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Simulation of Corn In-Field Drydown

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Scott Daniel Piggott

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Major Professor's Signature

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Simulation of Corn In-Field Drydown

By

Scott Daniel Piggott

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ABSTRACT

Simulation of Corn In-Field Drydown

By

Scott Daniel Piggott

Corn (Zea Mays L.) drying in the field is an important consideration for grain quality and for economic assessment of corn production. With an accurate model of in-field grain water loss, farmers can select a harvest date that minimizes yield loss and mechanical drying and maximizes grain quality and economic benefit. The purpose of this work was to develop a model of corn drydown with readily available weather inputs. The model structure evolved from reviewed literature and is of differential form. Model function is dependent on CERES-Maize, a process oriented corn growth and development model, for phenological timing. The model also incorporates simulation of grain-filling and vapor pressure. The resultant model was tested and calibrated using data collected from a 1999 experiment in Michigan as well data available from the literature. The 1999 Michigan experiment also reviewed the influence of in-field precipitation variability and plant population on corn drydown. The work eventuated in a robust corn drydown model that requires only daily maximum and minimum temperature and precipitation as weather inputs.

For my mothers and fathers (great, grand, God, Mom & Dad),
Without whom this work would lack place.

For my wife, Donna,
Without whom this work would lack passion.

For my children,
Without whom this work would lack purpose.

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LIST OF ABBREVIATIONS

$e^{o}T_{dew}$ =	Saturation vapor pressure at the dewpoint temperature.
$eT_{ambient}$ =	Actual Vapor pressure of the air.
DBT =	Dry Bulb Temperature
rh =	relative humidity (%)
T_{wet}=	Wet bulb Temperature
WBD =	Wet bulb depression
R1=	silking phase
R2=	blister phase
R3=	milk phase
R4=	dough phase
R5=	dent phase
R6=	physiological maturity
DTT_8=	Daily thermal time with an 8 degree C base temperature.
TTx =	Accumulated thermal time for x phase of development.
P1=	The accumulated thermal time from seedling emergence to the end of juvenile phase where x = 1.
P5=	The accumulated thermal time from silking to physiological maturity where x = 5.
WCWB =	water content wet basis
M =	water content at time t (% dry basis)
Me =	equilibrium moisture content (% dry basis)
k =	proportionality constant

Mo = initial water content (% dry basis)

t = time (days)

Td = daily average dewpoint temperature (K)

Tmin = minimum daily temperature (K)

Tmax = maximum daily temperature (K)

EF = $\ell_{EP/day}$ / ℓ_{PANN} = daily potential evapotranspiration (m) / annual precipitation (m)

$\ell_{EP/day}$ = $[(E_p/\rho_w)\ t_{day}]$ =daily potential evapotranspiration (m)

t_{day}= period when the sun is above the horizon (estimated from station lattitude)

ρ_w= density of water (kg/m^3)

E_p = potential

$k_{developmental}$ = proportionality constant for developmental water content loss phase = the rate of DTT_8 accumulations expressed as a percentage of the P5 coefficient.

$k_{post\text{-}maturity}$ = proportionality constant for developmental water content loss phase

P = precipitation (mm)

ω = wetting parameter (dimensionless)

t_G = time since the end of linear grain filling (days)

δ = drying constant (dimensionless)

INTRODUCTION

Knowledge of the rate at which corn (Zea Maize L.) dries in the field is significant to grain quality and farm profitability. An improved understanding of this process would empower farmers to assess risk regarding weather factors that may impede harvest timing and economic risk associated with an increased need for mechanical drying that may degrade grain quality.

The objective of this work was to develop a process-oriented model of pre-harvest corn kernel water content that is usable at the farm level utilizing a limited number of environmental inputs. For the duration of this work, the pre-harvest loss of water from corn kernels is referred to as drydown. In addition to drydown simulations, models of daily dewpoint temperature and grain-filling rate were employed or developed in support of the stated objective. The drydown model will use CERES-Maize (Jones and Kiniry, 1986), a process oriented corn growth and development model, for daily weather inputs and for estimation of plant phenology.

Chapter 1

LITERATURE REVIEW

The displacement of kernel water by dry matter in corn kernels is a biological process that has received attention from agronomists, plant physiologists, and engineers. Analysis of this process is dependent on research scope and has involved complex examination of geometric relationships of molecules, osmotic potentials, plant physiological development, and atmospheric interaction that facilitates heat and mass transfer. The focus of this research is functional plant-atmosphere relationships influencing changes in kernel water content.

Formulation of a drydown model for corn is dependent on knowledge of plant characteristics and weather variables that influence kernel-atmosphere water exchange. Ritchie and Hanway (1997) defined the stages of plant growth and development for corn. The stages are divided into vegetative and reproductive periods. Of these phasic stages, the timing and duration of the reproductive stages are important to the plant's drydown pattern. Knowledge of the plant's progression through reproductive stages as influenced by the weather is essential for the formulation of an accurate drydown model.

The reproductive stages of corn plant development as defined by Ritchie and Hanway (1997) include silking (R1), blister (R2), milk (R3), dough (R4), dent (R5), and physiological maturity (R6). Kernel water content assessment begins with silking and continues beyond physiological maturity. The focus of the R1 period is kernel structure development. This stage is highly susceptible to atmospheric stress, especially soil water deficit that desiccates the silks and pollen grains (Ritchie and Hanway, 1997). The R2, R3, and R4 stages are associated with grain filling, a time when the water content of the kernels is displaced by plant assimilates. The influence of weather factors on grain filling declines with kernel maturity. The R5 or dent stage signals a slowed movement of assimilates into the kernels. The R6 stage is physiological maturity. This phase marks the end of dry matter accumulation into the kernels, after which change in water content is the primary influence of kernel weight change.

The loss of kernel water initiates with kernel formation in the silking phase. Silking phase duration is approximately 2-3 days, the time necessary for all silks on a single ear to be exposed and pollinated (Ritchie and Hanway, 1997). Knowledge of fertilization initiation is critical to drydown modeling as it marks the beginning of a nearly constant decline in kernel water content.

The grain filling stages include blister (R2), milk (R3), dough (R4), and dent (R5). The time between silking and blister is considered a lag period of grain filling as kernel structure is the focus of kernel development and not dry matter accumulation. For this reason, the lag period leading to blister (R2) is segmented from the other grain filling stages with respect to calculation of dry matter accumulation. The time difference between silking and beginning of dry matter accumulation is approximately 24 - 28 days (Ritchie and Hanway, 1997). This time differential can also be expressed in thermal time (TT_8). TT_8 is the summation of daily thermal time (DTT_8) that is used to express the duration of phenological periods and is expressed in °C/day (Ritchie and Hanks, 1991). DTT_8 refers to the daily thermal time associated with a base temperature of 8 °C. This system of temperature/time expression is used in CERES-Maize to simulate all processes except photoperiodic induction. There is little variation in thermal time for the post-silking lag period of different corn genotypes (Cross, 1975). This period is approximated at 170 °C/day in CERES-Maize.

The R2 - R4 stages represent the "effective" grain-filling period. At R2 initiation, the kernel water content is 85% water content wet basis (WCWB). Water contents numerically expressed in this work will use a wet basis where model variables may be expressed using dry basis. Differences in water content calculation is due to integration of several research efforts, but all model outputs and associated measured values for water content will be expressed in wet basis. Water loss from the kernels during effective grain filling is termed as "developmental" change in kernel water content as water is being displaced by translocated assimilates (Brooking, 1985). The effective grain filling period has been the subject of extensive research efforts. These efforts concentrate on atmospheric influence over rate and duration of grain filling for various genotypes of corn. The primary conclusions have three common findings:

1. The rate of dry matter accumulation during the effective grain fill period is nearly linear.
2. The duration of the effective grain filling period is influenced by temperature.

3. The rate of dry matter accumulation is affected by plant development prior to the period.

Several studies have shown the linearity of dry matter accumulation with respect to time during the effective grain fill period (Sprague, 1936; Kiesselbach, 1950; Johnson, 1972; Cross, 1975; Badu-Apraku, 1983; Brooking, 1985; NeSmith, 1992; Overman, 1995;). This linear trend is a function of the plant's ability to translocate assimilates from the vegetative plant parts to the kernels. Due to this constant movement of materials into the kernels, developmental water loss from the kernels is dependent on the rate of dry matter accumulation. Research has found that the rate of grain fill has a direct, positive effect on drydown rate during the grain filling period (Kang et.al., 1986). This relationship is reinforced by the findings of a study that measured the influence of six (6) weather variables on drydown (i.e. the potential evaporation, wind speed, precipitation, solar radiation, relative humidity, thermal time). Of these factors, only thermal time showed a consistent association with kernel water loss during grain filling (Hallauer, 1960).

Several researchers have worked to associate grain fill rate and accumulated daily thermal time. Johnson and Tanner (1972) calculated the length of effective grain fill in terms of thermal time. CERES-Maize utilizes a genotype specific thermal time from silking to maturity. This value, termed as the P5 coefficient, includes the period of approximately 170 ^{o}C/day from silking to initiation of the effective grain fill time. The P5 phenotype coefficient minus the thermal time representing the lag phase is the thermal time required to achieve physiological maturity from the beginning of the effective grain filling period. The effective grain filling period ends when 95% of P5 has occurred (Kiniry, 1985). Research has demonstrated that under high temperature conditions, assimilates that remobilize from other plant parts account for a greater proportion of kernel weight gain than assimilates produced by photosynthesis during grain filling (Badu-Apraku, 1983). Extreme temperatures (high and low) and soil water content deficits prior to grain-filling decrease yield by truncating the duration of the effective grain-filling period (Badu-Apraku, 1983; NeSmith, 1992).

With continued focus on the effective grain filling period, researchers now better understand developmental water loss from kernels as a function of grain filling parameters and weather variables. Schmidt and Hallauer (1966) developed a model that utilizes a series of linear equations to represent drydown for several water content ranges. The equation used for the effective grain fill period is a function of daily average temperature. The authors claimed a 95% confidence interval for modeled values around measured infield drydown for "any field, any year". Other experiments utilized statistical regression to determine relationships between drydown per unit thermal time and measured values (Kang, 1986; Cavalieri, 1984; Dwyer et.al., 1994). The proposed models are limited in application as simulations are dependent on assumed relationships between physiological stages and water content.

Near the end of the effective grain filling period, assimilate transfer into the kernels slows. The stage is called dent, or the R5 phase. The duration of the R5 phase can be truncated by adverse weather conditions such as an early frost that can promote premature physiological maturity. This circumstance can cause a decrease in yield due to premature stoppage of assimilate flow into the kernels and can cause delays in harvest operations as frost-damaged corn is slow to dry (Ritchie and Hanway, 1997). Johnson and Tanner (1972) paired this phase of grain fill with physiological maturity and labeled it as the "leveling off of dry matter accumulation". In their research, this phase accounted for approximately 10% of the total dry matter accumulation. 5% of P5 is used to represent the duration of this phase in CERES-Maize (Kiniry, 1985).

The dent phase of corn kernel development terminates in physiological maturity, or the R6 phase. Near the end of dent, a region of cells several layers thick forms between the basal endosperm of the kernel and the vascular area of the pedicel. As maximum dry matter accumulation is approached, these cells compress into a dense layer that appears black to the naked eye (Daynard, 1969). The formation of this black, abscission layer represents the end of assimilate transfer into the kernels and maturity. Several efforts have been made to link black layer formation to a common kernel water content (Schmidt, 1966; Rench, 1971; Daynard, 1972; VanEe, 1979; Brooking, 1990; Ritchie and Hanway, 1997). However, these values range from 25% - 43% for a variety of genotypes and weather conditions. Due to this wide range of values, attempts to model drydown processes using fixed water content values to represent black layer formation can lead to inaccurate simulation. Schmidt and Hallauer's work made no mention of black layer, but found 30% to be a break-point in model input requirements with temperature dominating the model above 30% and wet bulb depression below. This approximation was later changed to 37% by Van Ee (1979) upon further analysis of the data. Rench (1971) stated that use of 30% is only a rough estimate of physiological maturity. Daynard (1972) calculated mean values of 33.7% and 33.9% for a black layer water content in 1969 and 1970, respectively. Based on the reviewed literature, attempts to link the formation of "black layer" with a fixed water content is an approximation at best.

The literature reviewed thus far concentrates on kernel development and the loss of "developmental water". A black abscission layer has stopped the flow of assimilates into the kernel and maximum dry matter has been attained. The kernel water content at this time is between 24 - 43%. The exchange of fluids is no longer between the plant and the kernel but between the kernel and the atmosphere. The following section will discuss research attempts to understand post-maturity drydown in maize.

