ABSTRACT

ENVIRONMENTAL EFFECTS ON NAVY BEAN FIELD DRYING AND HARVESTING

By

Bachchan Singh

Two varieties of navy beans, Seafarer and Sanilac, were studied to evaluate environmental effects on field drying and harvesting. These varieties were planted on two dates in 1973, and three different dates in 1974. Pod and grain samples were taken at two-hour intervals together with weather data to investigate the effect of the environment upon drying rate.

The growing-degree-day-unit system was used to determine physiological and harvesting maturity dates. Physiological maturity was defined as the time when grain moisture content was 50%. Harvesting maturity is reached when the crop achieves 18 to 20% moisture content. To supplement this field study, phenological data were collected from mail surveys of farmers in bean-growing areas of Michigan for the years 1972, 1973 and 1974. Growing degree days determined from the surveys were comparable to those developed from the intensive field study.

Stepwise regression techniques were applied to the 1974 data to develop models of rate of change of pod and grain moisture content of both varieties. The independent variables in the final models were initial pod moisture content, rate of change of temperature (°C) per unit of time and difference in pod and grain moisture content. Verification of the model was made utilizing data from 1973. Comparison of observed and predicted pod moisture content showed good agreement.

Regression model for rate of change of grain moisture content indicated that grain drying within the pod was not statistically dependent upon weather variables used in this study.

Linear relationships were found between the rise in moisture content overnight and the number of hours of dew. These models are adequate to predict rise in pod and grain moisture content. However, they are valid only for dew duration of 6 to 12 hours.

A linear relationship was established between pod and grain moisture content from 1974 data and validated with 1973 data. Grain moisture content predicted from the relationships showed good agreement with observed values.

The model for unthreshed loss included pod moisture and cylinder speed as independent variables. The model indicates that there are varietal differences in threshing behavior and that pod moisture content influences threshability. Seafarer was harder to thresh than was Sanilac.

Relationships for damage loss were established. The independent variables in the model were grain moisture content and cylinder speeds. The model indicates that minimum damage can be achieved if the navy bean grain moisture content is in the range of 18 to 20%.

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I. INTRODUCTION

Michigan is a leading producer of dry edible beans (*Phaseolus vulgaris*). Approximately one-third of the dry beans produced in the United States at the current time are grown in Michigan.

Agriculture has become a highly complex undertaking where man, machine, money, biology and environment must interact to produce food and fiber at a profit (Von Bargen, 1967). During the past few years, techniques of bean production have changed considerably. Input costs such as land, machinery, and labor have increased relative to the selling price of beans. It is increasingly necessary for farmers to carefully manage their farming operations to profitably stay in business.

Much of the effort in the past has been on bean harvest methods and combine performance. However, many of the variables in bean production and harvesting are influenced more by weather than the mechanical method of production. Timely harvesting of navy beans is essential for low threshing losses (cylinder loss), freedom from impact damage and good quality. It is usually stated that beans should be combined when grain moisture is within the range of 15 to 20% (Judah 1970, Pickett 1972).

In recent work, Pickett (1972) indicated that threshing loss depended largely on the moisture content of bean pods. On the other hand, mechanical damage to beans during harvesting depended on the moisture content of the grain. Climatological conditions are responsible for diurnal variation of moisture content of both the bean pod and grain. Hence bean quality and threshability are directly affected by current weather conditions.

The general practice in Michigan is to pull the bean plant, leave the plants in windrows to dry, then thresh with a combine. Bean and pod moisture content vary significantly, usually increasing during the night and lowering throughout the daylight hours. Farmers could possibly use combines more efficiently if they knew the rate and extent of drying each day during navy bean harvest periods. Harvesting under these circumstances requires careful adjustment of the combine to compensate for changing plant and environmental conditions.

A method for evaluating bean development and harvesting and specifying the necessary values for many of the parameters would provide valuable information to extension workers, growers, researchers, designers and processors. The use of simulation modeling techniques are useful in solving machinery management and scheduling problems. Machinery selection (Scott 1970), harvest operations under stochastic conditions (Sorensen and Gilheany 1970), and harvesting of hay (Von Bargen 1967) have already been studied. Our goal is to add the edible dry bean to this list.

The objectives of the research reported herein are:

1. To formulate and test a method representing the phenological stages of the bean plant from the time of planting until it reaches maturity.

2. To develop a model which will be suitable for predicting navy bean seed and pod moisture content at the time of harvest.

3. To determine the limits on bean seed and pod moisture for effective threshing.

4. To verify the use of plant development models for predicting the time of harvesting.

5. To utilize seed and pod moisture values and combine settings for predicted threshing loss and mechanical damage during harvesting.

II. REVIEW OF CROP MODELS

The bush bean (*Phaseolus vulgaris*) is a warm season crop with an optimum germination temperature of 25°C (Anonymous). The optimum temperature for growth is in the range of 18°-24°C (Martin and Leonard 1949).

Models have been developed by several research workers to predict the growth behavior of various crops. The models of Chen, Huang and Splinter (1968), Chen and Huang (1969) and Stapleton (1970) predict growth behavior of cotton and tobacco. Morey *et al.* (1971) developed models to simulate corn production systems where the emphasis was on corn growth relationships and simulation of the harvesting and drying portion of the system. Temperature was the primary variable used to describe growth. A heat unit technique involving temperature was used by Stapleton (1970) to simulate cotton growth and Morey *et al.* (1971) to simulate corn growth.

Several other investigators have considered the total plant environment system in developing crop growth and production models (Morey *et al.* 1972). Leaf orientation and angle (Duncan *et al.* 1967), and light interception by successive leaf layers (Monteith 1965a and 1965b) have been considered in simulating photosynthesis and crop production functions. De Witt (1959) provided a simulation of the total crop system including soil moisture, root development and other physiological processes.

Simulation models have been used to determine the optimal policies for planting and fallowing wheat (Burt and Allison, 1967). Donaldson (1968) developed a simulation model for cereal grain harvest. The combine harvest rate in acres per hour, weather's influence and diurnal fluctuations of grain moisture were regarded as probabilistic with known distributions based on empirical data.

Machinery cost systems for harvesting, drying and storing shelled corn (Carpenter and Brooker 1970) and wheat (Audsley and Boyce, 1974 and Boyce 1972) have been studied. In both of these studies, the effects of weather, grain moisture content, field losses, harvesting and drying rates were considered. The number of working days was determined from weather parameters.

Holtman *et al.* (1970) introduced a general model for simulating corn production systems. They included the simulation of weather inputs, soil moisture, soil tractability, grain moisture content, and harvesting. The plant processes as well as individual climatic factors were considered by Baker and Horrocks (1973) while simulating corn grain production. The importance of feedback in dynamic programming was illustrated in their study. Link and Bockhop (1964) had previously studied the problems of scheduling machines for corn production systems where a sequence of operations was required.

III. EXPERIMENTAL PROCEDURE AND EQUIPMENT

The Crop

A randomized block design with five replications in 1973 and three replications in 1974 was used to grow dry beans for harvesting trials. Two varieties of beans, Seafarer and Sanilac, were planted on June 8 and 25 in 1973 and on June 10, 20 and 28 in 1974. Each replication consisted of four rows of Seafarer and four rows of Sanilac. The plantings were made on land provided by the Michigan Agricultural Experiment Station, near East Lansing, Michigan.

Plant Sampling and Moisture Determination

We started to take moisture samples from the field soon after pod formation. Sampling locations in the field were chosen by a random number process each day. Samples were taken once each day at about 2 p.m. until grain reached 25 to 30% moisture content. The oldest pods from two plants in each row were picked to represent the maximum stage of maturity.

From the time bean moisture contents were 25-30% until harvesting was completed, moisture content data were taken at two-hour intervals from 9 a.m. eastern daylight time (EDT) until 5 p.m. to determine the rate of moisture loss by pods and grain. Pod and grain were separated, dried in a 100°C forced air oven for a period of 72 to 96 hours and weighed to an accuracy of .001 grams to determine the moisture content.

Weather Data

The following weather data were collected:

1. Dry bulb temperature
2. Relative humidity
3. Radiation
4. Precipitation
5. Piche evaporation
6. Pan evaporation
7. Wind velocity
8. Dew

Dry bulb temperature, relative humidity, radiation, piche evaporation and pan evaporation were measured at the East Lansing Climatological Station. Precipitation was measured at the research plot as well as at the Climatological Station. Wind velocity was obtained from the Lansing Capital City Airport national weather service station.

Equipment

Air temperature and relative humidity were recorded by standard hygrothermographs. Radiation data were recorded with an Eppley Black and White Pyranometer and recording unit. A Dew Balance Recorder[1] was used to measure dew. Dew deposited on a 100 sq. cm. close-meshed nylon sieve is weighed in the range from 0.0 to 5.0 grams with a sensitivity of 0.05 grams. Hourly dew amounts and daily totals were determined with this instrument.

A recording Piché Evaporimeter was used to measure evaporation rate. Evaporation from a standard class A evaporation pan was also measured.

Precipitation at the sites was directly measured with a Truchek wedge-type rain gauge[2]. An 8-inch recording rain gauge unit at the East Lansing Climatological Station was also used to obtain rainfall amounts and rates.

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[1]Model No. 299, Science Associates Incorporated, 23-Nassau St., Princeton, N.J. 08540.

[2]Manufactured by Tru-check Rain Gauge Division, Edwards Mfg. Co., Albert Lea, Minn.

IV. PREDICTING BEAN PHENOLOGICAL STAGES

Bean phenology may be divided into emergence, flowering, physiological maturity and harvesting maturity stages. Breeders, producers and processors are interested in how the bean develops through each of these stages. If the duration of growth is known then maturity ratings can be determined that will allow each variety to be sown at the proper geographical place and time. Maturity ratings of different crops can also be used during the growing season as an aid in scheduling of harvesting operations. One method of assessing plant development used successfully with a variety of crops is the Heat Unit or Growing Degree Day Method.

Literature Review

The relationship between temperature and the rate at which plants grow and develop was classified by Aspiazu 1971, Aspiazu and Shaw (1972) as: 1. exponential first developed by Livingston and Livingston (1913), 2. physiological developed by Livingston (1916) and Brown (1960, 1969) and 3. remainder described by Gilmore and Rogers (1958).

Such systems may be used to determine the requirements for a crop to reach a particular stage of development, and, therefore, can be used to predict timing of phenological stages of a crop. Examples of different types of heat unit indexes are listed in Table 4.1.

Table 4.1. Heat-Unit Indexes Determined from Temperature °F Measurements and Used with Various Crops.

