe stress at stage 2.5 and 3 reduced the percentage of developed kernels. Stress at stage 2.5 affected the middle and lower sections of the ear while stress at stage 3 affected the top section of the ear. Hanway [23] notes that a moisture deficiency at stage 3.5 "may seriously reduce the number of kernels that develop."

At stage 3, the stalk is in the middle of the period of rapid growth and elongation which continues into stage 3.5 and 4. The stalk grows by elongation at each successively higher internode until the last internode below the tassel has been fully elongated. Claassen and Shaw [9] observed "that short stress periods had their greatest effect on stalk height late in the vegetative period, i.e. during elongation of the tassel and (or) upper internodes of the stalk." They found that stress reduced the height by as much as 6.4 cm at stage 3.5 and 15.2 cm at stage 4 [9].

The tassel emerges from the leaf whorl at stage 4 (56 DAE) and is almost fully developed [23], [13]. From tassel emergence to its full development and shedding of pollen, it will take approximately ten days at which time vegetative growth is completed [13]. During that time the silks are developing, starting at the base of the top ear at stage 3.5 and at tassel emergence they are elongating rapidly from the base of the ear. Hanway observed that moisture stress at that time "will delay silking more than tassel emergence and pollen shedding [23]."

Also at tassel emergence the ear shoot begins to develop rapidly. The husks and the ear within the husks are the parts that are developing at that point. The husks are visible at the uppermost ear and the ear is about one inch long. Both are beginning rapid growth at that time.

With tassel emergence complete the plant's vegetative growth has practically ceased. Except for the accumulation of labile carbohydrates that will later be translocated to the grain, dry matter accumulation in the leaves, leaf sheathes and stalk has ceased. The plant is ready for grain production which will be discussed in terms of ear development.

Ear Development Phase

The ear development phase begins approximately halfway between tasseling and silking (about 61 DAE or about stage 4.5) and ends at physiological maturity (stage 10). Researchers disagree as to whether the length of that phase is relatively constant or varies. Some researchers [22], [12], [44] have observed relatively constant periods from silking to maturity under different environmental conditions and different planting rates. Yet, Hanway and Russell [24] and Duncan [13] report the length of the ear development phase varying as much as 17 days, and the former reported that the length of that phase had marked effect on yields. Hanway and Russell, and Duncan found that the type of hybrid, different planting dates, and different geographical location affect the length of the ear development phase.

At the beginning of the ear development phase, vegetative growth has practically ceased. The tassel is almost fully emerged and the silks are elongating rapidly and will soon emerge. Also the stalk and leaf sheaths are beginning to accumulate labile carbohydrates that will later be transported to the grain [13], [23]. The accumulation of labile carbohydrates usually occurs after vegetative growth and before the rapid near linear rate of dry matter accumulation in the grain. That period is approximately 17 days long and ends by stage 6. Under normal conditions approximately 20 per cent to 50 per cent of the dry matter in the grain will come from accumulations elsewhere in the plant [13], [8].

By stage 5 (66 DAE) most of the plants are silking and pollen is shedding. An individual plant will shed pollen for about a week [13] while the silks will continue to elongate until they are fertilized [23]. The silks are receptive from 10 days to two weeks or more [13], but most of the pollination occurs in a short period of time. "Extreme heat or drought may damage a high percentage of tassels or environmental stresses may delay silking until after all pollen is shed in some cases, particularly in single cross hybrids or inbreds with high uniformity [13]."

From stage 4.5 through 5 is the most critical period of corn plant development in terms of grain yield. At that time the number of ovules that will be fertilized is determined. Moisture stress at that time may result in poor pollination and seed set. Claassen and Shaw [10] observed a 53 per cent grain yield reduction and significant reductions in kernel numbers from moisture stress at that time. They reported significant reductions in kernel weights from stress during or after silking. These same authors report that others have observed grain yield reduction from 40 per cent to 73 per cent as a result of 4 to 8 days of wilt at silking. Wormley [49] reports research done at Davis, California, where "yields dropped 43 per cent to 88 per cent as the result of water deficits during tasseling and silking. Claassen and Shaw [10] reported a yield reduction of 29 per cent due to a short severe moisture stress when silking was almost completed (97 per cent silking).