Most corn growth and development models, such as CORNF (Stapper and Arkin, 1980) and CERES-Maize, end simulation of plant phenology with physiological maturity. One of the first works to model post-maturity drydown was the work performed by Schmidt and Hallauer in 1966. The equations and the associated water content boundary values are presented in Figure 1. Notice the only weather inputs used in the calculations are dry bulb temperature (DBT in degrees F) and wet bulb depression (WBD in degrees F).

Figure 1: **Schmidt and Hallauer equations and drydown boundary values.**

75% (Milky roasted ear)	
50% (Complete Dent)	R = -2.00 + 0.047*DBT
30% (Average Maturity)	R = -0.54 + 0.021*DBT
25% (Matured)	R = -0.08 + 0.119*WBD
20% (Drying)	R = -0.432 + 0.146*WBD

- DBT = Dry bulb temperature
- WBD = Wet bulb depression
- R = Kernel Water Content Reduction (%/day)

Van Ee (1979) changed the model to better statistically represent the Schmidt and Hallauer data. The resultant model was implemented into a corn production simulation called CORNSIM. Only the post-maturity drydown was changed as the equation representing developmental water loss remained as Schmidt & Hallauer hypothesized. The major changes to the model included changing the water content that represents the end of developmental water loss from 30 to 37% and the incorporation of equilibrium water content. While the change of break-point water content enhanced model output correlation with the data, the introduction of equilibrium water content is a major improvement of the model's ability to mimic the asymptotic behavior of corn infield drydown. Equilibrium water content is defined as the tendency of a stored farm product toward a water content value that is controlled by the ambient environment (Henderson, 1952). Equilibrium water content establishes a lower limit to which grain can dry (Thompson, 1969).

While the model fit the base data, the structure of the model limits robust application in several ways. First is the dependence of the model on use of fixed water content values. Secondly, the model does not take into account possible re-wetting of the kernels by precipitation. Third, the model input of wet bulb depression as a function of wet bulb temperature is not readily measured nor available. Fourth, the model does not differentiate plant genotype characteristics. Many research findings have emphasized that genotype specific traits such as phenologic timing, ear size, husk number, angle of ear, and husk and pericarp permeability influence the rate of drydown (Crane et.al, 1958; Purdy and Crane, 1967; Troyer and Ambrose, 1971; Cavalieri and Smith, 1985; Baron and Daynard, 1984).

A break from the use of discontinuous drydown models came when Bruns (1975) developed a post-maturity drydown equation using the following differential form.

$$M_{\iota} = M_{(\iota - t)} - (\Delta M_i / \Delta t) * t$$

- $(\Delta M_i/\Delta t)$ is change in water content (%/day) = f (evaporation rate, precipitation, occult precipitation, vapor resistance factor, wetting resistance factor, and number of days since physiological maturity)
- M is water content (%)
- ι is day number
- t is time interval in days

While this model's input parameters are less readily measured on farms, the differential structure of the model, lack of reliance on subsequent water content values for change in parameters, and use of a wetting parameter warrant further investigation. For the samples collected, Bruns observed a 90% confidence interval for the daily mean observed water content, with simulated/measured difference values ranging from 0.18% to 0.48% with an average of 0.34% and a sample standard deviation of 1.0%.

The drydown models reviewed herein provide a collection of attributes that contribute to a greater understanding of drydown processes. First, the preceding work provides an understanding that certain weather factors influence drydown. These variables include forms of temperature, vapor pressure, and wetting. A second beneficial characteristic of the reviewed models is the use of a differential equation structure as posed by Bruns. This model structure allows for a continuous simulation of processes based on daily weather variables. Third is the use of equilibrium water content in drydown analysis, as proposed by Van Ee (1979). Implementation of these characteristics is essential to accurate modeling of drydown.

The relative accuracy of Bruns post-maturity drydown model acts as a bridge to another segment of drydown research, that of mechanical grain drying simulation. Henderson and Perry (1955) reported that the declining water content of grain was inversely proportional to the water to be removed. This statement takes the following equation form:

$$dM/dt = -k(M - Me)$$

- M = water content at time t (% dry basis)
- Me = equilibrium water content (% dry basis)
- k = proportionality constant

The solution to this equation is as follows:

$$MR = \text{water content ratio} = (M - Me)/(Mo - Me) = e^{-kt}$$

- Mo = initial water content (% dry basis)

This model utilizes equilibrium water content. Henderson (1952) developed the following equation to calculate Me:

$$1 - rh = e^{(-c\ (t+460)\ Me^\wedge n)}$$

- rh = relative humidity
- $c = 1.1 * 10^{-5}$
- n = 1.90

Several models for equilibrium water content have been developed for corn (Strohman, 1967; Thompson et.al, 1968; Bakker-Arkema et.al.,1974). Two of the most adopted models are those formulated by Thompson (1969) and Bakker-Arkema (1974). Thompson's model is a revision of Henderson's (1952) model with the following changes:

$$1 - rh = e^{(-c\ (t+50)\ Me^\wedge n)}$$

- rh = relative humidity
- $c = 3.82 * 10^{-5}$
- n = 2.0

Bakker-Arkema's model has been found to be more accurate than Thompson's model in controlled environments, but Thompson's model may be accurate enough to estimate equilibrium water content estimation for grain that has constant atmospheric exposure.

A common requirement for equilibrium water content calculation is relative humidity. Relative humidity is not an input variable for most corn production models, including CERES-Maize, and it is not often measured on farms. Weather variables utilized by CERES-Maize include minimum daily temperature (degrees C), maximum daily temperature (degrees C), daily precipitation (mm), and daily solar radiation (MJ/m^2). To keep this model applicable at the farm level, an existing model should be utilized or a new model created to simulate relative humidity as a function of commonly measured daily weather variables.

Several models use daily minimum temperature as a surrogate for dewpoint temperature and corresponding vapor pressures in the absence of recorded vapor pressure (Abawai, 1995; Koon, 1986). While this approximation is relatively accurate for climates with relatively high annual rainfall averages, this assumption is imprecise when considering more arid climates. Figures 1 and 2 chart the average daily dewpoint temperature versus the minimum daily temperature for thirty year average data sets for Lansing, Michigan (relatively high annual rainfall) and Phoenix, Arizona (Arid).

Figure 2: Lansing comparison of min. temp and dewpoint

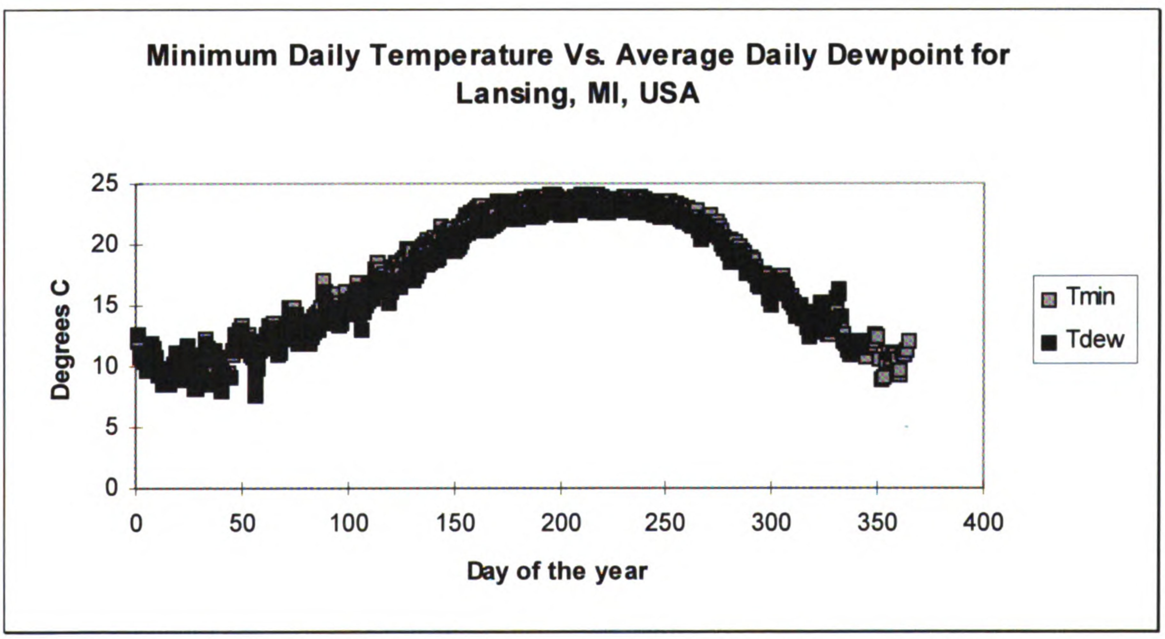
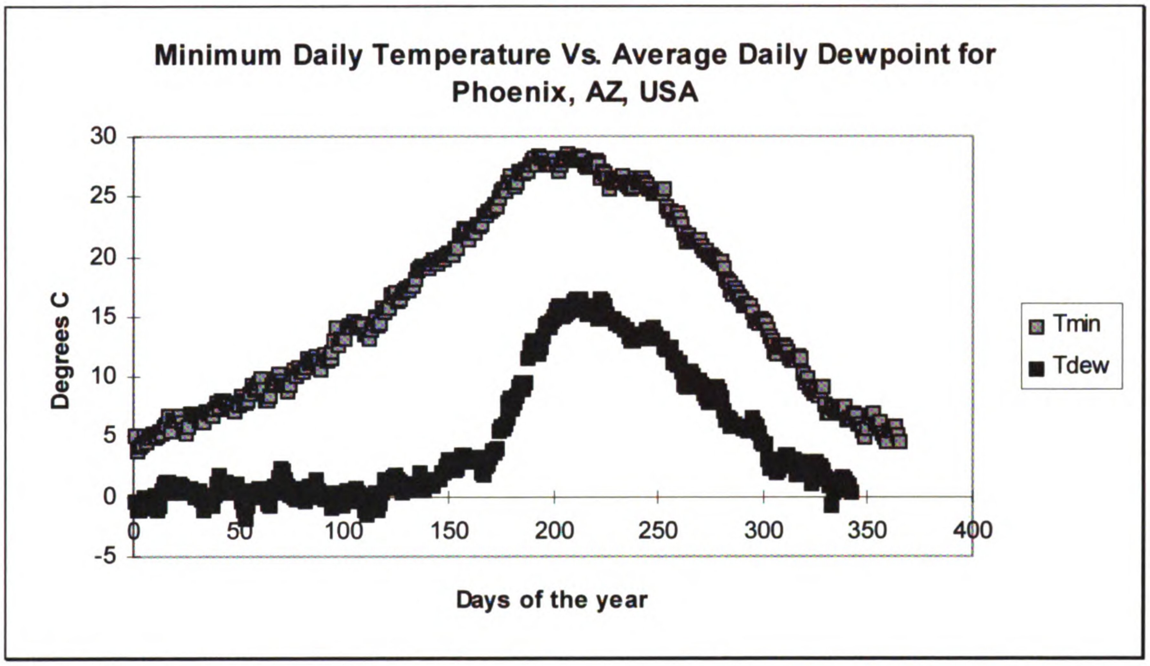


Figure 3: Phoenix comparison of min. temp and dewpoint



The graphs illustrate both the accuracy and inaccuracies of implementing this assumption. Researchers have developed a few regression based models that attempt to model the daily dewpoint temperatures using the daily minimum temperature (Vasic, 1981; Koon, 1986; Abawai, 1994; Kimball et.al., 1997). The most comprehensive of these is the work performed by Kimball, Runnings, and Nemani (1997). Their work developed an empirical model to improve the accuracy of the minimum temperature estimates of dewpoint temperature using daily air temperature, annual precipitation, and estimated daily evapotranspiration. The model used daily meteorological weather data for 52 weather stations in the continental United States and Alaska. The model structure and associated sub-calculations are as follows:

$$Td = Tmin\,[\,-0.127 + 1.121(1.003 - 1.444\,EF + 12.312\,(EF)^2 - 32.766\,(EF)^3 + 0.0006(Tmax - Tmin)]$$

Td = daily average dewpoint temperature (K)

Tmin = minimum daily temperature (K)

Tmax = maximum daily temperature (K)

EF = $\ell_{EP/day} / \ell_{PANN}$ = daily potential evapotranspiration (m) / annual precip. (m)

$\ell_{EP/day} = [(E_p/\rho_w)\, t_{day}]$ =daily potential evapotranspiration(m)

t_{day}= period when the sun is above the horizon (estimated from station lattitude)

ρ_w= density of water (kg/m^3)

E_p = potential evapotranspiration (Priestly & Taylor method, 1972)

Accurate values of Me are dependent on accurate estimation of relative humidity. The model of relative humidity model developed by Kimball et.al. (1997) reduced humidity estimation errors by up to 80% for the 52 sites used in the original analysis. A model that requires Me for operation should rely on such a model if measured values for vapor pressure are not available.