Type	Equation	Remark
Exponential	$U = 2^{(T-40)/18}$	Livingston *et al.* 1913 U = Growth index
Physiological	$Y_{max} = 1.85(T_{max}-50)$ $-0.026(T_{max}-50)^2$	Brown 1960
	$Y_{min} = T_{min}-40$	
	$H = (Y_{max} + Y_{min})/2$	H = Growing Degree Unit
Remainder	$H = ((T_{max}+ T_{min})/2)-50$	Gilmore and Rogers 1958

The National Weather Service (NWS) uses a form of the remainder heat unit equation with restrictions on the temperatures. Their technique assumes a linear growth rate between 50°F (10°C) and 86°F (30°C) and essentially no growth outside this range. In this method all maximum temperatures above 86°F (30°C) are designated as 86°F (30°C) and all minimum temperatures below 50°F (10°C) are designated as 50°F (10°C).

Growing degree days are determined by the remainder technique.

Another modification of the remainder system was developed by Newman *et al.* (1969) for use with corn.

If

$$T_{max} \geq 90°F \text{ and}$$

$$T_{av} = \frac{T_{max} + T_{min}}{2} \geq 75°F$$

Then

$$\text{Daily GDD} = (T_{av} - 50°F) - (T_{max} - 90°F)$$

But

$$\text{if } 50°F \leq T_{av} \leq 65°F$$

Then

$$\text{Daily GDD} = T_{av} - 50 + (T_{max} - 65)$$

otherwise

$$\text{Daily GDD} = T_{av} - 50.$$

Katz (1952) studied the relationship between heat unit accumulation and tenderometer readings of canning peas and found essentially a linear relationship between the two. The difference between the results obtained by using a direct summation and the exponential method was small.

Neild and Greig (1971/72) used the basic heat unit system to predict the dates of plantings and length of harvest season, for several vegetables and sweet corn.

They used base temperatures of 40°F and 50°F depending upon the crop to determine the heat units required. Van Den Brink (1971) also used the basic heat unit to determine growing degree days in Michigan for corn.

Kish *et al.* (1972) conducted experiments to study the accuracy of the heat unit system in predicting maturity dates of snap beans. The growing degree-hour method was found to be unreliable in predicting the maturity of three plantings of snap beans. They pointed out that predicting the maturity of snap beans was improved by integrating available soil moisture data into the heat unit model.

Data and Procedure

Two navy bean varieties, Seafarer and Sanilac, were used in our tests. On June 8 and 25, 1973, beans were planted on the Michigan State University Crop and Soil Farm. In 1974, beans were planted on June 10, 20 and 28 at the Michigan Crop Improvement Association Farm located 4 miles south of the Crop and Soil Farm. Data collected during the two growing years included the following phenological information:

1. Date of planting
2. Date of emergence
3. Beginning of flowering
4. Maximum flowering
5. End of flowering

6. Date of 50% moisture content
7. Date of 20% moisture content
8. Date of harvest

To supplement our field observations, crop development data were obtained from cooperating farmers for the years 1972, 1973 and 1974 by use of a mail survey. Data requested on these surveys included:

1. Navy bean variety
2. Date of planting
3. Date of emergence
4. Date of flowering
5. Date of harvesting
6. Approximate moisture content at the time of harvest
7. Average yield in kg. ha^{-1} ($bu \cdot a^{-1}$)

These data were obtained from two counties in the bean growing area -- Tuscola and Gratiot counties. Climatological stations at Bay City, St. Charles, Caro, Alma, and St. Johns were selected to describe the temperature conditions in these counties. The weather data required to compute growing degree units for our MSU plantings came from the records of the East Lansing Climatological Station.

The phenological data obtained from the surveys lack uniformity because they were taken by different observers. Data for beginning of flowering, maximum flowering and end of flowering were recorded only on our research plots. The 50% grain moisture content data were used to estimate physiological maturity. This value may reflect end of accumulation of dry matter in the grain. The harvesting maturity data were estimated when the entire field reached an average grain moisture content of 18-20%.

Daily growing degree day units (GDD) for each variety were summed during each phenological period by using the modified National Weather Service equation using temperatures in degrees Celsius and base temperature 10°C. The total GDD for each growth period was obtained regardless of planting date and locations. The average and standard deviation of the GDD were then determined.

Results and Discussion

The average growing degree units for each variety are shown in Table 4.2 for our plantings as well as the counties surveyed. Actual growing degree units and standard deviation for each growth period and year are shown in Appendix A.

The difference in growing degree units for the two varieties Seafarer and Sanilac calculated from farmers' observations and from research plots for each growing peiod was not significantly different. On the basis of this limited amount of data we can say that from planting

Table 4.2. Average Growing Degree Day Units in °C for Various Phenological Periods.

Variety	Data Source	Emergence	Beginning of flowering	Harvesting
Seafarer	Counties	60	452	967
	MSU	66	424	926
Sanilac	Counties	61	473	1003
	MSU	66	458	960

to harvesting Seafarer requires 950 and Sanilac 980 growing degree units when temperature is in degrees Celsius.

The growing degree units required for each phenological period are shown in Table 4.3. This table reveals that Sanilac remains in the vegetative stage for a longer time than does Seafarer. From emergence to beginning of flowering Seafarer required only 358 GDD, whereas Sanilac required 392 GDD. Similarly, if we look from emergence to end of flowering, Seafarer takes 566 whereas Sanilac takes 610 GDD. On the other hand, both Seafarer and Sanilac have taken the same amount of GDD, i.e. 502, from beginning of flowering to harvesting maturity.

From date of planting to harvesting maturity the sum of the growing degree day units in both years were almost the same, whereas there were 11 calendar days

Table 4.3. Average Growing Degree Day Unit (°C) Between Phenological Stages for Two Years (MSU Data).

Planting	Emergence	Flowering Beginning	Flowering Maximum	Flowering End	M_e 50%	M_e 20%	Harvesting
Planting							
Seafarer	66	424	520	632	804	865	926
Sanilac	66	453	555	676	845	913	960
Emergence	0						
Seafarer		358	454	566	738	799	860
Sanilac		392	489	610	779	847	894
Flowering Beginning		0					
Seafarer			96	203	380	441	502
Sanilac			97	218	287	455	502
Maximum			0				
Seafarer				112	284	245	406
Sanilac				121	290	358	405
End				0			
Seafarer					172	233	294
Sanilac					169	237	284
50% M.C.					0		
Seafarer						61	122
Sanilac						68	115
20% M.C.						0	
Seafarer							61
Sanilac							47
Harvesting							0
Seafarer							
Sanilac							

difference for the Seafarer variety between 1973 and 1974 (Appendix A, Tables 1 and 2). Similarly, for Sanilac an average of 16 days difference was noted between the two years (Appendix A, Tables 1 and 2).

It must be remembered that except for the two years' data from our plantings, other data were farmers' field observations. A carefully controlled state-wide investigation involving trained observers would give more accurate relationships.

Growing degree day information may be useful in advance arranging the planting schedule so that the number of hectares planted on each planting day will approximate the daily harvesting capacity for direct harvesting. Since heat unit accumulation is more rapid at harvest time than during planting time, the interval between plantings must be greater than the interval between harvestings.

Conclusions

The growing degree day unit is a better technique for predicting physiological development than are calendar-day techniques. For harvesting maturity Seafarer required 90 days during 1974, whereas only 79 days were required during 1973 with a growing degree day difference of only four units. Similarly, Sanilac required 97 days in 1974 and only 81 days in 1973 with a difference in growing degree day units of 20.

More climatological data will be required to accurately describe the GDD units variation within counties in the bean-growing areas of Michigan. The Great Lakes have their effect on temperatures in the bean-growing area. Within-county variation in response to lake effects on temperatures have not been determined in this study.

V. FIELD DRYING OF NAVY BEANS

The problem of field drying of navy beans is considered as one of the dynamics of daily field drying of pod and grain during the harvest period. The influence of daily temperature, relative humidity, radiation and wind velocity on crop moisture content is abundant. A knowledge of pod and grain moisture content is considered essential for decision making during the harvest period as the former affects threshability and the latter affects damage (Pickett 1972).

The purpose of this phase of the study is to determine quantitative relationship among pod and grain moisture content of navy beans and various weather factors influencing moisture content during the harvest period. If we were to include all crop and weather variables, the resulting models would be very complex. Our effort here is to determine the minimum number of variables having the greatest influence upon field drying of navy beans.

Literature Review

Mathematical modeling of drying of biological products is becoming of greater interest to researchers. Most of the experimental work on drying has been done under controlled conditions. Molecular diffusion of water through porous structures was studied by Sherwood (1929). A theoretical model in the form of a differential equation describing diffusion within a sphere was reported by Hustrulid and Flikke (1959). Allen (1960) presented the general concept of moisture movement in porous materials and applied this to the drying process. A basic thin layer drying study on corn revealed that drying mechanisms are controlled by mass diffusion within the kernel (Pabis and Henderson 1961).

Obtaining diffusion coefficients for most crops is complex. Due to non-availability of diffusion coefficients past investigators have attempted to develop semi-empirical or empirical drying equations. Equation 5.1 is one of the most widely used drying equations found in the literature.

$$\frac{dM}{dt} = -k\ (M-M_e) \qquad (5.1)$$

A solution to equation 5.1 is

$$\frac{M - M_e}{M_o - M_e} = \exp\ (-kt) \qquad (5.2)$$

In these equations

M = Moisture content of the particle

M_e = Equilibrium moisture content at time t

M_o = Initial moisture content of the product

k = A drying constant.

Although functional relationships for k have been reported by several workers, they do not agree with each other in form (Pabis and Henderson 1961, Morey *et al.* 1971, Kemp *et al.* 1972). The most common expression accepted for k is

$$k = c_1 \text{ EXP } (c_2/T) \tag{5.3}$$

where

c_1 and c_2 are crop constants

T = absolute temperature °K.

Equation (5.3) is known as the Arrhenius function for the diffusion coefficients. The drawback of this equation is that it does not contain a moisture flow variable.

Since drying is a diffusion process, it only takes place when there is a difference in vapor pressure between the air and the surface to be dried. Thus factors such as a diffusion of moisture inside the particle (e.g. grain and pod), properties of the air surrounding the particles, and the flow characteristics of the air are the controlling mechanisms in natural field drying.

Much of the work on field drying has been done with hay, wheat and barley. Brück and Elderen (1969) formulated field drying models for hay and wheat. Van Kampen's wheat model (1969) was written in an exponential form. It expressed the relationships between drying of the kernel and daily radiation. Rise in kernel moisture content was affected by both precipitation and nightly hours of dew.