The cob is also developing rapidly through that period. During late silking the cob is sensitive to stress [9] and by stage 6 the cob is fully developed.

At stage 6 (78 DAE) the kernels are in the blister stage. They have enlarged considerably but contain very little dry matter. Stage 6 is the beginning of the period of rapid, nearly constant rate of dry matter accumulation in the kernel, which will continue until near maturity, stage 9. Starting with stage 6, almost all the dry matter accumulation is in the grain.

Moisture stress at stage 6 may cause significant reductions in grain yield. Claassen and Shaw [10] observed reduced yields of approximately 30 per cent as a result of a short severe moisture stress at about that time. They also reported that other researchers had found yield reductions of 48 per cent and 22 per cent in single-eared and two-eared varieties for a 4 to 5 day stress during the blister stage.

Moisture stress at stage 6 has several effects that may result in reduced grain yields. The first is that during moisture stress the rate of photosynthesis will be lowered which decreases the rate of dry matter accumulation in the grain. Also moisture stress at that stage and later stages may result in firing or hastened senescence of the lower leaves [9] which may reduce the rate of photosynthesis in later stages. Moisture stress at that time may also reduce translocation of labile carbohydrates to the grain from other plant parts.

Hanway [22], [23] reports the loss of nitrogen and phosphorus from other plant parts to the developing grain begins at stage 6 and continues until physiological maturity. The translocation of labile carbohydrates probably begins at the same time. Therefore "factors that limit translocation (during that period) will also limit grain yield [8]." Boyer found that translocation was less sensitive to water stress than photosynthesis. He reported that dry matter continued to accumulate in the grain from other plant parts when leaf photosynthesis had virtually ceased.

Through both stages 7 (90 DAE) and 8 (102 DAE) dry matter accumulation in the grain is rapid. "Unfavorable conditions (at either stage) will result in unfilled kernels and 'chaffy' ears [23]." At stage 7 the kernels are in the dough stage. Moisture stress at that stage resulted in approximately 30 per cent reduction in yield in tests conducted by Claassen and Shaw [10].

Denting begins with a few kernels at stage 8. By stage 9 (114 DAE) all kernels are fully dented. This "denting is associated with drying of the ear. . .[44]."

At stage 9 the corn plant has almost reached maturity. The embryo in the kernels is morphologically mature. The rate of dry matter accumulation has begun to decline and there will be relatively little increase in grain weight after stage 9.

Physiological maturity occurs at stage 10 (126 DAE). Physiological maturity is understood as *ceasation of dry matter* accumulation [22], [23], [44], [13]; therefore growth is completed. The grain will no longer increase in dry weight, but it will continue to lose moisture. Senescence of the husks and leaves has begun.

Wormley [49] reports that California researchers could not improve yields significantly with irrigations after the blister stage. He also reported that sometimes irrigations after the blister stage (stage 6) actually cut yields. Claasses and Shaw [10] stressed the corn plant after the dough stage (stage 7) in only one year. Their stress treatments after stage 7 either increased the yield over the control (when stressed at stage 8) or had no effect (when stressed at stage 9). Those limited data indicate that sometime after stage 7 water deficits have little or no adverse effect on grain yields and may actually increase yields.

Plant-Soil Moisture Stress

Soil moisture stress takes place when the plant can not withdraw enough water from the soil to meet the demands placed on it by the atmosphere.

The plant obtains its water needs from thin films and wedges that surround the soil particles. It is by these films and wedges that the soil holds water against gravitational forces. In other words, the soil attracts water with a potential energy known as soil-water potential.[2] The maximum amount of water a soil will hold against gravitational forces after it has been saturated is known as field capacity. The soil-water potential at field capacity is about -1/5 to -1/3 bar [29].