Henderson and Perry's (1955) grain drying model and the equilibrium water content models were formulated for mechanical drying simulation and discretion must be exhibited when attempting their use for infield drydown. As mentioned, these equations represent controlled or closed systems. Application of these models to in-field drydown requires an understanding of plant/atmosphere relationships. The most glaring difference between the controlled and uncontrolled system is re-wetting of the grain by precipitation.

The purpose of an equilibrium water content term in mechanical drying models is to represent re-wetting of the grains. When the equilibrium water content is greater than the existing water content of the grains, the grain water content trends toward equilibrium with the atmosphere. The phenomenon where the adsorption isotherm obtained by placing a dry biological material in atmospheres of increasing relative vapor pressures of water lags behind the desorption isotherm obtained by placing the wet product in atmospheres of decreasing relative humidity is termed hysteresis (Ngoddy & Bakker-Arkema, 1975). Many changes to Henderson's original equation (1955) have been formulated to better model this hysteresis effect. The bulk of these modifications are formulated for input into Thompson's model for drying simulation (Thompson et.al., 1968), which is derived from Henderson's findings. Many of these modifications are attempts to increase the accuracy of the model for precisely controlled systems where slight adjustments in a constant or use of a different model for a system variable calculation are required for hysteresis manifestation (Javas et.al., 1991; Krueger and Bunn, 1985; 1988).

Bruns addressed the effects of re-wetting on infield drydown in his model, reporting that the amount of wetting due to dew formation and higher equilibrium water content seems to be small compared to the wetting due to precipitation, but the duration of those conditions is important (Bruns et.al., 1975). The use of an equilibrium water content variable is important in drydown modeling as it sets a lower limit of water content that the grain must approach and follow asymptotically. Therefore, the incorporation of precipitation into a drydown model must amplify the hysteresis revealed by differences between grain water content and the equilibrium moisture content. Researchers have concluded that the magnitude of water content change due to hysteresis, called the hysteresis loop, is sometimes dependent on the speed and frequency with which the loop is traversed, lending that the effect of precipitation on drydown may be time dependent (Ngoddy and Bakker-Arkema, 1975).

In conclusion, the conception of a robust, easily applied model for infield drydown of corn is conditional to the inclusion of the following characteristics:

1. The model must work relatively independent of assumed relationships between water content values and plant phenological stages.
2. The model's environmental inputs should be limited to relatively easily measured parameters.
3. The model should incorporate equilibrium water content and precipitation for the purpose of modeling grain hysteresis and for setting a lower boundary of water content.
4. The model must simulate genotype specific plant phenology.

Chapter 2

METHODS AND MODELS

Models

General drydown equation

The objective of this work is to develop a process-oriented drydown model that is usable at the farm level utilizing a limited number of weather inputs. The basic structure of the model will be the first order differential equation proposed by Henderson and Perry (1955).

$$MR = \text{moisture ratio} = (M - Me)/(Mo - Me) = e^{-kt}$$

Use of CERES-Maize as a model platform

The functional corn growth and development model CERES-Maize will be utilized as the platform of operation for the drydown model. The new model will rely on CERES-Maize for calculation of plant phenology with respect to genotype specific variables and for daily weather parameters. These measured parameters include minimum and maximum daily temperature (degrees C), daily accumulated precipitation (mm), and daily accumulated solar radiation (MJ/m^2). The accuracy of the drydown model is dependent on accurate calibration of CERES-Maize with respect to site conditions (soils, weather) and experiment design (plant population, fertility, genotype, management practices).

The proposed starting point of the model is the CERES-Maize approximation for time of silking. The model will progress from silking to initiation of the effective grain filling period by accumulating 170 ^{o}C/day.

Modeling Grain filling

Progression from silking to the beginning of the effective grain filling period is an exclusive function of daily temperature in the proposed model. The next stage of the model is simulation of the grain-filling period. The genotype specific P5 coefficient of CERES-Maize is an estimation of the amount of daily thermal time required for a corn plant to progress from silking to physiological maturity. As outlined in the literature review, CERES-Maize uses the difference between 95% of P5 and the TT_8 required to connect the R1 (silking) and R2 (blister) phases of reproductive development to model linear grain filling duration. This is better outlined in the equation below.

Effective grain filling duration $(TT_8) = [.95 * P5(^{o}C/day)] - 170(^{o}C/day)$

The proposed drydown model will follow this methodology but will change the .95 multiplier to .90 to more closely align with other work (Johnson and Tanner, 1972). Using data from performed research, CERES-Maize was calibrated for each site and year of data collection (Kiniry and Ritchie, 1984; NeSmith, 1992; Brooking, 1990). Genotype specific information, especially the P5 coefficient if not known, was estimated to best fit the experimental data using CERES-Maize. For each experiment, data sets were obtained that shared these common elements:

1. Date of silking initiation.

2. Value of the P5 coefficient.
3. Daily accumulated values of DTT_8 from date of silking to physiological maturity.
4. Measured values of individual kernel weight with respect to time.

The duration of the effective grain filling period was calculated for each data set as a function of respective genotype-specific P5 values. The resultant thermal time was then expressed as 100% of the dry matter accumulation for the effective grain filling period. The rate of effective grain filling as a function of daily thermal time accumulation was then expressed as a percentage of the of the total dry matter accumulation for the effective grain filling period. These values are compared with measured grain filling for each data set (also expressed as a percentage of maximum dry matter with respect to time for the effective grain fill period) in Figures 4-6.

Figure 4: Nesmith and Ritchie grain filling data

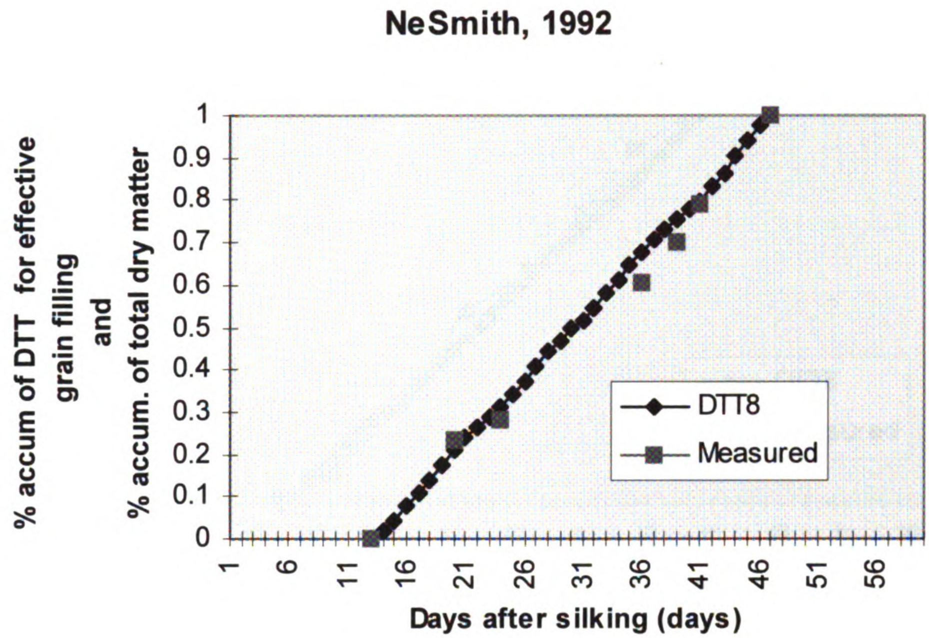


Figure 5: Brooking grain filling data

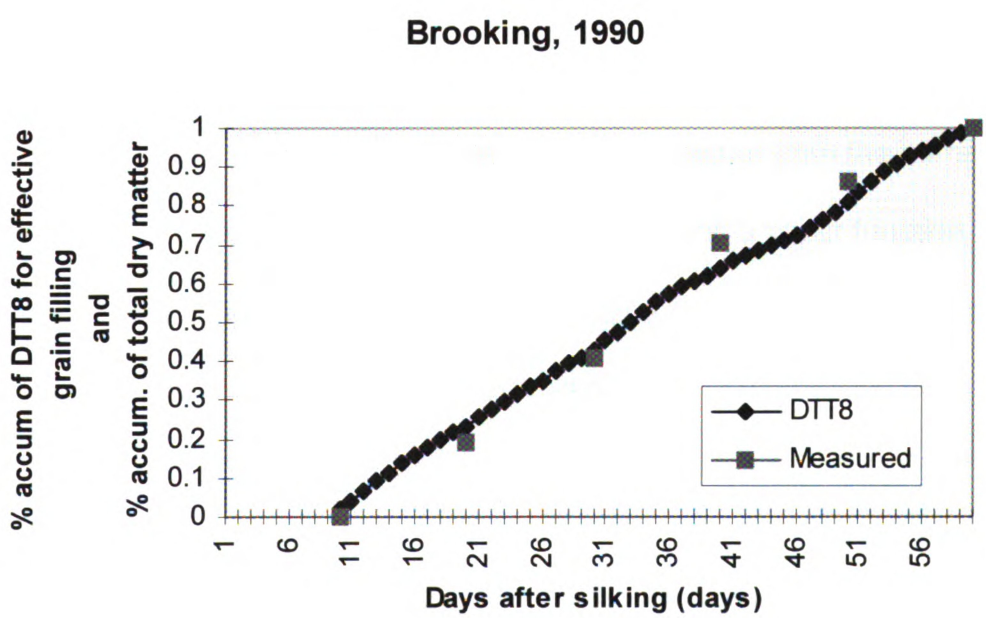
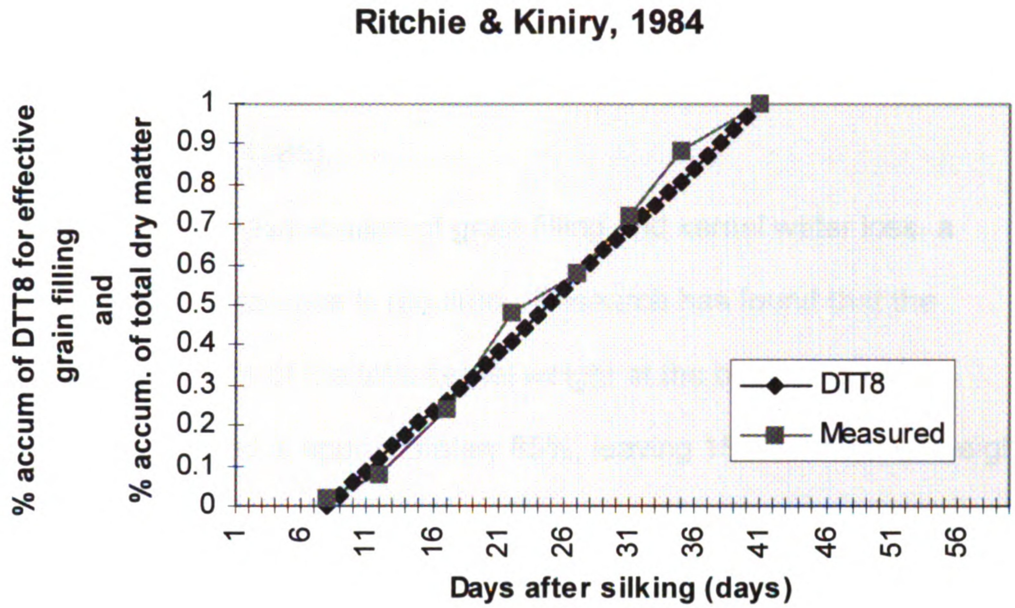


Figure 6: Kiniry et.al. grain filling data



As shown graphically, the grain-filling rate and thermal time accumulation closely correlate for the analyzed data sets (all $r^2 > 0.98$). A model of the grain-filling rate during effective grain-filling period will be used in the drydown model to represent the analogous displacement of developmental water from the kernels. This function uses a smaller percentage of TT_8 to determine a linear function for grain-filling as use of a high percentage of thermal time may conflict with the dent stage when assimilate movement into the kernels slows and grain-filling is no longer linear. The model does not attempt to simulate the period between the end of linear grain-filling and physiological maturity.

As the rate of dry matter accumulation is not a dependent function of temperature, simulating kernel water loss as a dependent function of temperature can only be viewed as a model and not a dependent relationship. Research has found no direct, positive correlation between temperature and kernel water loss prior to maturity nor any other weather variable (Hallauer & Russell, 1960). Research has found that the rate of grain fill has a *direct, positive effect* on grain water content reduction per unit thermal time during the grain filling period (Kang et.al., 1986).

To understand the association of grain filling and kernel water loss, a common time frame of reference is required. Research has found that the approximate water content of the total kernel weight at the beginning of the effective grain filling period is approximately 85%, leaving 15% of the total weight to structural dry matter (Ritchie and Hanway, 1997). Using this fact as an origin, the following conditions were set for analysis of the drydown model:

1. Two proportionality constants are needed to describe developmental and post-maturity water content.

   $\underline{k_{developmental}}$ = proportionality constant for developmental water loss phase = thermal time expressed as a fraction of the effective grain filling period duration.