Weather records have been used to develop a model for wheat and barley grain moisture for periods with rain and for periods without rain (Crampin and Dalton 1971). The equations in this study were derived with regression techniques from experimental data. Elderen and Hoven (1973) developed an explanatory model for the continuously changing moisture content of wheat in the field based on physical quantities and characteristics of moisture movement processes.

Modeling Field Drying

If pod and grain moisture could be measured at hour t then a knowledge of how weather affects field drying should permit the prediction of moisture content at some later hour ($t + \Delta t$). Navy bean grains are enclosed by a pod. Both pod and grain are subjected to the same basic physical processes so far as a change in moisture content due to weather is concerned. However, there may be some interaction between pod and grain drying.

In our modeling process, we are considering pod and grain drying separately. Two types of variables, plant and environmental, are considered to affect drying rate. These variables are

M_p = % pod moisture content, wet basis,at time t

M_G = % grain moisture content, wet basis, at time t

T_A = Air temperature (°C) at time t

RH = Relative humidity in (%) at time t

EVP = Evaporation rate ($mm\text{-}t^{-1}$)

RAD = Radiation, cal $cm^{-2}h^{-1}$

W_s = Wind speed, m. sec^{-1}

VPD = Vapor pressure deficit, mb

Functional Relationships

The moisture content of pods and grain at any time can be determined by the relationships

$$M_p\ (t + \Delta t) = M_p\ (t) + \left(\frac{\Delta M_p}{\Delta t}\right)\Delta t \tag{5.4}$$

$$M_G\ (t + \Delta t) = M_G\ (t) + \left(\frac{\Delta M_G}{\Delta t}\right)\Delta t \tag{5.5}$$

where

$M_p\ (t + \Delta t)$ = % pod moisture content at time $(t + \Delta t)$

$M_G\ (t + \Delta t)$ = % grain moisture content at time $(t + \Delta t)$

$(\frac{\Delta M_P}{\Delta t})$ = rate of change of % pod moisture content

$(\frac{\Delta M_G}{\Delta t})$ = rate of change of % grain moisture content

Δt = time interval.

Thus knowledge of the rate of moisture change will permit the prediction of final moisture content.

Field samples of moisture content and concurrent weather data can be used to formulate the rate of change of moisture content relationship. The model was postulated to take the form

$$\frac{\Delta M}{\Delta t} = F\ [M(t), Yi] \tag{5.6}$$

where

$\frac{\Delta M}{\Delta t}$ = rate of change of % moisture content

Yi = rate of change of weather variables occurring between sampling time.

Substituting this to equation (5.4) and (5.5) will then give moisture content at time $(t + \Delta t)$.

Estimated Relationships

It was assumed that the rate of change of moisture content of navy beans is governed by energy input and moisture content of the air. We did not consider an equilibrium moisture content in the model, though it has an effect on moisture change due to constant air conditions in the absence of radiation. Under field conditions, however, there is a rapid change of moisture content with rapid changes of air temperature, wind and radiation.

In our preliminary study two models of the form given below were studied to predict the rate of change of moisture content. The models were of the form

$$\left(\frac{\Delta M}{\Delta t}\right) = b_o + b_1 M_p + b_2 M_G + b_3 \frac{\Delta T}{\Delta t} + b_4 \frac{\Delta RH}{\Delta t} + b_5 EVP + b_6 RAD + b_7 W_s + b_8 M_{(p-G)} + b_9 W_s \qquad (5.7)$$

and

$$\left(\frac{\Delta M}{\Delta t}\right) = b_O + b_1 M_p + b_2 M_G + b_3 EVP + b_4 RAD + b_5 VPD + b_6 M_G + b_7 M_{(p-G)} + b_8 M_p VPD + b_9 M_G VPD + b_{10} W_s VPD \qquad (5.8)$$

where

$\frac{\Delta T}{\Delta t}$ = rate of change of temperature ($°c hr^{-1}$)

$\frac{\Delta RH}{\Delta t}$ = rate of change of relative humidity ($\% hr^{-1}$)

$M_{(P-G)}$ = difference between pod and grain moisture content.

Other variables have been defined previously.

The parameter estimation procedure consists of statistical estimation using stepwise addition of variables (Rafter and Ruble, 1969) to allow for the large number of variables and to avoid the possibility of singularity problems. The stepwise deletion of variables (Rafter and Ruble 1969) was also used to permit all variable combinations to account for the variation in the dependent variable. Since the selection of candidate variables for deletion is closely tied to the stopping criterion, the preset significance probability level was set at .005 for these models.

The simple correlation matrix for the variables in equations (5.7) and (5.8) is shown in Table 5.1. This table was developed with 1973 Seafarer data. The Sanilac simple correlation matrix was similar. When using 5.7 the prominent independent variables determined from stepwise regression were initial pod moisture content, rate of change of temperature °C, and difference between pod and grain moisture content evaporation rate. In (5.8) the independent variables were initial pod moisture content, vapor pressure deficit, difference between pod and grain moisture content, and evaporation rate. The coefficients of determination of both models were almost the same.

Table 5.1. Simple Correlation Between Variables from the 1973 Data.

Variables	M_p	M_G	$\frac{\Delta M_p}{\Delta t}$	$\frac{\Delta M_e}{\Delta t}$	$\frac{\Delta T}{\Delta t}$	$\frac{\Delta RH}{\Delta t}$	EVP	RAD	W_s	VPD	M_{P-G}	VPD M_p	VPD M_G	VPD W_s
M_p	1.0													
M_G	.75	1.0												
$\frac{\Delta M_p}{\Delta t}$	-.783	-.47	1.0											
$\frac{\Delta M_G}{\Delta t}$	-.486	-.716	.385	1.0										
$\frac{\Delta T}{\Delta t}$	.54	.123	-.599	-.175	1.0									
$\frac{\Delta RH}{\Delta t}$	-.47	-.118	.589	.149	-.855	1.0								
EVP	-.45	-.156	.145	.071	-.104	.074	1.0							
RAD	-.306	-.041	.103	-.074	-.025	.017	.78	1.0						
W_s	-.142	.173	.011	-.083	-.202	.17	.588	.44	1.0					
VPD	-.674	-.176	.46	.04	-.57	.48	.592	.45	.35	1.0				
M_{P-G}	.720	.08	-.633	.019	-.686	-.58	-.516	-.42	-.39	-.84	1.0			
VPD.M_p	-.50	.012	.31	-.055	-.46	.35	.602	.50	.40	.95	.77	1.0		
VPD.M_G	-.54	.011	.378	-.085	-.51	.42	.588	.46	.38	.97	-.84	.98	1.0	
VPD.W_s	-.58	-.07	.390	-.005	-.51	.46	.686	.52	.66	.9	-.81	.88	.90	1.0

The simple correlation among independent variables, R^2 to delete and significance level of each independent variable remaining in the equation were examined to determine if further deletion of variable was possible. This analysis indicated that rate of change of relative humidity, radiation, evaporation, wind velocity, vapor pressure deficit, and all interaction terms had no significant effect on the rate of change of moisture content. This analysis also revealed that pod drying rate can be predicted more accurately than grain drying rate.

With a limited number and range of observations for rate of change of pod and grain moisture content during 1973, it was felt that a more reliable model could be developed with more observations collected during the 1974 crop season.

Crop and environmental variables identified with 1973 data were applied to 1974 data to determine regression parameters. Higher-order terms were included, they were not found statistically significant. The range in variables for both varieties are shown in Appendix B, Table 1.

Pod Drying

The relationship corresponding to (5.6) for rate of change in pod moisture content of Seafarer and Sanilac varieties is as follows

$$\frac{\Delta M_p}{\Delta t} = b_1 M_p + b_2 \frac{\Delta T}{\Delta t} + b_3 M_{(p-G)} \qquad (5.9)$$

where

$\frac{\Delta M_p}{\Delta t}$ = rate of change in % pod moisture content

Other variables have been defined previously.
The regression coefficients and other statistics are shown in Table 5.2.

Pod moisture content can be obtained by substituting (5.9) in equation (5.4). Many times multiple regression equations contain a constant. The constants in these relationships were omitted only because the dependent variables must be zero if the independent variables are zero.

The value of R^2 and overall standard error of estimate (S.E.) for the two varieties in the above models suggest that there is a definite relationship between the dependent variable $(-\frac{\Delta M_p}{\Delta t})$ and independent variables (M_p, $\frac{\Delta T}{\Delta t}$ and $M_{(P-G)}$). In the models for both Seafarer and Sanilac, the initial pod moisture had the greatest effect on the rate of change of moisture content. Initial pod moisture content, rate of change of temperature $(\frac{\Delta T}{\Delta t})$, difference in pod and grain moisture content ($M_{(P-G)}$) were significant at the 95% level. From this we concluded that the effect of

Table 5.2. Parameter Values and Regression Statistics of the Model $\frac{\Delta M_p}{\Delta t} = b_1 M_p + b_2 \frac{\Delta T}{\Delta t} + b_3 M_{(p-G)}$.

Variety	b_i		s.e.[1]	R^2 Delete[2]	Sig. Level	Regression Statistics[3]
Seafarer	b_1	-0.067	0.003	.180	<.0005	R^2 = .753
	b_2	-0.227	0.049	.722	<.0005	$\bar{R}^2$ = .750
	b_3	-0.153	0.014	.570	<.0005	S.E. = .554
Sanilac	b_1	-0.056	.003	.178	<.0005	R^2 = .712
	b_2	-0.322	.045	.619	<.0005	$\bar{R}^2$ = .709
	b_3	-0.148	.016	.551	<.0005	S.E. = .554

[1]s.e. = standard error of regression coefficients, b_i.

[2]R^2 Delete = the R^2 which would be obtained if xi were deleted from the least squares equation and the equation recalculated.

[3]R^2 = multiple coefficient of determination

$\bar{R}^2$ = multiple coefficient of determination adjusted by degree of freedom.

S.E. = Overall standard error of estimate of complete equation.

initial moisture content was independent of the other drying variables. Thus the inclusion of initial pod moisture content was justified. This analysis shows that the linear model was adequate to describe the rate of change of pod moisture content of both Seafarer and Sanilac varieties under field crop conditions during the harvesting period.

The regression coefficient of Seafarer and Sanilac varieties were tested to see the independence of variables in the models by using 't' test. The test showed that initial moisture content ($M_p(t)$) and rate of change of temperature ($(\frac{\Delta T}{\Delta t})°Ch^{-1}$) were significant at the 95% level. However, difference of pod and grain moisture content ($M_{(P-G)}$) was not significant. This indicates that the moisture transfer phenomenon from pod to grain and from grain to pod is the same in both varieties.