The plant can withdraw water from the soil until the soil-water potential reaches approximately -15 bars [29]. When the soil-water potential reaches this level the plant can no longer meet its evaporative needs and looses turgor, or wilts. The soil moisture content at which the plant undergoes complete wilting is known as the permanent wilting point.

The amount of water held in the soil between permanent wilting point and field capacity is the amount of water available for plant uptake, and is called available soil moisture. The amount of available soil moisture present expressed as a percentage of the total possible amount for a particular soil is known as available soil moisture percentage.

The atmosphere places demands on the plant for water described as the evaporative potential of the atmosphere. Some of the factors affecting evaporative potential are solar radiation, temperature, humidity, and wind speed.

The plant meets those demands through transpiration. The plant withdraws water from the soil through the roots. The water travels up the stem and is transpired mostly from the leaves. As the water is withdrawn from the soil, the soil holds the remaining water more tightly, thus

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[2] Soil-water potential has a negative value because its direction is opposite that of the plant. A unit of soil-water potential is commonly called the bar and is equal to 1,000,000 ergs per gram of water [29].

the plant must work harder to extract remaining water and the soil-water potential decreases.

When the soil-water potential obtains approximately -5 bars (available soil moisture percentage is about 35) the leaf-water potential may be approximately -15 to -20 bars. At this point, the plant loses turgor and begins to close its stomata which reduces transpiration. The closing stomata also reduces photosynthesis, thereby reducing the rate of dry matter accumulation and the growth rate. Reduction in the growth rate might seriously affect grain yield depending on its severity and its timing.

CHAPTER III

THE CROP RESPONSE MODEL

The crop response model was developed to simulate corn grain yield response to soil moisture availability throughout the corn plant's development. The model integrated the biological and physical relationships discussed in the previous chapter. To represent the growth and development of the corn plant a growth function was used, which also represented the plant's response to water as the plant developed. To represent the plant's response to various levels of available soil moisture a plant-soil moisture stress function was used.

The crop response model was represented by

$$X_d = [\Gamma(d)]^{\sigma_d} X_{d-1} \qquad d = 1,2,3,\ldots,D'' \qquad (1)$$

where X_d was the state of corn development in period d, X_{d-1} was the state of corn development in the previous period (d-1), $\Gamma(d)$ was the appropriate relative growth rate, σ_d was the plant-soil moisture stress function, and D" was maturity.

The model was represented by recursive equation because plant growth in any period is a function of accumulated growth in the previous period and the relative growth rate.

The plant-soil moisture stress function was assumed to affect only the relative growth rate (potential for growth in this period) and not previous growth. It was a non-decreasing function being equal to zero at permanent wilting point and one at field capacity. Therefore when the soil was at field capacity there was full growth and when the soil was at permanent wilting point there was no growth.

The final result of the crop response model was a yield index. It indicated the percentage of optimum yield calculated by the model given the soil moisture conditions during the growing season.

Estimation of the Growth Function

The crop response model consisted of two phases that corresponded with the two phases of corn growth. In the development of the model I was particularly interested in the direct effect of water availability on grain yield. I was interested in the effect of water on plant growth only to the extent that it affected grain yield. The latter situation existed in the vegetative growth phase, since it was during that phase that the plant developed its "factory" from which it would produce the grain. During the vegetative period I was primarily interested in those aspects of vegetative growth that affected grain yield. A more direct relationship exists between water availability and grain yield during ear development because nearly all of the dry matter produced then accumulates in the grain and other ear parts. Therefore the crop response model consisted of two phases -- vegetative growth and ear development.

Vegetative Growth

Vegetative growth is a complicated process. It involves the development of a number of different plant parts. Growth of most of those plant parts is initiated at different times. While several may be developing at the same time, they are usually at different stages of development and are developing at different rates. In addition, Claassen and Shaw's [9] observation that "the effects of moisture stress on final-dry-matter yield of each vegetative component was closely related to the coincidence of water deficit with initial and (or) rapid growth phase of the respective period" makes it difficult to estimate the corn plant's response to water deficits during vegetative growth, especially in relation to grain yield.