   $\underline{k_{post\text{-}maturity}}$ = proportionality constant for post-maturity water content loss phase expressed as a constant.

2. The initial water content Mo is assumed to be 85% at the beginning of effective grain filling.

As described above, the proportionality constant used to calculate the period of developmental water loss has been initially set to the rate of thermal time accumulation for the effective grain filling expressed as some fraction of P5. This is only an initial setting.

Estimation of dewpoint temperature

The remaining input variable of the existing model that can be directly calculated using a measured parameter is Me. Relative humidity is required to calculate Me but is not a data requirement for CERES-Maize. To retain farm level applicability, relative humidity is calculated using an empirical model to estimate dewpoint temperature (Kimball, Runnings, and Nemani,1997).

$$Td = Tmin\,[\,-0.127 + 1.121(1.003 - 1.444\,EF + 12.312\,(EF)^2 - 32.766\,(EF)^3 + 0.0006(Tmax - Tmin)]$$

The only additional model inputs required for site characterization are estimated annual rainfall (m) and site latitude. Of these, only estimated annual rainfall is not provided by standard CERES-Maize weather files.

The model was tested against 30-year weather data sets for sites in Florida, Iowa, Michigan, Idaho, Arizona, and Texas. The associated graphs of the modeled and measured daily dewpoint data are represented in Figures 7-12.

Figure 7: Tampa,FL comparison of estimated and measured dewpoint.

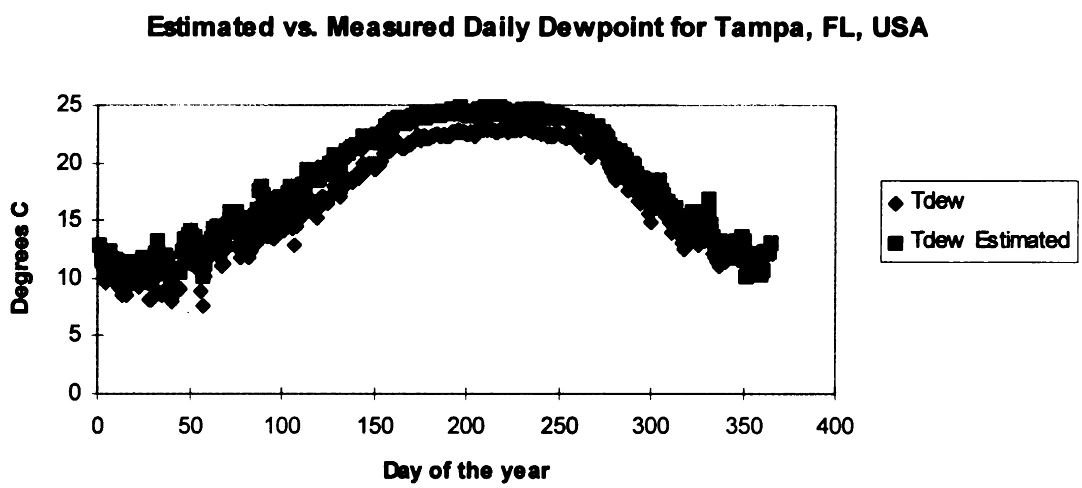


Figure 8: Dew Moines, IA comparison of estimated and measured dewpoint.

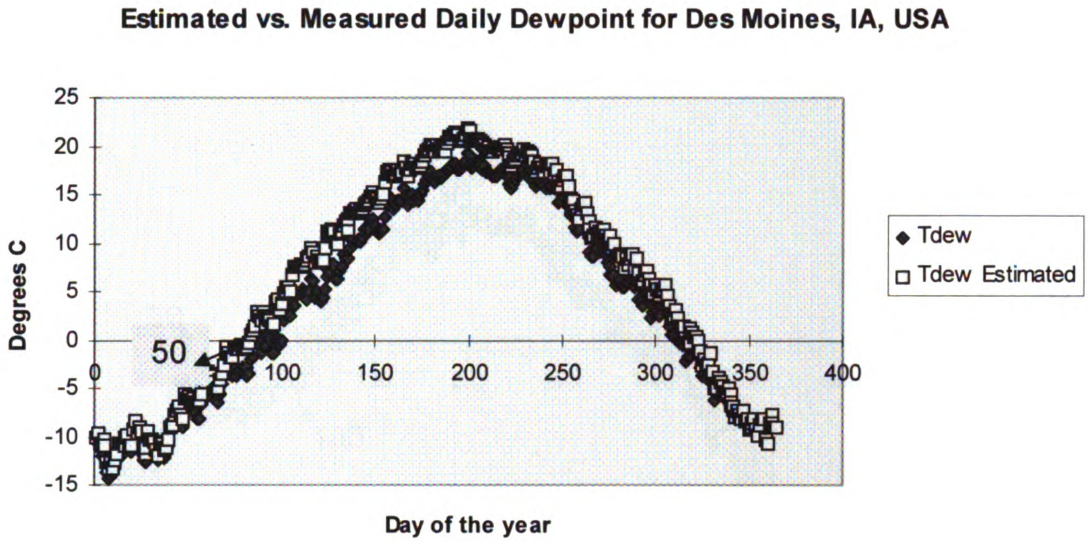


Figure 9: Lansing, MI comparison of estimated and measured dewpoint.

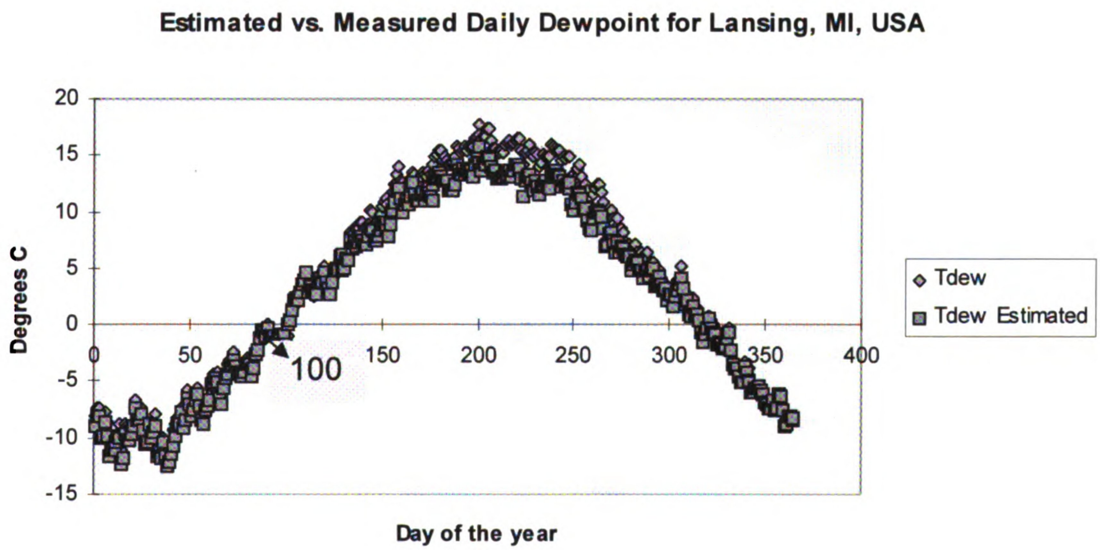


Figure 10: Boise, ID comparison of estimated and measured dewpoint.

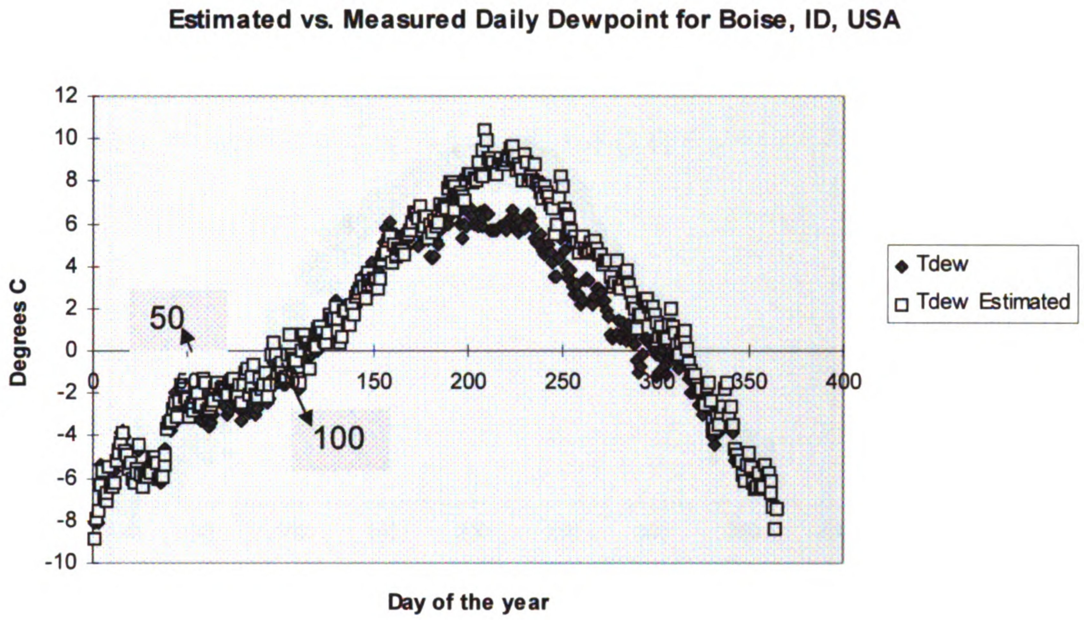


Figure 11: Phoenix, AZ comparison of estimated and measured dewpoint.

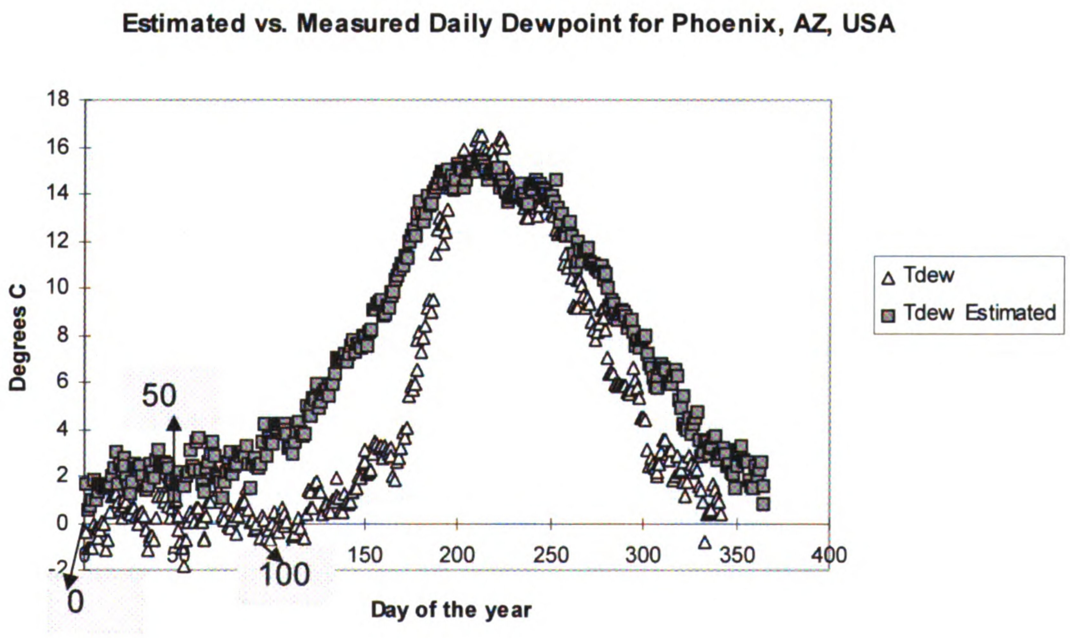
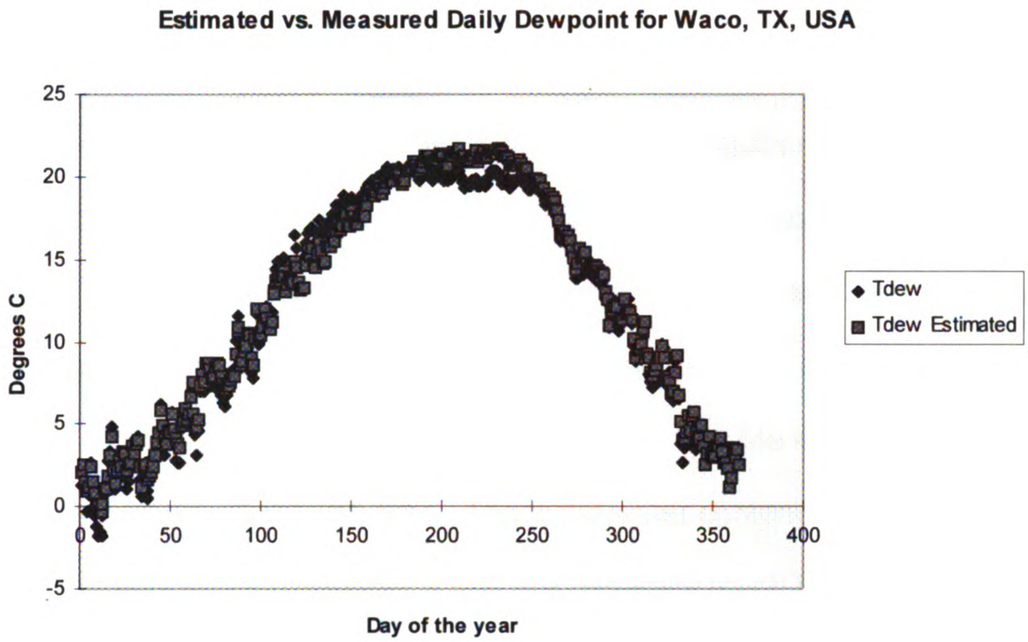


Figure 12: Waco, TX comparison of estimated and measured dewpoint.