Model Validation

The 1974 data were used to develop the models. 1973 data were then used to validate the models. The rate of change of moisture content for Seafarer and Sanilac was calculated using the observed value of $M_p(t)$, $\frac{\Delta T}{\Delta t}$ and $M_{(P-G)}$. The observed value $(\frac{\Delta M_p}{\Delta t})$ and calculated value $(\frac{\Delta M_p}{\Delta t})$ for Seafarer and Sanilac are shown in Figures 5.1 and 5.2, respectively. The R^2 calculated from observed and predicted value were .65 and .58 and variance S^2 were .43 and .64 for Seafarer and Sanilac, respectively. These statistics and figures indicate that the models for Seafarer and Sanilac were adequate to describe the rate of change of pod moisture content during 1973.

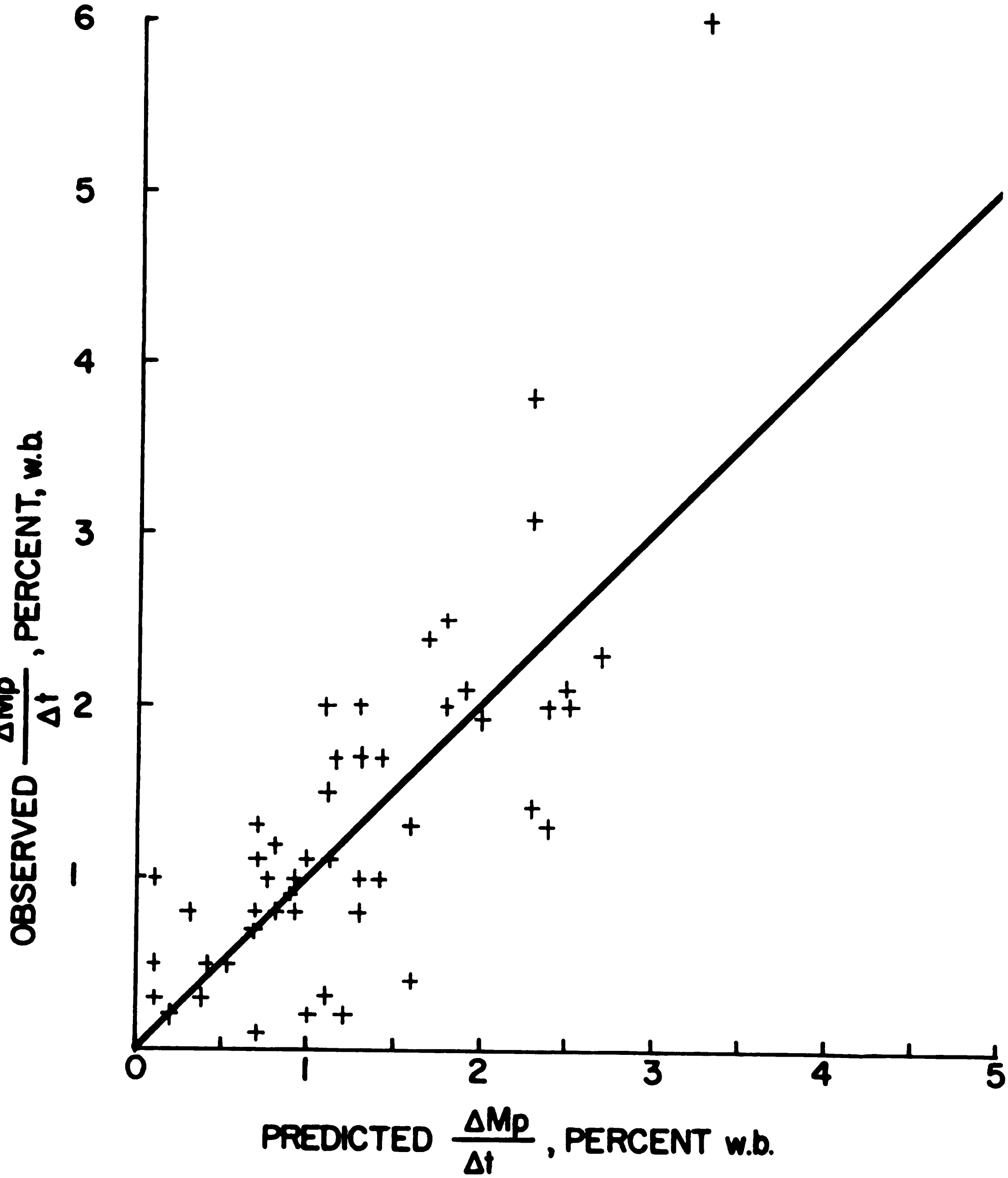

Figure 5.1. Observed rate of change of Seafarer pod moisture content for 1973 versus predicted moisture content from the relationship shown in Table 5.2.

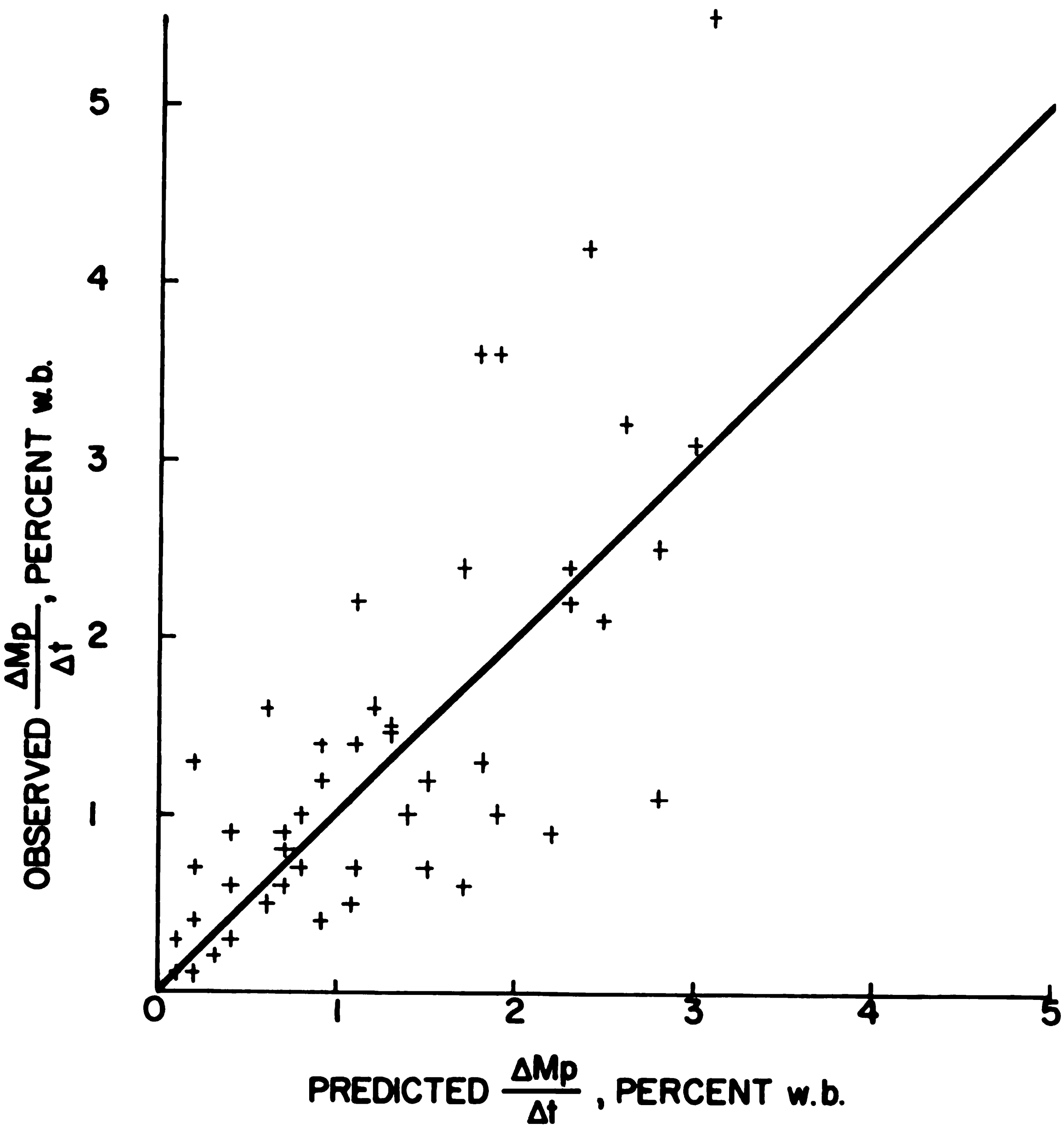

Figure 5.2. Observed rate of change of Sanilac pod moisture content for 1973 versus predicted moisture content from the relationship shown in Table 5.2.

Grain Drying

The same variables were considered in grain drying models. The estimated relationship for Seafarer and Sanilac is given below.

$$\frac{\Delta M_G}{\Delta t} = b_0 + b_1 M_G + b_2 \frac{\Delta T}{\Delta t} + b_3 M_{(P-G)} \quad (5.10)$$

The regression coefficient and statistics for rate of change of grain moisture content for Seafarer are shown in Table 5.3. On the basis of R^2 and other statistics, we conclude that the model is not adequate to describe grain drying of navy beans. Environmental variables used in this analysis had little direct effect on grain drying. It seems that grain drying of navy beans is a complex phenomenon, which must be described with a complex model.

Increase of the Pod and Grain Moisture Content Under Influence of Dew

Whole pod (pod and grain) moisture content can be increased under field conditions chiefly due to water uptake from precipitation and dew. Dew occurs on most nights during the harvest period in varying quantities. An approximate value for the influence of dew on pod and grain moisture content of the navy bean crop can be obtained if we could measure the dew duration and initial

Table 5.3. Parameter Values and Regression Statistics of the Model $\frac{\Delta M_G}{\Delta t} = b_0 + b_1 M_G + b_2 \frac{\Delta T}{2\Delta t} + b_3 M_{(P-G)}$.

Variety		b_i	s.e.	R^2 Delete	Sig. Level	Regression Statistics		
Seafarer	b_0	.352	.141	.2564	.013	R^2	=	.2824
	b_1	-.044	.007	.1253	<.0005	$\bar{R}^2$	=	.2699
	b_2	-.065	.031	.2644	.039	S.E.	=	.33
	b_3	-.019	.009	.264	.037			
Sanilac	b_0	.064	.14	.12285	.649	R^2	=	.1240
	b_1	-.024	.007	.06199	.001	$\bar{R}^2$	=	.1071
	b_2	-.091	.026	.05489	.001	S.E.	=	.303
	b_3	.011	.01	.11708	.270			

moisture contents of pod and grain as the main factors affecting the rate of uptake of water.