Fortunately, grain yield is greatly affected by and highly correlated with two measures of vegetative growth -- leaf area and stalk size. Both components provide much of the photosynthetic capacity of the plant. A number of researchers including Eik and Hanway [15], Hanway [18], and Duncan [13] have noted significant relationship between leaf area and grain yield. The size of the stalk is also thought to affect grain yield. Stalk size determines the amount of labile carbohydrates that can be stored in the stalk for later transport to the grain [13].

The development of leaf area and stalk size, as well as the development of the tassel and ear shoots during vegetative growth has led to the conclusion that "grain yield potential at anthesis (pollination) is a function of the previous growth of the plant [13]." To represent previous (vegetative) growth, a vegetative growth function was estimated using a dry matter accumulation curve reported by Hanway [23] (Figure 1).

The portion of the dry matter accumulation curve in Figure 1 from emergence to 60 DAE (just prior to silking) was used in estimating the growth function for the vegetative phase. It was estimated using least squares regression and an exponential equation. The exponential equation used was

$$G_t = e^{\gamma+\delta t} \qquad t = 1,2,3,\ldots,T \qquad (2a)$$

where G_t was dry matter accumulation at day t, t corresponded with the days in Hanway's data, T was the last day of vegetative growth which was 60, and γ and δ were unknown constants to be estimated. By taking a log transformation of (2a), I was able to estimate γ and δ using least squares regression. The least squares estimate for γ and δ was -1.7 and 0.094, respectively, with an R^2 of .947. The growth curve obtained from the estimated function is shown with Hanway's curve in Figure 2.

The vegetative growth function expressed in (2a) is only applicable when the vegetative period is exactly 60 days long. To generalize this function for vegetative growth phases of various lengths, I substituted (T/D)d for t in equation (2a) where d is the day of the vegetative phase, D is the total number of days for a particular vegetative growth phase, and T is the total number of days for the vegetative phase in Hanway's data. This substitution implies that the same growth curve is applicable for all lengths of vegetative phases, only the time scale is changed. The more generalized expression of (2a) is

$$G_d = e^{\gamma+\delta(T/D)d} = e^{\gamma+\delta Td/D} \qquad d = 1,2,3,\ldots,D \qquad (2b)$$

where T = 60.

No attempt was made to model the factors that affect the length of the vegetative growth phase because little information is available on that aspect of corn growth.

Equation (2b) was expressed in recursive form because the recursive form more accurately describes the daily process stated earlier. The recursive form of (2b) is

$$G_d = e^{\gamma+\delta Td/D} = e^{\gamma T/D}\ e^{\gamma+\delta T(d-1)/D} = e^{\delta T/D}\ G_{d-1} \qquad (3)$$

where G_{d-1} is accumulated growth in the previous day and $e^{\delta T/D}$ is relative growth rate.

Equation (3) represents the vegetative growth function when water availability is sufficient so as not to limit growth.

Since it was assumed that soil moisture stress affected only the relative growth rate which in this case is $e^{\delta T/D}$, the relative importance of water to yield as the plant grows from emergence to just prior to silking as indicated by that model can be determined by analyzing $e^{\delta T/D}$.

Since $e^{\delta T/D}$ is constant for a particular vegetative growth phase, the same degree of soil moisture stress will have the same percentage effect on plant growth anywhere in the vegetative phase. In other words, all plants having the same levels of stress at different periods in the vegetative phase would have the same total growth. Presently with the available information, one can not assess the appropriateness of that simplification.

Physiologically the entire period is important. Throughout that time, the plant is initiating the development of different parts of the plant. For example, the leaves are continually developing, but different aspects of leaf development are initiating, rapidly growing and ceasing at different times. The first aspect of leaf development is leaf initialization which is completed by the end of the second week after emergence. Yet potential leaf area is not determined until the sixth week after emergence and the final dry weight of the leaves is not complete until the end of vegetative growth.

The understanding of grain yield response to conditions during the vegetative phase is not well integrated or very complete. Our present understanding is based on test plot experiments that have provided useful