For this analysis and the original error analysis performed by Kimball et.al. (1997), the model relatively reduced humidity estimation errors by up to 80% in semi-arid and arid sites (like Phoenix, Idaho, and Texas) and had minimal effects when the minimum temperature based humidity estimates were relatively accurate (Michigan, Iowa, and Florida). Based on these findings, this model was integrated into the proposed drydown model calculations where the estimated daily dewpoint temperature is used to solve for relative humidity.

Implementation of a re-wetting parameter for precipitation

The model proposed for simulation of drydown was originally intended to represent post-harvest mechanical drying. This paper has described the benefits of its application to pre-harvest drying. Adaptation of the model structure to simulate drydown is reliant on the model's ability to expand and simulate plant/atmosphere interaction. The weather parameters that most influence drydown are temperature, relative humidity, and precipitation. Of these, only precipitation is not expressed in the proposed model. Temperature and relative humidity are represented in the model via equilibrium water content and the proportionality constants if they are defined as functions of thermal time.

The difference between the initial water content (Mo) and Me represents both desorption and adsorption of water to/from the kernels depending on their respective magnitudes. The difference between Mo and Me is initially very large and reduces exponentially with time. The initial water content is 85% while Me is a function of atmospheric conditions that are generally much lower in water content. As the model increments daily, Mo takes on the value of the previous day's kernel water content minus the water lost to drydown during that day. When Me > Mo, the grain is being wetted and the grain water content moves toward the water content of the atmosphere. For grain drying in an enclosed system, the model can simulate re-wetting of the grains with the difference of kernel and atmospheric water content alone or with simple modifications to the proportionality constant. Krueger & Bunn (1988) demonstrated hysteresis by performing independent simulations for the same data sets with different models for equilibrium water content. The difference in simulation results correlated with measured values of hysteresis. These methods will not suffice for simulation of a wetting with precipitation. To simulate wetting, a term must be added to the original equation structure to increase the magnitude of Me when a precipitation event occurs. Simulation of the effect of precipitation on drydown would only be required for post-maturity simulation as precipitation has not been shown to effect developmental moisture content changes. The following model structure amendments are proposed to simulate the effects of precipitation.

IF ($TT_8 < P5$), $M_{DEVELOPMENTAL} = (Me) + (Mo - Me)e^{-kdevelopmental * t}$

IF ($TT_8 > P5$):

$$M_{POST\text{-}MATURITY} = (Me + Pe^{-\omega(tg)}) + (Mo - (Me + Pe^{-\omega(tg)}))e^{-kpostmaturity * t}$$

P = precipitation (mm)

ω = wetting parameter

t_g = time since the end of linear grain filling (days)

The form and placement of the precipitation term into the drydown equation was selected for experimental testing based on the following assumptions. First, the exponential form was selected to better represent reduction of the hysteresis loop as its size is sometimes dependent on the speed and frequency with which the loop is traversed, surmising that the effect of precipitation on drydown may be time dependent. A hypothesized declining effect of precipitation on drydown with respect to time gains feasibility as other factors such as loss of kernel membrane permeability, increased water shedding by the ear due to development of an obtuse ear angle with the top of the stalk, and increased air movement between stalks due to leaf dropping contribute to this reasoning. Secondly, making the term additive to the equilibrium water content forces the term to zero when there is no precipitation thus retaining the original model structure. Third, initiation of the precipitation term's influence is at the end of linear grain filling. Using this initial time removes extreme values from the decline in the precipitation curves. The precipitation term is not used until 100% of the P5 thermal time has accumulated. This allows for an acclimation period for the precipitation term that represents about 5% of the P5 duration. Creation of this acclimation period reduces the dramatic effect of a precipitation event that may occur near the end of grain filling.

Experiment Methods and Materials

Experiment Objective

The objective of this work is to test the hypothesized drydown model using data sets collected spatially and temporally. The following questions are the focus of experimental design and hypothesis testing:

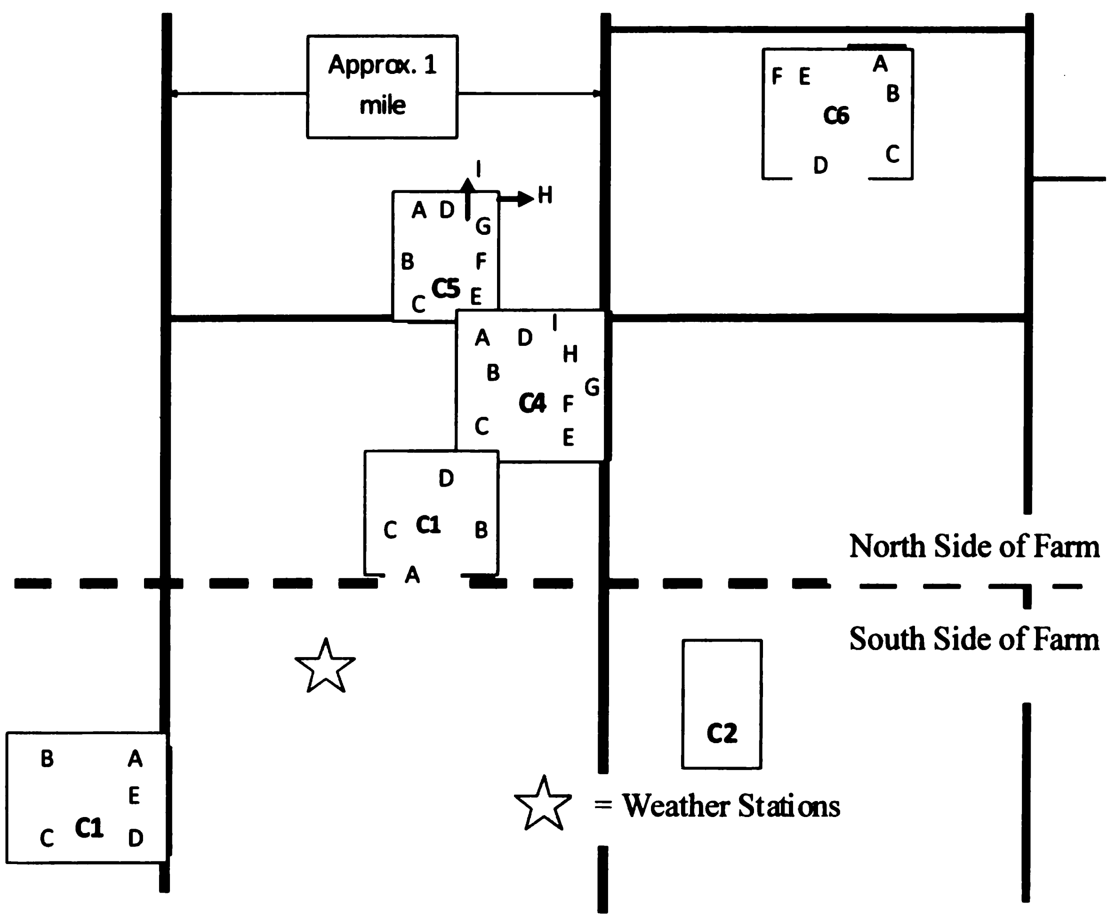
1. Can the model work relatively independent of assumed relationships between kernel water content values and plant phenological stages?
2. What is the influence of spatial variability of precipitation on drydown? Are there other required model inputs for accurate implementation at the producer level?
3. Does the proposed precipitation term in the model accurately describe the hysteresis effect? Are there other requirements for explaining this effect?
4. How sensitive is the model to changes in the CERES-Maize P5 coefficient?

Experimental Design

The experimental phase of this project was performed near Fowler, Michigan, U.S., during the summer growing season of 1999. The farm utilizes approximately 1200 acres of land to raise corn, soybeans, wheat, and alfalfa. The corn, soybean, and wheat enterprises shift spatially on a three- year crop rotation. Soybeans and wheat utilize conservation tillage practices with respect to planting where as the corn enterprise relies on prepared soils and conventional planting. The farm soils range from sandy loam to heavy clay loams. Most of the farm is moderately well drained.

The 1999 corn enterprise included 270 acres in six different field locations within the 3-mile radius of the farm as shown below in Figure 13.

Figure 13: Farm overview schematic



Planting dates ranged from May 4th through May 14th, 1999. The hybrids used for the experiment were Dekalb brands 535, 493, 477, and 471 that range in relative maturity's from 103 - 97 days, respectively. The farmer selected the hybrids based on previous success. Soil characteristics, management practices regarding fertilization and planting, and genotype specific estimates of plant phenology were quantified for CERES-Maize input for field and genotype specific simulation.

With the base information for CERES-Maize set, the remaining inputs to the model were measured weather variables. Two (2) LI-COR weather stations were installed on the farm, one representing the "north" ½ of the corn enterprise and the 2nd representing the "south" one-half. The weather stations were calibrated with respect to one another twice during the season by placing the stations side-by-side for a period of two days and changing the calibration coefficients of a single unit. The weather stations began logging data prior to planting and continued through harvest.

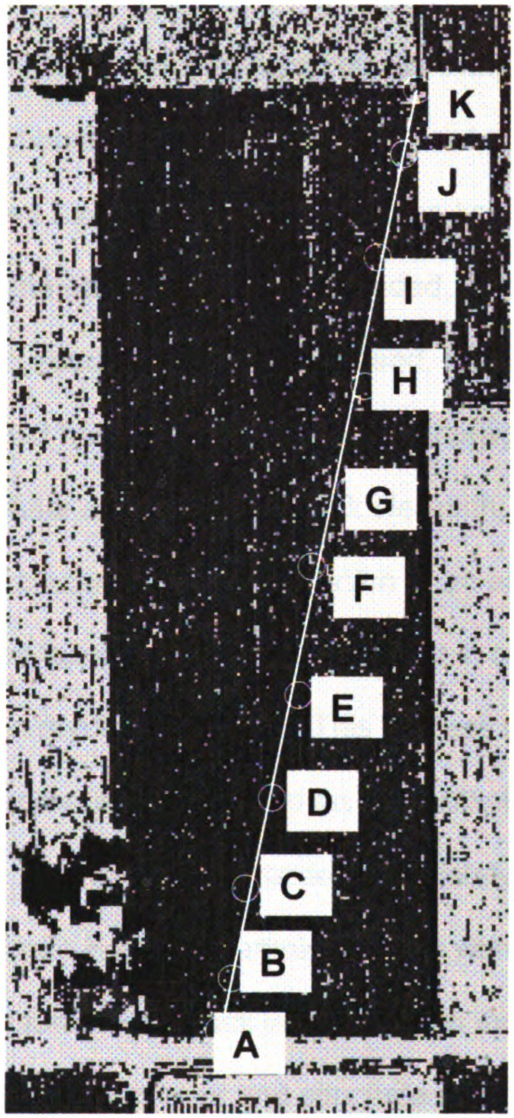
In addition to weather station measured variables of temperature and solar radiation, a network of 32 wedge style Tru-Chek® rain gauges was installed throughout the corn fields on the farm. Rain gauges were placed to best characterize the total area of the field as one rain gauge represented approximately 8 - 9 acres. The reasoning for intense sampling of precipitation was two-fold. First, the sample points for drydown were undetermined at the beginning of the season and as precise precipitation quantities were imperative to model accuracy, a network approach to rain measurement reduced the need for interpolation. Second, spatial variability of precipitation does exist at the field level (Basso, 1998) and needs to be quantified for its effects on plant growth and development as well as its unknown effects on in-field drying.