During the experimental period, pod and grain moisture contents were measured from 9 a.m. to 5 p.m. For the purpose of this study, the 5 p.m. moisture content was taken as the initial moisture content and 9 a.m. of the following day was taken as the final moisture content. An exponential model with moisture ratio was fitted and constants were determined for pod and grain. The relationship for the pod can be expressed as

$$\frac{M_{pf}}{M_{pi}} = a\, e^{bt} \qquad (5.11)$$

where

M_{pf} = the final % pod moisture content

M_{pi} = the initial % pod moisture content

t = the length of dew hours

a and b = constants depending on type of pod

The influence of dew on both varieties was assumed to be the same. The coefficients are based on 1973 year data only since we were unable to obtain dew data for 1974.

The parameters a and b were estimated by least squares exponential fit. The relationship was determined from 1973 data describing increase in pod moisture content due to dew duration is

$$\frac{M_{pf}}{M_{pi}} = .68 \exp (.11t) \qquad (5.12)$$

The coefficient of determination for this relationship was .80.

The exponential model for grain was described as

$$\frac{M_{Gf}}{M_{Gi}} = ab^{t} \qquad (5.13)$$

where

M_{Gf} = the final % grain moisture content

M_{Gi} = the initial % grain moisture content

a and b = constants depending on type of grain

The parameters a and be were estimated by a least squares exponential fit. The model developed from 1973 data describing increase in grain moisture content due to dew duration is

$$\frac{M_{Gf}}{M_{Gi}} = (.74)\ (1.06)^{t} \tag{5.14}$$

The coefficient of determination for this model was .65.

Figures 5.3 and 5.4 show the relationship between observed value and predicted value of dew duration and moisture ratio. There are a few points which may indicate observational error. However, residual analysis of pod and grain moisture showed a biased pattern. Thus the exponential model may be misleading. A linear relationship was then established for pod and grain moisture. The linear model developed from 1973 data to describe increase in pod moisture content due to dew duration is

$$\frac{M_{pf}}{M_{pi}} = .056 + .196t \tag{5.15}$$

The coefficient of determination for this relationship was .77.

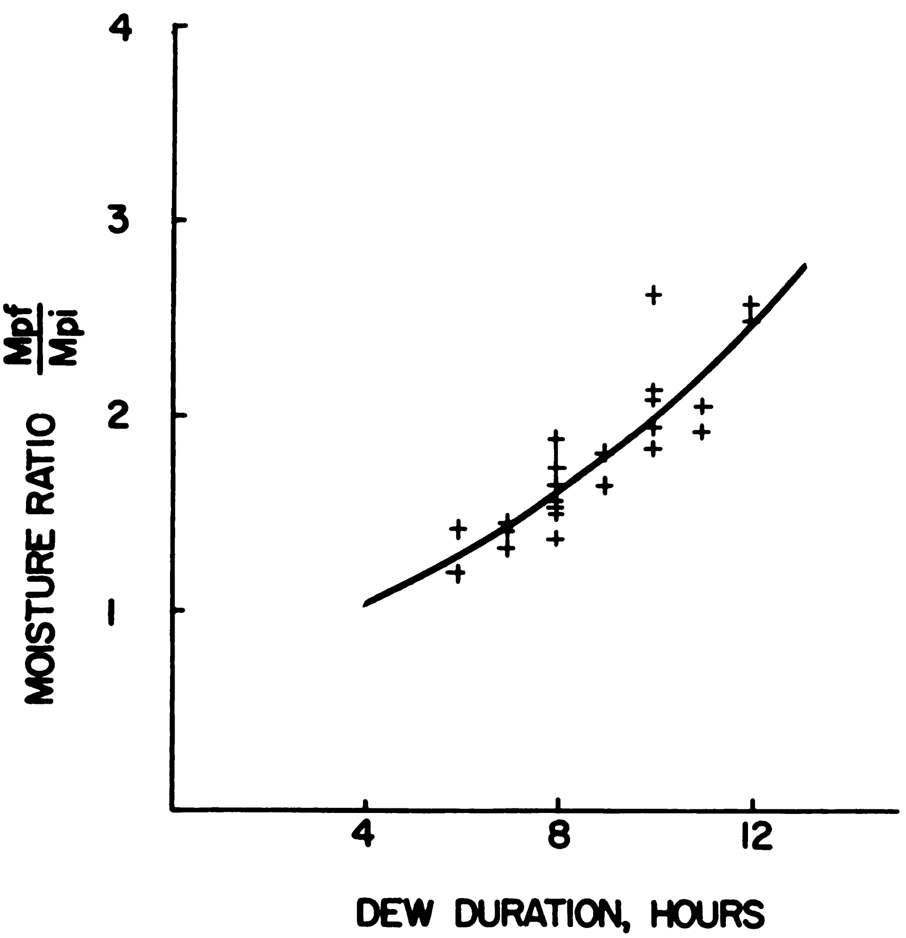

Figure 5.3. Relationship between moisture ratio of Seafarer and Sanilac pods and dew duration from equation 5.12.

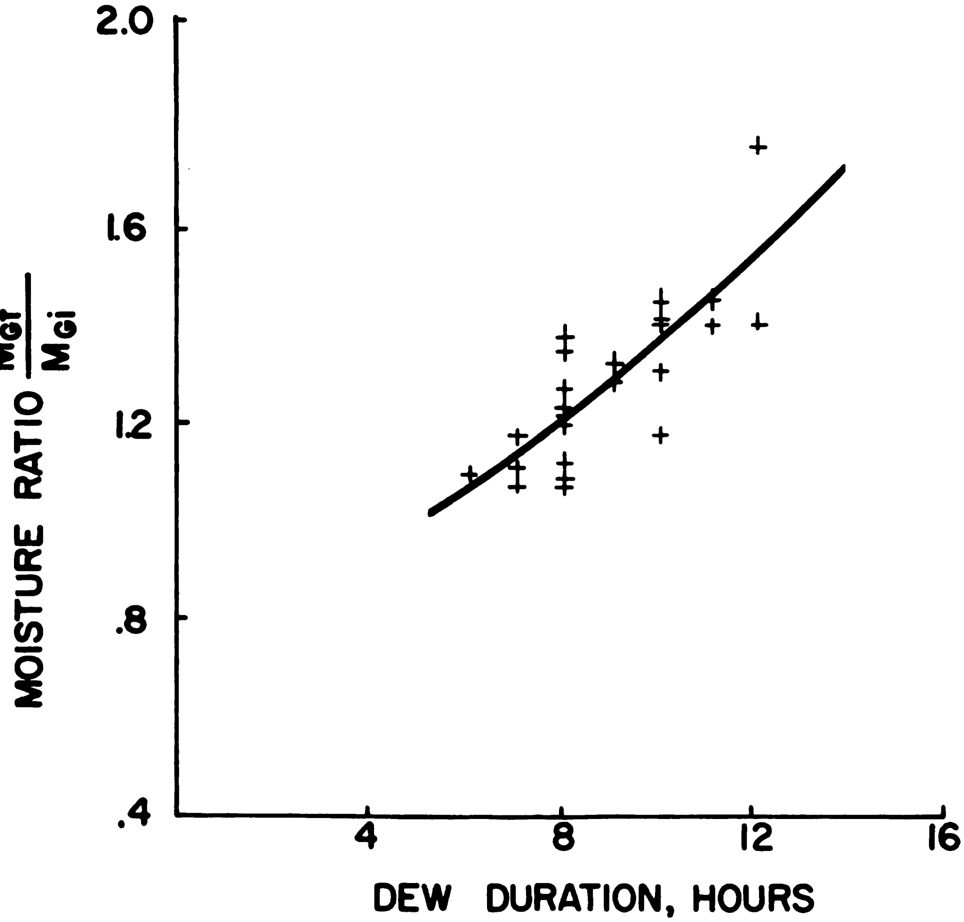

Figure 5.4. Relationship between moisture ratio of Seafarer and Sanilac grains and dew duration from equation 5.14.

The linear relationship describing increase in grain moisture content due to dew duration is

$$\frac{M_{Gf}}{M_{Gi}} = .602 + .079t \qquad (5.16)$$

with a coefficient of determination of .62.

The residual analysis did not show a biased pattern but almost a uniform distribution of residuals about zero. On the basis of this analysis the linear models (5.15) and (5.16) may be used to predict the increase in pod and grain moisture content under the influence of dew. These models are valid only for dew duration of 6 to 12 hours (Figures 5.5, 5.6). Since periods shorter than 6 hours and longer than 12 hours were not observed in 1973, further study is necessary to extend the range of dew duration effect on pod and grain moisture content.

Relationship Between the Pod and Grain Moisture Content

Pod moisture content and grain moisture content follow similar patterns for a large part of the day. This indicates that a relationship can probably be determined between the kernel and pod moisture content. The relationship for Seafarer and Sanilac pod and grain moisture content is of the form

$$M_G = b_0 + b_1 M_P \qquad (5.17)$$

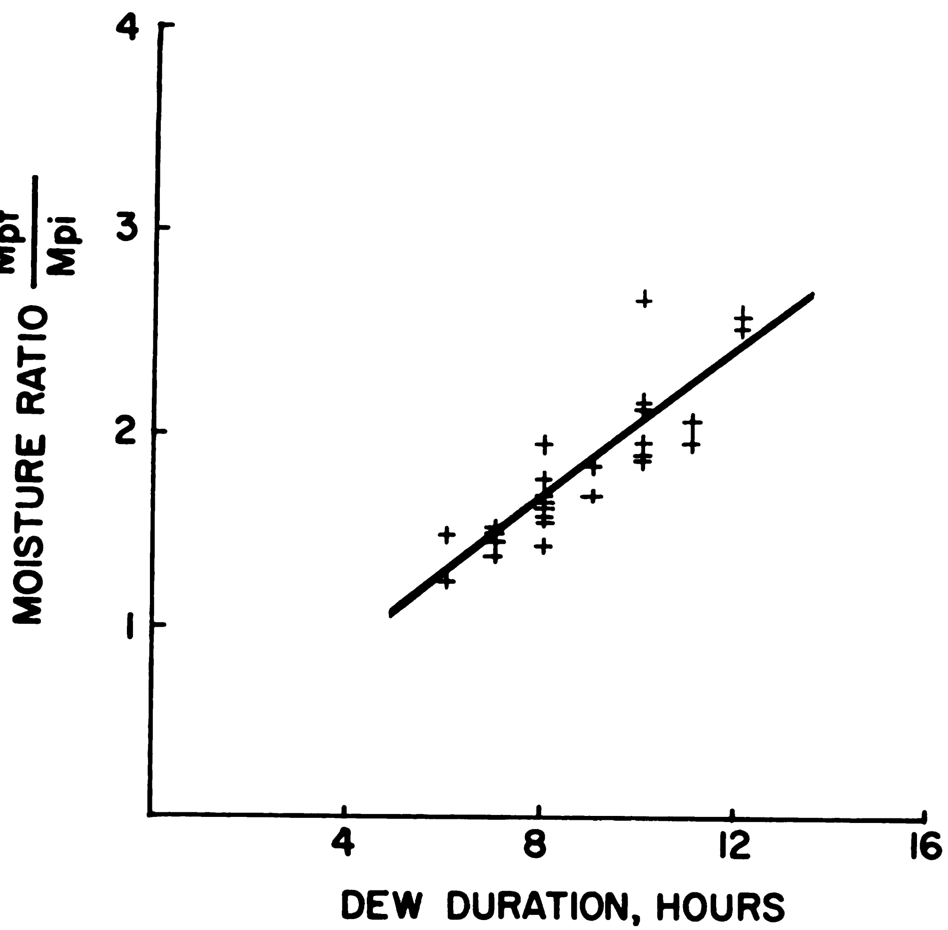

Figure 5.5. Relationship between moisture ratio of Seafarer and Sanilac pods and dew duration from equation 5.15.