Precipitation was initially measured after every independent rainfall event for all gauges. This practice eventually became extensive as the crop developed, requiring a global positioning system to locate the gauges. The measurement of precipitation was eventually broadened to larger time intervals for the vegetative and reproductive phases of development with more intense, event specific measurement during the post-maturity period. A differential global positioning system was utilized for the duration of the experiment for data collection of drydown and precipitation measurements. To eliminate the pending canopy interference with precipitation measurement, the rain gauges were placed atop 4 foot sections of PVC pipe that were secured to the top of a steel fence post that was driven into the ground past the base spade. Vertical leveling of the gauges was checked intermittently throughout the season.

A third source of weather data in the form of radar estimated weather parameters was provided by WSI, Inc. Two measurement "sites" were provided to represent the northern and southern halves of the farm as shown in Figure 13. Each data set was based on 2 km resolution radar data. These quantities were used for comparison with measured values and not for model inputs.

Limited inspections of crop growth and development were performed throughout the season to check the CERES-Maize modeled phenology. Airplane derived remote sensing images were obtained on July 6th, 1999 for each of the corn fields. The images represented a 1 m resolution aerial view of in-field crop growth and developmental differences for the approximate V15 stage (about 10 - 12 days prior to tassel. The infrared band of the images was singled out for further analysis as it visibly showed the greatest amount of spatial variability when compared to the other bands. The correlation of a single band of an interlaced remotely sensed image and yield components of corn has been reported in the literature (Senay et.al., 1998). The remote sensing images were used to select sites for experimental measurement of in-field drydown that represented the greatest spatial variability with respect to hybrid and field level development. A sample of one of these images with the selected measurement points is shown in Figure 14.

Figure 14: Image if field C5 with selected measurement points.



Index	
Blue	0 – 62
Black	63 – 111
Dark Pink	112 – 145
Light Pink	146 – 300

Red dots = Rain Gauges
Circles = 30 m sampling radius

Tassel initiation and silking were observed for each selected field location and were compared with modeled dates in CERES-Maize. The model's P1 coefficient, the thermal time from seedling emergence to the end of the juvenile period, was calibrated for each genotype to conform the modeled phenology for monitored plant development.

Kernel sampling for drydown began on September 1st and continued through harvest on approximately 3-day intervals. Intervals of measurement were decreased or increased depending on timing and duration of precipitation events. Drydown was monitored by removing several kernels (20 - 30) from ears of two neighboring plants per dasiteta point and collection event. Husks were gently pulled back from each ear and the kernels were removed from the center section of the ear using a knife if needed. The husk was then replaced against the ear and secured with a rubber band. This method has been used in past research and has been found to have a negligible effect on grain-filling and water loss (Tollenaar and Daynard, 1978; NeSmith, 1992). When more than one-half of the kernels from the central portion of an ear were removed, a second kernel sample was taken from an adjacent plant in an attempt to suppress plant to plant variability in drydown patterns. This process was repeated at the stated intervals through harvest with no more than three plants per site required for data collection. Samples were frozen immediately after collection for collective drying at a later time. For each sample, kernels were inspected upon collection for black layer formation. Black layer began in the first planted field on September 17th as a light brown layer and concluded as complete black layer in the last planted field on September 21st, 1999. The P5 coefficients were genotype-calibrated for CERES-Maize and drydown simulations using black layer formation timing.

Each sampling area was hand harvested on a per row basis. Measurement cell size ranged from 900 (30 x 30 ft) - 100 (10 x 10 ft.) square feet with size of cell changing due to time constraints. In addition to yield component information, plant population data including plant number and spacing was also recorded per cell. Hand-harvested yield samples were shelled and analyzed for their yield components including water content, grain weight, and sample temperature. The crop was mechanically harvested after hand harvest of the cells using a yield monitor with integral water content sensor. Hand measured information will be used for model formulation as the spatial information provided by the harvester water content sensor and yield monitor were less accurate.

The collected kernel samples were weighed separately and collectively dried at 80 C for 5 days at the season's end (NeSmith, 1992). The kernels were then re-weighed and water contents for each sample were calculated. Site-specific samples were arranged chronologically to represent site-specific drydown curves.

With data collection complete, site-specific CERES-Maize simulations were performed using soil texture, measured plant population, and precipitation data from the field. Soil texture differences were simple field approximations based on observations and existing county-level soil maps. Precipitation data sets were either stand-alone precipitation measurements from a single gauge or a linear interpolation of the two closest gauges depending on distance from the sampling point to the gauges.

With site-specifically calibrated CERES-Maize simulations, the proposed drydown model could be tested using the required phenological timing information from CERES-Maize and the measured, site-specific drydown curves.

Initial formulation and testing of the model utilized spreadsheet analysis. Non-linear optimization was used to determine $k^{developmental}$ and $k^{postmaturity}$ by minimizing the sum of squared differences between measured and modeled values of moisture content for each site-specific drydown curve. The drydown curves were collectively analyzed such that single values of constants could be used to represent the complete data set as well as in-field drydown processes for other places and times.

Chapter 3

RESULTS AND DISCUSSION

Analysis of results

The systematic analysis of this experiment follows an outline of questions that initially focuses on the collected data and culminates in reviewing the proposed model's accuracy and applicability. Below is a detail of these examinations:

1. Based on a statistical comparison of measured drydown values, which data sets would be used as reference curves for model parameter development?
   A. Were site-specific data sets affected by any unaccounted influence?
   B. What are the possible sources of error for the collected data?
2. Did the proposed model meet the experiment/thesis objective?
   A. Did the integral "parent models" (CERES-Maize, grain filling, dewpoint as a function of minimum daily temperature) perform accurately?
   B. Is the model accurate for other data sets?

Initial analysis concentrates on the collected data. Regression analysis of the measured and modeled drydown curves was performed per genotype and field. Examples of the complete data set are shown in the following tables and figures.

Figure 15: Modeled and measured drydown curves for DK 535 Hybrid in field C4 (reference Figure 13).

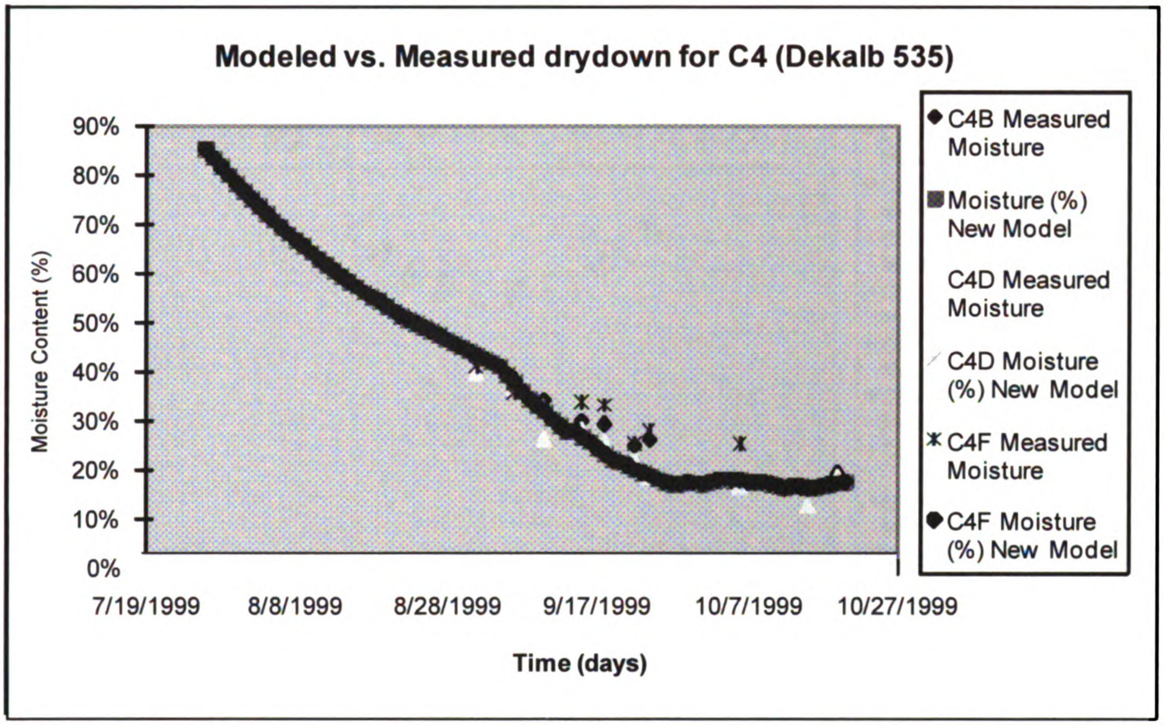


Table 1: Regression analysis for C4 drydown curves plotted in Figure 15.

Plant Population:		6.53	7.18			
Regression Coeff. (r^2):		0.99	0.98	0.95		
Date	***Model***	***C4B Measured Moisture***	***C4D Measured Moisture***	***C4F Measured Moisture***	***MEAN***	***Standard Deviation***
7/27/1999	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	43.2%	42.3%	39.5%	40.9%	40.9%	1.44%
9/6/1999	37.6%	38.5%	36.2%	35.2%	36.6%	1.71%
9/10/1999	31.7%	33.9%	26.0%		29.9%	5.55%
9/15/1999	26.6%	29.8%	28.1%	33.6%	30.5%	2.79%
9/18/1999	23.1%	29.0%	25.4%	32.9%	29.1%	3.72%
9/22/1999	19.8%	24.6%	21.6%	25.0%	23.7%	1.87%
9/24/1999	18.7%	25.7%	18.4%	27.7%	23.9%	4.94%
10/6/1999	17.6%	17.6%	16.4%	25.1%	19.7%	4.74%
10/15/1999	16.1%		12.3%	15.6%	13.9%	2.30%
10/19/1999	17.1%	19.0%	18.6%		18.8%	0.34%

Figure 16: **Modeled and measured drydown curves for DK 535 Hybrid in field C5 (reference Figure 13).**

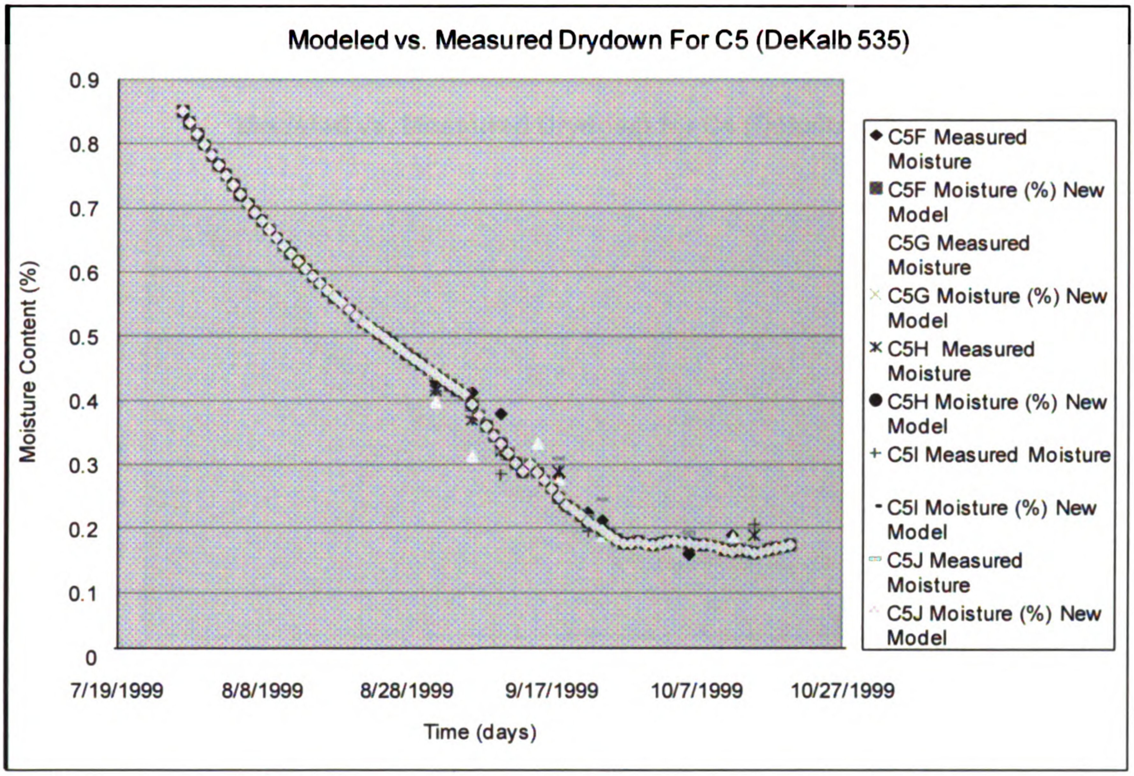


Table 2: Regression analysis for C5 drydown curves plotted in Figure 16.

Population (plants/m²):		5.77	6.41	6.33	6.46			
Regression Coeff.(r²):		0.987	0.965	0.991	0.991	0.987		
Date	***Model***	***C5F Measured Moisture***	***C5G Measured Moisture***	***C5H Measured Moisture***	***C5I Measured Moisture***	***C5J Measured Moisture***	***MEAN***	***Standard Deviation***
7/27/1999	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	43.2%	42.9%	39.7%	41.5%	41.4%	43.5%	41.8%	1.48%
9/6/1999	37.6%	41.1%	31.3%	36.8%	37.4%		36.6%	4.06%
9/10/1999	31.7%	37.7%		32.1%	28.3%	32.1%	32.6%	3.89%
9/15/1999	26.6%		33.2%		29.4%		31.3%	2.73%
9/18/1999	23.1%	27.9%	27.6%	28.8%	24.0%	31.0%	27.9%	2.55%
9/22/1999	19.8%	22.3%		21.4%	19.4%	21.9%	21.3%	1.31%
9/24/1999	18.7%	21.1%	18.7%	20.4%	19.4%	24.7%	20.9%	2.30%
10/6/1999	17.6%	15.8%		16.8%	18.0%	19.4%	17.5%	1.52%
10/15/1999	16.1%	18.8%	18.6%				18.7%	0.14%
10/19/1999	17.1%			18.9%	20.6%		19.8%	1.22%

Figure 17: **Modeled and measured drydown curves for DK 493 Hybrid in field C4** (reference Figure 13).

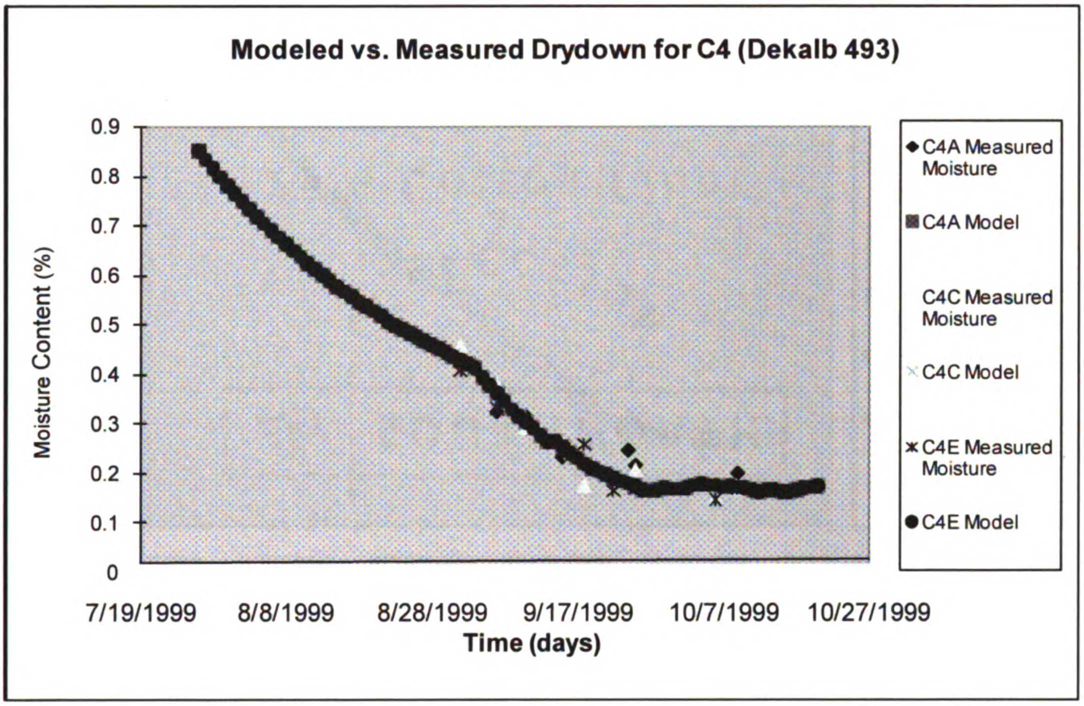


Table 3: Regression analysis for C4 drydown curves plotted in Figure 17.

Population *(plants/m^2):*		8.29	6.21	6.07		
Regression Coeff.(r^2):		0.980	0.987	0.991		
Date	***Model***	***C4A Measured Moisture***	***C4C Measured Moisture***	***C4E Measured Moisture***	***MEAN***	***Standard Deviation***
7/27/1999	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	42.7%	43.6%	45.6%	40.5%	43.2%	2.57%
9/6/1999	36.0%	32.3%	37.8%	32.8%	34.3%	3.07%
9/10/1999	30.3%	31.3%	29.1%		30.2%	1.58%
9/15/1999	25.1%	23.1%	25.8%	24.5%	24.5%	1.37%
9/18/1999	21.8%	21.6%	17.4%	25.6%	21.5%	4.11%
9/24/1999	17.9%	24.5%			24.5%	
9/25/1999	17.3%	21.4%	20.6%	16.7%	19.6%	2.54%
10/6/1999	17.5%	17.2%	14.8%	14.6%	15.5%	1.46%
10/9/1999	17.1%	19.9%	16.8%	16.8%	17.8%	1.80%

Figure 18: Modeled and measured drydown curves for DK 477 Hybrid in field C1 (reference Figure 13).

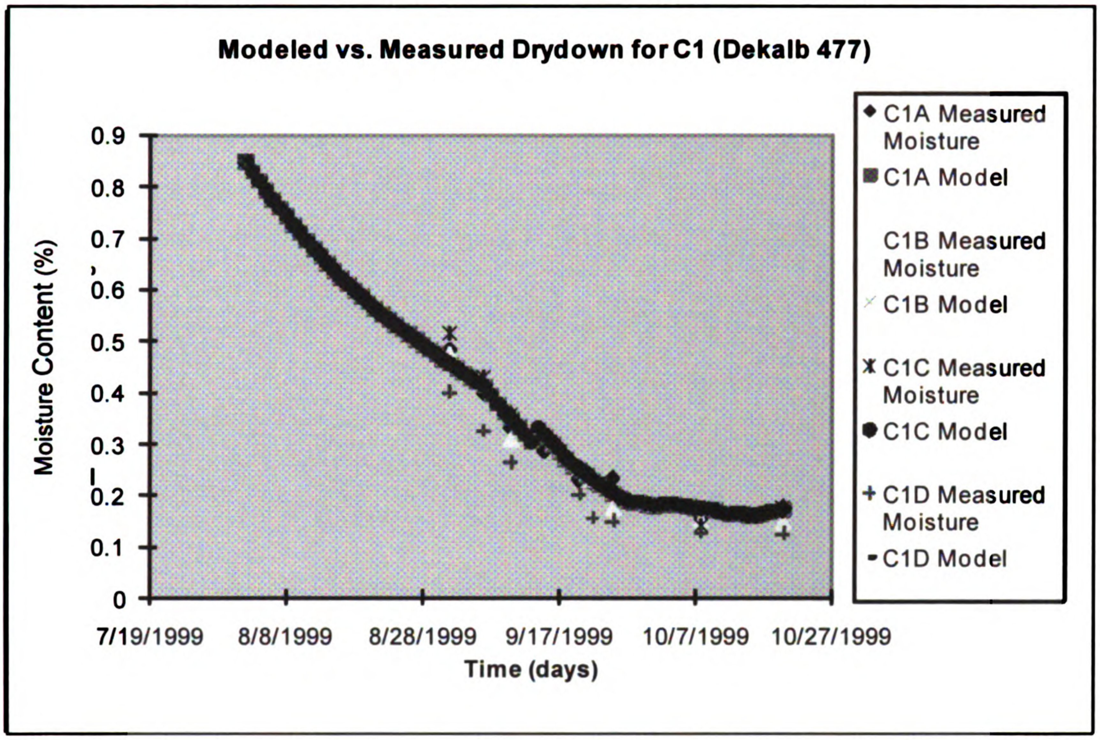


Table 4: Regression analysis for C1 drydown curves plotted in Figure 18.

Population (plants/m²):				5.92			
Regression Coeff.(r²):		0.991	0.994	0.988	0.991		
Date	***Model***	***C1A Measured Moisture***	***C1B Measured Moisture***	***C1C Measured Moisture***	***C1D Measured Moisture***	***MEAN***	***Standard Deviation***
8/2/1999	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	45.7%	48.3%	47.4%	51.4%	40.1%	46.8%	4.75%
9/6/1999	41.5%	39.9%		43.0%	32.6%	38.5%	5.32%
9/10/1999	35.1%	33.3%	30.7%	35.8%	26.5%	31.6%	3.99%
9/15/1999	31.5%	28.6%				28.6%	
9/20/1999	25.0%	23.2%		24.8%	20.3%	22.8%	2.27%
9/22/1999	22.9%	22.2%	23.0%		15.7%	20.3%	3.98%
9/25/1999	20.4%	23.4%	17.4%	22.1%	15.1%	19.5%	3.93%
10/8/1999	17.8%	15.9%	15.1%	14.0%	12.8%	14.5%	1.35%
10/20/1999	17.5%	17.9%	14.7%	17.9%	12.6%	15.8%	2.57%

Figure 19: Modeled and measured drydown curves for DK 477 Hybrid in field C3 (reference figure 13).

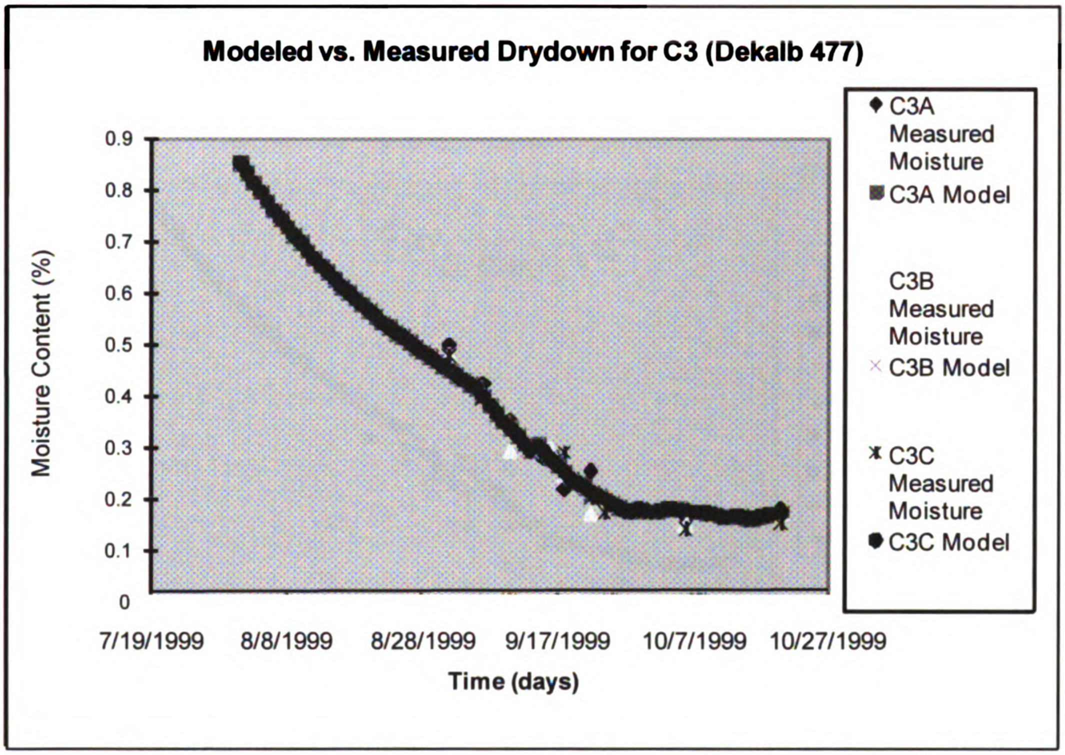


Table 5: Regression analysis for C3 drydown curves plotted in Figure 19.

***Population** (plants/m^2):*		7.26	5.7	6.6		
***Regression Coeff.** (r^2):*		0.984	0.988	0.990		
Date	***Model***	***C3A Measured Moisture***	***C3B Measured Moisture***	***C3C Measured Moisture***	***MEAN***	***Standard Deviation***
8/1/1999	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	44.9%	49.6%	47.7%	47.4%	48.2%	1.18%
9/6/1999	39.9%	42.2%	40.3%	39.1%	40.6%	1.56%
9/10/1999	33.7%	35.0%	29.0%		32.0%	4.21%
9/15/1999	29.1%	27.4%		28.1%	27.8%	0.46%
9/16/1999	27.9%		29.6%		29.6%	
9/18/1999	25.2%	21.6%	24.4%	28.8%	24.9%	3.62%
9/22/1999	21.3%	25.2%	17.0%	19.9%	20.7%	4.18%
9/24/1999	20.0%		19.4%	17.2%	18.3%	1.55%
10/6/1999	17.8%	16.1%	14.9%	14.0%	15.0%	1.06%
10/20/1999	17.4%	17.9%	16.8%	15.0%	16.5%	1.47%

Figure 20: Modeled and measured drydown curves for DK 471 Hybrid in field C6 (reference figure 13).