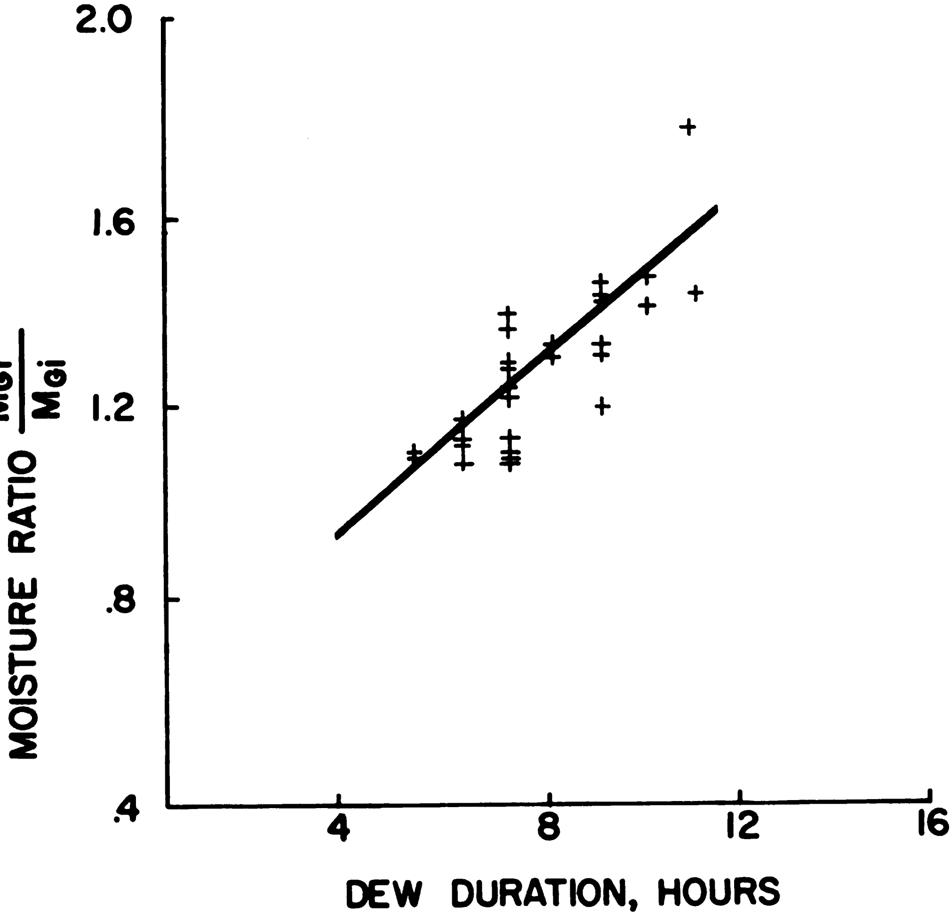

Figure 5.6. Relationship between moisture ratio of Seafarer and Sanilac grains and dew duration from equation 5.16.

The regression coefficients and other statistics are shown in Table 5.4.

Table 5.4. Parameter Values and Regression Statistics of the Model $M_G = b_0 + b_1 M_P$.

Variety		b_i	s.e.	R^2 Delete	Sig. Level	Regression Statistics
Seafarer	b_0	8.41	.543	.2018	<.0005	R^2 = .664
	b_1	0.540	.029	0.00	<.0005	$\bar{R}^2$ = .662
						S.E. = 2.10
Sanilac	b_0	8.04	.58	.2771	<.0005	R^2 = .675
	b_1	0.57	.032	0.00	<.0005	$\bar{R}^2$ = .673
						S.E. = 1.97

These models are based on data from 1974. The models were used to predict grain moisture content of Seafarer and Sanilac varieties for 1973. Figures 5.7 and 5.8 show the predicted versus observed values of Seafarer and Sanilac grain moisture content. The R^2 calculated from observed and predicted values were .54 and .71 and variance S^2 were 3.0 and 4.0 for Seafarer and Sanilac varieties, respectively. From these figures it is apparent that a few points are far from the actual value which may indicate observational error. In fact,

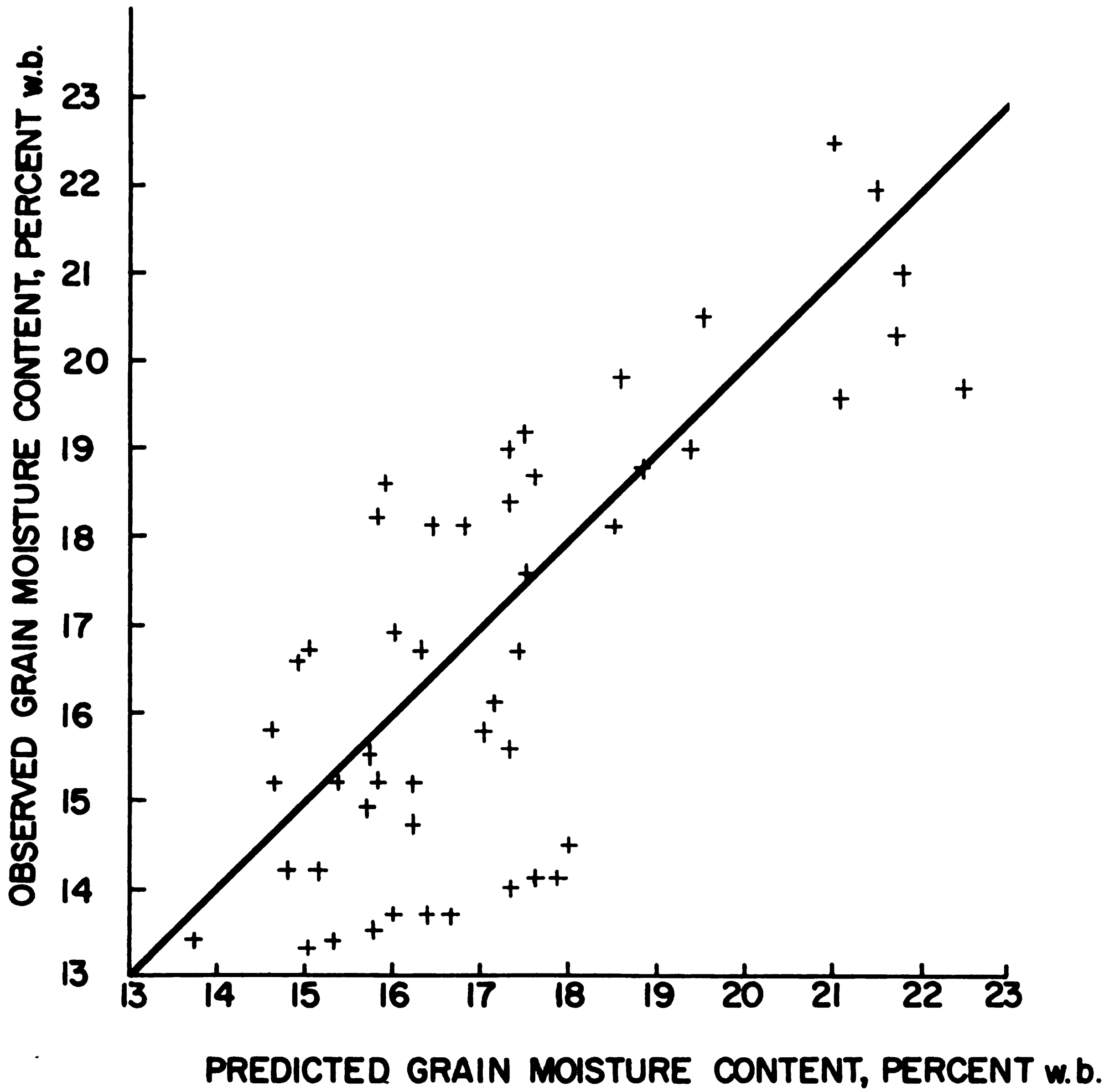

Figure 5.7. Observed Seafarer grain moisture content for 1973 versus predicted grain moisture content from the relationship shown in Table 5.4.

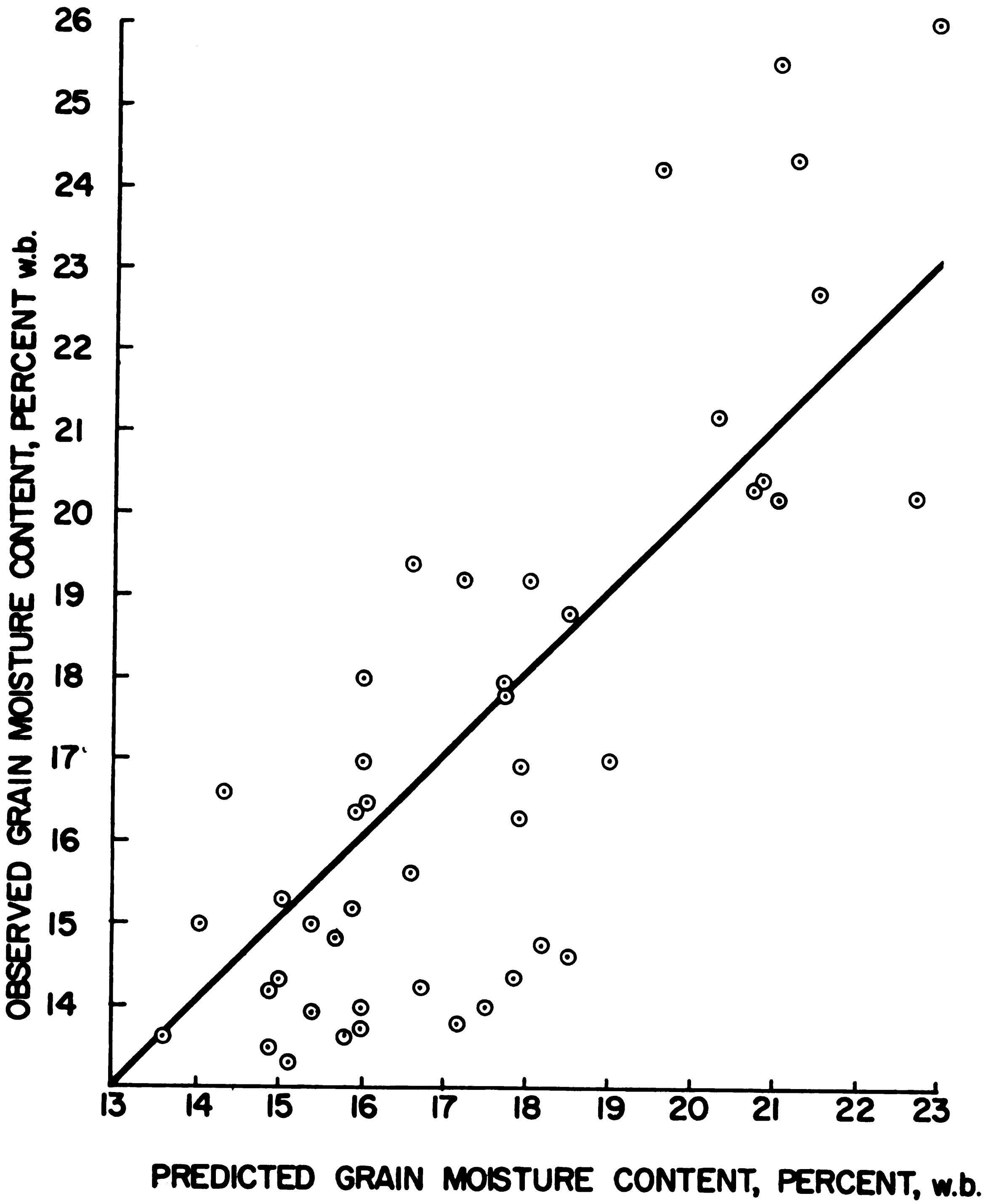

Figure 5.8. Observed Sanilac grain moisture content for 1973 versus predicted grain moisture content from the relationship shown in Table 5.4.

deletion of these points for Seafarer increases the R^2 to .71 and changes the S^2 to 2.08. In the absence of a grain drying model, this relationship could be used to predict grain moisture content at any time during the harvest period for Seafarer and Sanilac varieties.

Conclusion

Rate of change of pod moisture content can be predicted. The model developed above is associated with 71 and 75 percent of the variance in the dependent variables for Sanilac and Seafarer varieties, respectively.

The increase in pod and grain moisture content can be estimated provided dew duration is known but very poorly.

The relationship of grain and pod moisture content may be used to predict grain moisture content in the absence of a grain drying model.

VI. THRESHING LOSS AND DAMAGE

Threshing losses depend upon threshing action. Threshing action can be so severe that even though all the grain is removed from the pod it may cause considerable damage to kernels. During threshing of grain, the kernels are subjected to mechanical impact which can cause stress cracks and breakage. This deteriorates the product quality.

Grain quality is a measure of the economic value which both the buyer and seller understand. Quality of commercial edible beans is important for storage. Damage to kernels can also reduce germination of seeds. Thus a compromise must be reached between cylinder speed and concave settings in order to have maximum threshing and minimum damage. Emphasis is given to splits and crushed cotyledons but not to checked seed coats in the Michigan Standards for dry edible beans (1959).

Our primary objective was to formulate a model to predict the effect of pod and grain moisture content on threshing loss and damage. This will give a mechanism to study the effect of various levels of moisture content and cylinder speed upon loss and damage. This will give us enough information to design control strategies for maximizing harvest yield and minimizing damage.

Literature Review

McDow (1949) reported a splitting effect on pea beans, it may be caused by poor machine adjustments and/or low grain moisture content. Damage to beans (and to other crops) could be reduced by avoiding high cylinder speed even at fairly low moisture content (King and Riddolls 1960 and 1962, Tabiszewski 1968). Impact velocity, moisture content, temperature and size of bean each has its effect on damage (Perry 1959, Hoki and Pickett 1972). Hoki and Pickett reported that damage to only the seed coat increased from 5% at an impact velocity of 10.6 meter per second to over 60% at a velocity of 17.78 meter per second. Specific examples of grain moisture content and cylinder speed effect on damage are shown in Table 6.1. Bilanski (1966) indicated similar results regarding the effect of bean moisture content on susceptibility of soybeans to mechanical damage. Narayan (1969) reported optimum moisture content for minimum checking of navy bean seed coats in the range of 13.4 to 15.6% grain moisture content. According to Pickett (1972), the ideal conditions for harvest are when bean moisture content is between 17 and 20% and pod moisture content is as low as possible, preferably below 12%. Koning (1973) has reported that threshing of wheat is always better when the moisture

Table 6.1. Effect of Grain Moisture Content and Speed on Damage of Bean.

Grain Moisture Content	Cylinder Speed	Total Damage (%)	References
16.5	-	low	McDow 1949
low	-	20.0	Toole *et al.* 1951
15.2	-	7.2	
9.7	-	70.3	Solorio 1957
13.0	900 rpm	minimal	Green 1966 for soybean
11.0	200 rpm	16.3	Asrar 1967
18.9	230 rpm	1.4	
15.3, 18.5	7.62 meter/sec	2.5, 1.15	Pickett 1972
	10.16 "	3.0, 1.75	
	12.7 "	3.5, 1.8	
	15.24 "	8.0, 2.6	

content of the kernel is lower.

Equipment and Procedure

The moisture content of pod and grain is a very important factor in our calculations. The method of determining pod and grain moisture content was

discussed in Chapter III. It is also very important to know the moisture changes during the daytime harvesting period. This was discussed in Chapter V.

In order to determine the limits on pod and grain moisture for threshing (after the bean grain moisture is below 25%) threshability tests were conducted at 11 a.m., 1 p.m. and 3 p.m. An Allis Chalmers Model 66 all crop harvester was used for this test. Cylinder concave clearance of 9.52 mm was kept throughout the test. Two cylinder speeds were used, 10.16 m sec^{-1} (2,000 feet per minute) and 15.24 m sec^{-1} (3,000 feet per minute).

For each test 100 plants were pulled and kept in canvas bags until threshed. These sample bags with bean plants were weighed, whole pods were taken to determine pod and grain moisture content and then the beans were threshed. Threshed grain from the sample was weighed and recorded. Some of the threshed grain rolled down together with the straw at the rear of the straw walker and was collected along with the straw in a bag. This free grain was separated from the straw, weighed and recorded.

Some grain was not threshed out from the straw. In order to thresh the remaining grain from the straw, the combine was operated at a higher speed and the material rerun through the combine. This grain was collected separately, weighed and recorded. To make sure that all the grain was threshed out, the straw was fed through twice and was examined carefully before discarding. Grain obtained during rethreshing was used to determine the percent of unthreshed loss (threshing loss) as:

$$\text{Percent unthreshed loss (threshing loss)} = \frac{\text{weight of unthreshed grain}}{\text{weight of total grain}}$$

Total grain = threshed grain collected + threshed free grain collected from straw + unthreshed grain

Sub-samples of approximately 150 gms were taken from the threshed grain to determine mechanical damage. We were interested only in splits, smashed, cuts and cracks in cotyledons. A sieve was used to separate split and broken beans. Cracked and bruised beans were observed carefully and taken out manually. These were weighed together and were used to determine percent of split grain.

Modeling Threshing Loss and Damage

Threshing Loss (unthreshed loss)

It was stated above that threshing loss and damage are primarily functions of moisture content (pod and grain) and cylinder speed. Besides these two factors, date of maturity (Hunt and Harper 1967) and time of day (Koning 1973) may affect threshing loss and damage. Pickett (1972) pointed out that threshability of beans is more likely dependent on pod moisture than on grain moisture content.

The unthreshed loss was postulated to take the form

$$U_L = F[M_P, M_G, S] \tag{6.1}$$

where

U_L = % unthreshed loss

M_P = % pod moisture content

M_G = % grain moisture content

S = Cylinder speed $m.sec^{-1}$

Two cylinder speeds, 10.16 $m.sec^{-1}$ and 15.24 $m.sec^{-1}$, were used in this study.

The method of stepwise addition and deletion (Rafter and Ruble 1969, Draper and Smith 1966) of variables was used to allow for the large number of variables and to permit all variable combinations to account for the variation in the dependent variables. A significance probability level of 0.005 was used in the stepwise regression analysis. The resulting regression equations were carefully examined. The magnitude of the coefficient of each explanatory variable, simple correlations with each variable and its sign were of particular interest. The standard errors of the regression coefficients, the magnitude of the coefficient of determination (R^2) and overall standard error of estimate (S.E.) for this relationship were given particular attention. Significance level of each explanatory variable and R^2 necessary to delete were examined to see that unwanted variables were not in the model. Finally with the remaining independent variables least squares equations were estimated. The estimated relationships corresponding to 6.1 for unthreshed loss are as follows.

$$U_L = b_0 + b_1 M_p \tag{6.2}$$

where

b_0 and b_1 are constants (regression coefficients) depending on crop and cylinder speed.

The corresponding regression coefficients, their standard error, R^2, and overall standard error of estimate for Seafarer and Sanilac for each speed are shown in Table 6.2 The maximum, minimum, mean and standard deviation of all variables are shown in Appendix C, Table 1.

In the final equation (6.2) only pod moisture content has appeared. Grain moisture content does not affect threshability. The high value of R^2 and low value of standard error of estimate indicate that there is close relationship between pod moisture content and unthreshed loss for each cylinder speed and variety.