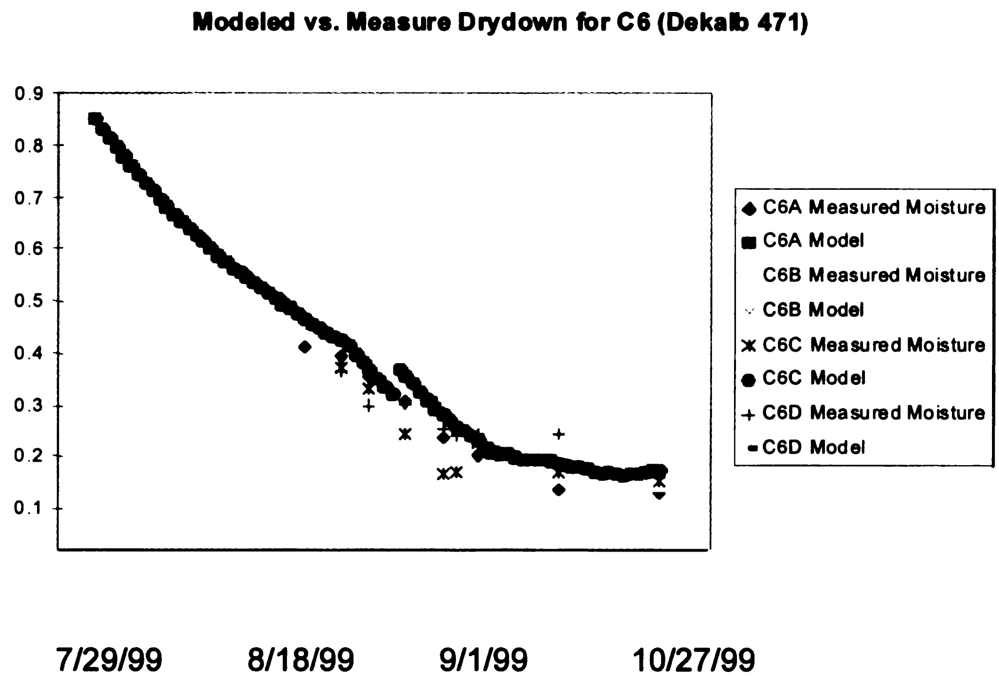


Table 6: Regression analysis for C6 drydown curves plotted in Figure 20.

Population (plants/m²):							
Regression Coeff.(r²):		0.992	0.987	0.962	0.963		
Date	***Model***	***C6A Measured Moisture***	***C6B Measured Moisture***	***C6C Measured Moisture***	***C6D Measured Moisture***	***MEAN***	***Standard Deviation***
8/3/1999	85.0%	85.0%	85.0%	85.0%	85.0%	85.0%	0.00%
9/1/1999	46.6%	41.2%				41.2%	
9/6/1999	42.3%	39.3%	46.3%	37.2%	36.5%	39.8%	4.46%
9/10/1999	36.7%	35.4%	39.4%	32.9%	29.8%	34.4%	4.08%
9/15/1999	35.4%	30.5%	34.1%	24.4%	30.1%	29.8%	4.00%
9/20/1999	28.2%	23.6%	29.9%	16.8%	25.4%	23.9%	5.42%
9/22/1999	25.7%	25.8%		17.1%	24.0%	22.3%	4.58%
9/25/1999	22.8%	20.3%	26.4%	22.7%	24.5%	23.5%	2.61%
10/6/1999	18.7%	13.6%	19.2%	17.1%	24.4%	18.6%	4.54%
10/20/1999	17.5%	12.8%	14.1%	15.2%	16.0%	14.5%	1.36%

The results provided two important findings. The first is spatial variability of drydown rate with respect to position within a field of common genotype exists. This effect is demonstrated in measurement locations nearest to the outside edges of the field. These sites produced the greatest difference between measured and modeled values and were primary sources of error in the evaluation of model constants. This circumstance was most prevalent at sampling point C1D (Figure 18). Cell C1D was located in the second row (east to west orientation) from the edge of field that is adjacent to a heavily used road. A possible reason is that increased air movement and increased availability of solar radiation due to a lower "effective plant population" caused faster drydown. The term "effective plant population" for this work refers to the fact that the outside rows of a corn field are not sheltered by a local array of plants like those in the center of the field. While intra-row plant spacing may be common, the severing of a local plant array by removal of rows creates an effective plant population that is less than the intended population. Evidence of this relationship between plant population and drydown rate was observed at an interior site (C5E). The measured plant population for this point was the lowest in the study while it's drydown rate was the fastest. Because the objective of this work is to test a robust model that is applicable at the farm level, the effects of differing plant population on drydown rates are not incorporated into the model.

A second finding from this result is the exponential decline in water content from physiological maturity except for precipitation events. This is most obvious for precipitation events that occurred early in the post-maturity phase of drydown. The best example of this phenomenon is the difference between the measured water contents on September 22nd and 24th, 1999. On September 23rd, a rainfall event of approximately 10.2 mm lasting approximately 2.5 hours was recorded. On the 24th, samples were collected in the late afternoon after plant surface water had evaporated. Special care was taken not to manually wet the kernels during the sampling process. As shown in the tables, a hysteresis effect was not expressed in all data sets for these dates due to site-specific development differences related to genotype or planting date. As mentioned in the model & methods section, the hysteresis effect has been found to dissipate due to changes in the number of times the hysteresis "loop" has been activated. Precipitation influenced the water content of later maturing hybrids more so than hybrids that matured earlier. This could be attributed to a lack of rainfall in the initial weeks after the earlier hybrids reached physiological maturity when changing water content would have been most susceptible to hysteretic effects due to increased kernel membrane permeability. Precipitation had a great influence for the later hybrids, particularly DK 471 & 477, as 2 sites did not show increased water contents near precipitation events. Based on this analysis, the proposed form of the drydown model's precipitation term will be retained.

While the model is relatively sensitive to precipitation amount during early post-maturity simulation, in-field spatial variability of rain events was not significant relative to measured changes in water content. Further research regarding the proposed wetting factor via manual re-wetting of corn is required for a more comprehensive understanding of its value.

Using this information, cells that exhibited a water content reduction rate due to decreased plant population would not be included in model formulation. These cells include C1D & C5E (for aforementioned reasons) and C6C (also due to population of less than 5 plants/m^2). Two other cell drydown curves, C5G & C4F, have also been removed from model formulation due to possible erroneous data points. Each of these measurement locations were relatively protected from possible "effective plant population" effects and each had comparable plant populations with neighboring cells. In each case, a single measurement point was out of agreement with others near it and therefore that cell was removed from model consideration. Possible causes for these errors include samples that were water contaminated during kernel removal, kernel destruction during removal that may have caused wetting of the sample, and weighing errors made during the mechanical drying process.

Formulation of the drydown equation

With the remaining data sets, the proposed model structure was tested by solving for undetermined constants and analyzing differences between model output and measured data sets. Below is the proposed model.

IF ($TT_8 < P5$), $M_{DEVELOPMENTAL} = (Me) + (Mo - Me)e\text{-}^{kdevelopmental * t}$

IF ($TT_8 > P5$):

$M_{POST\text{-}MATURITY} = (Me + Pe^{-\omega(tg)}) + (Mo - (Me + Pe^{-\omega(tg)}))e\text{-}^{kpostmaturity * t}$

The modeled grain filling rate as a function of fraction accumulation of the P5 coefficient in thermal time was a good estimate of the $k_{developmental}$ proportionality constant. This can be seen in Figures 15 - 20 where the modeled water content fit well with measured values prior to the onset of physiological maturity. This value ranged from .025 to .027 for early and late maturing hybrids, respectively. As the P5 coefficient was re-calibrated for this analysis to reflect measured dates of black layer development, tests could not be made to determine if the P5 coefficient is a good predictor of physiological maturity. However, the observed value of P5 was within one day of daily thermal time of the manufacturers assessed time from mid-pollination to physiological maturity. This relationship gives merit to the use of the P5 coefficient as a basis for developmental timing in the model.

The $k_{post\text{-}maturity}$ constant was more difficult to calibrate. As mentioned earlier, the hysteresis effect decreases with time after maturity and the number of wetting events for biological materials. For this work, an exponential model of the precipitation term was used successfully for modeling hysteresis effects. Analogous to hysteresis is an increased ability of the kernel to dissipate water when there is significant difference between grain water content and the equilibrium water content. To simulate this effect, it was necessary to change the $k_{post\text{-}maturity}$ term to reflect the kernel's increased ability to dry when the (Mo - Me) was relatively large. $k_{post\text{-}maturity}$ was chosen to represent this drying function as it was not associated with a measurable event such as precipitation. Changing drying model constants (k) to represent time dependent processes is common throughout the literature (Jayas et.al., 1991). The following relationship is used in this work to model the increased rate with which kernels change in water content after hysteresis:

$k_{post\text{-}maturity} = \delta/Mo$

δ = drying constant

This change in model structure worked well for modeling the drying process for post-precipitation drydown rate and required not equation. Use of Mo in the formulation of the post-maturity proportionality constant was also found successful for a like temperature regime in other research (Misra & Brooker, 1980).

The remaining unsolved constant is the precipitation constant ω. With accurate phenological timing provided by CERES-Maize and observations, ω and δ were solved for using non-linear optimization to minimize the sum of squared differences between measured and modeled drydown values. The results of this analysis concluded that the following values, when used in the model, best simulated corn drydown.

$k_{post\text{-}maturity} = \delta/Mo$ = (drying constant = .027)/Mo
ω = wetting parameter = .49

The model simulated drydown accurately for the measured data sets (Figures 15 – 20 and Tables 1 – 6). The mean difference between the measured and modeled values decreased with respect to time as mean errors of less than 1.5% were common near harvest.

One of the major objectives of this work was accurate application of a drydown model for different environments. To test the models applicability to other data sets, weather and moisture content data collected in Iowa in 1964 were used to test the model. Model accuracy mirrored those found during the 1999 Michigan experiment.

Chapter 4

CONCLUSIONS

The objective of this work is to forge a robust, farm-level applicable model for infield drydown of corn from reviewed literature and experimental results. Meeting this objective required adhering to the following conditions. First, the model needs to work relatively independent of assumed water content values and plant phenology. This constraint was observed with one exception, as a value of 85% water content is assumed at the beginning of linear grain filling. A second constraint called for the model's required environmental parameters to be easily measured by farmers. This condition was meet and exceeded as only daily maximum and minimum temperatures and precipitation are required model inputs. These variables are common to the CERES-Maize weather file format and will allow for the drydown model to be easily integrated into CERES-Maize. A third constraint included incorporation of equilibrium moisture content and precipitation into the model. This condition is of extreme importance with respect to understanding the environmental processes that control changes in grain water content with respect to time. The precipitation term showed relevance to simulation of measured changes in water content in the performed experiment, but it's exact effect at all points in the post-maturity drydown curve requires further research. The inclusion of an equilibrium moisture content term increased the model's ability to simulate the effects of the environment on kernel water content as it approached atmospheric water content.

The result of this work culminates in a robust, highly applicable model of in-field drydown of corn. Accurate use of the model is dependent on a calibrated CERES-Maize platform with respect to site and environmental conditions. Both CERES-Maize and the drydown model are highly reliant on accurate assessment of genotype characteristics related to plant phenology, in particular the time from silking to physiological maturity.

Needs for future research regarding in-field drydown should be concentrated in the following areas:

1. The effect of precipitation with respect to time in the post-maturity drydown phase. Mechanical wetting could help to better define the influence of precipitation on a physiologically changing kernel.
2. The effect of plant population corn drydown. "Effective plant population" for plants near open regions and for areas of the field that have different plant populations due to problems with planting and emergence needs to be further addressed.
3. The effect of an early killing frost is abscent from the model. This season's first killing frost came on September 22, 1999 and did not cause pre-mature formation of black layer.
4. Applications in different places and seasons. This research is limited to only a few data sets. Future data sets are needed to strengthen the model's spatial and temporal application vigor.

Continued work regarding in-field drydown may provide answers regarding the aspects of plant growth that most determine spatial variability in corn production. If drydown is quantified as a function of hybrid selection and the environment, producers and researchers can shift their focus to improving management practices based on reflected changes in the vegetative period of development.

Regardless of future research, this work will help farmer's to maximize grain quality and yield while minimizing mechanical drying and the risk of yield loss due to harvesting in less than ideal weather conditions.

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