The unthreshed loss models for both varieties and speeds indicate that an increase in pod moisture content increases unthreshed loss. This effect is shown graphically in Figures 6.1 and 6.2 for cylinder speeds of 10.16 and 15.24 $m.sec^{-1}$ for Seafarer and Sanilac, respectively. These models demonstrate that the Seafarer

Table 6.2. Parameter Values of the Model, $U_L = b_0 + b_1 M_p$.

Variety	Cylinder Speed in $m.sec^{-1}$	b_0	s.e.	R^2 Delete	Sig. Level	b_1	s.e.	R^2 Delete	Sig. Level	R^2	$\bar{R}^2$	Overall S.E. of estimate
Seafarer	10.16	-40.47	2.32	.27	<.0005	3.37	.160	-0.00	<.0005	.90	.90	3.75
	15.24	-10.16	.76	.46	<.0005	.85	.04	.00	<.0005	.92	.92	1.01
Sanilac	10.16	-27.11	1.93	.29	<.0005	2.27	.13	- .00	<.0005	.88	.87	2.99
	15.24	- 9.3	1.20	.43	<.0005	.76	.07	-0.00	<.0005	.82	.82	1.42

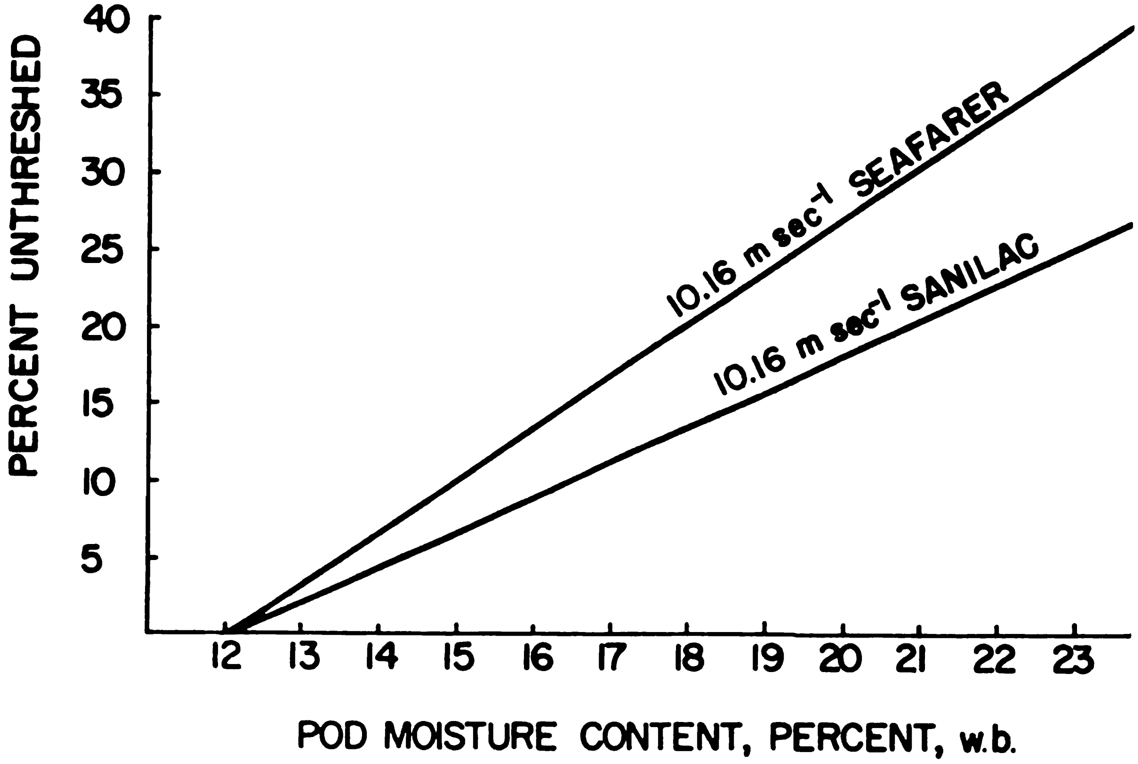

Figure 6.1. Effect of pod moisture content on unthreshed loss of Seafarer and Sanilac dry beans for a cylinder speed of 10.16 m sec^{-1}.

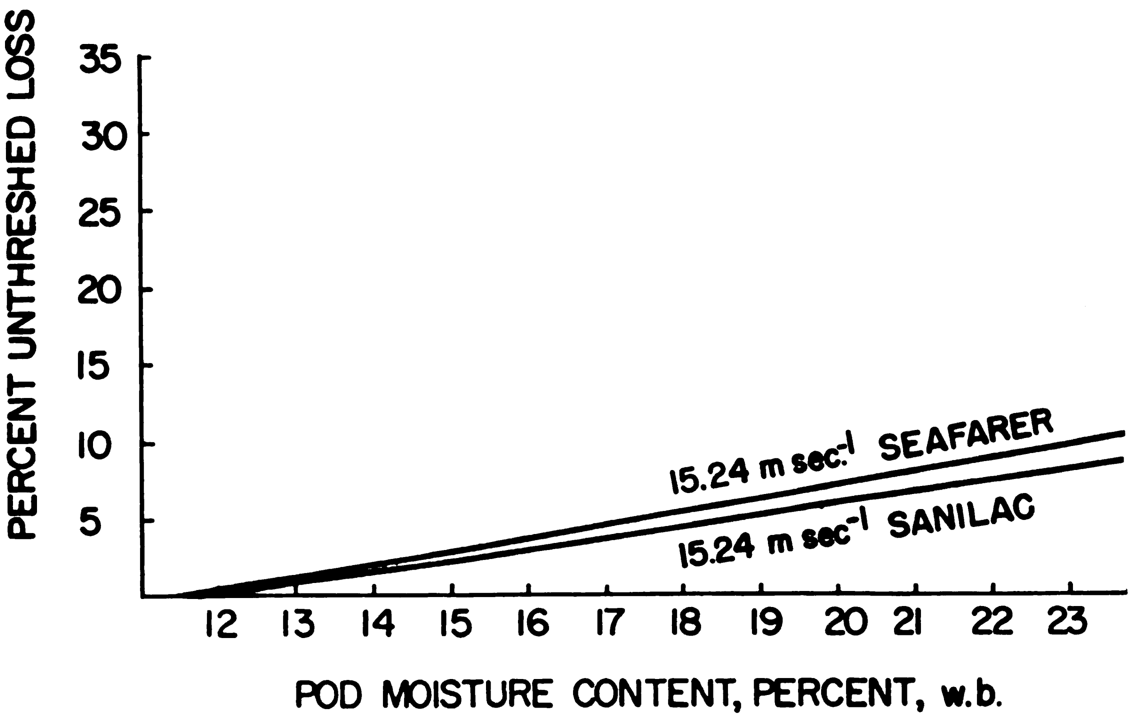

Figure 6.2. Effect of pod moisture content on unthreshed loss of Seafarer and Sanilac dry beans for a cylinder speed of 15.24 m sec^{-1}.

variety is a little harder to thresh than is Sanilac. This difference is probably due to physiological characteristics of the crop. This analysis also indicated that 82% to 92% of the variance in unthreshed loss was associated with the linear model.

Test of Independence of Varieties

In the preceding analysis we assumed that the variety models were truly independent. The following analysis of the regression coefficients show that each variety does indeed have its own threshing characteristics.

To test the independence of the varieties the 't' test was used. The test statistic is given by

$$t = (b_1 - b_1')/S_{b_1}$$

where

b_1 is the regression coefficient of Seafarer variety

b_1' is the regression coefficient of Sanilac variety

S_{b_1} is the standard error of b_1

The hypothesis was

$H_o: B_1 = B_1'$ i.e. the two varieties are the same with respect to threshability.

$H_1 : B_1 \neq B_1'$

The hypothesis H_o would then be rejected if

$$t \geq t_{(1 - \alpha/2)(n-2)}$$

or if $t \leq -t_{(1 - \alpha/2)(n-2)}$

In our case for testing this hypothesis $\alpha = .1$

Table 6.3 contains the results of these tests. It is apparent from the table that at the .1 significance level, the constant and pod moisture content are highly significant at the 10.16 $m.sec^{-1}$ cylinder speed, whereas the constant b_0, at the 15.24 $m\ sec^{-1}$ cylinder speed was not significant. However, it is significant at the .2 significance level.

Table 6.3. Calculated and Critical 't' Values for Testing Independence of Varieties.

Cylinder Speed $m.sec^{-1}$	Variable	$t = \frac{(b_1 - b_i)}{S_{b_1}}$	α	Critical 't'
10.16	b_0	5.751	.1	1.68
	M_P	6.873	.1	1.68
15.24	b_0	1.349	.1	1.697
	M_P	2.162	.1	1.697

Damage

We discussed above that bean damage during harvesting operations is affected by cylinder speed and grain moisture content. An evaluation of bean damage during harvesting was conducted by Judah (1970). He reported that 2.84% of the beans were mechanically damaged. However, mechanical damage ranged from .5 to 13% with over half of the damage due to seed coat checks. It seems that higher levels of damage are due to poor adjustment of the machine and crop conditions. We have used Pickett's (1971) data to develop a model for total damage, split and checked beans. In the split model we considered splits, smashed and cut beans. The checks damage includes those with cracks in the seed coat. Total damage is the sum of the splits and checks.

The damage was hypothesized to take form

$$D = F[M_G, S] \qquad (6.3)$$

where

D = % damage

S = cylinder speed ($m.sec^{-1}$)

M_G = % grain moisture content

Stepwise regression was used to determine how these variables affected damage. On the basis of simple correlations and R^2 to delete the interaction term between grain moisture and cylinder speed (M_G,S) was deleted from the relationship. The first-order terms alone accounted for the major portion of the variance as can be seen in the following analysis. The estimated relationship corresponding to (6.3) for total damage (D_t), splits (D_s) and checked bean (D_c) were determined as follows:

$$D = b_0 + b_1 S + b_2 M_G \qquad (6.4)$$

The corresponding regression coefficient, their standard error, coefficient of determination and overall standard error of estimate are shown in Table 6.4.

These models for total damage, splits and checked bean were determined for the Sanilac variety. The data for Seafarer were not available.

Although R^2 for these damage models may be adequate, a transformation in dependent variables seemed in order after careful examination of the data. We performed a log transformation of the dependent variable. The resulting transformed model involved the same terms, S and M_G. The model is

$$\text{Ln}\,(D) = b_0 + b_1 S + b_2 M_G \qquad (6.5)$$

or

$$D = \exp(b_0 + b_1 S + b_2 M_G)$$

Table 6.4. Parameter Values and Regression Statistics for Sanilac Damage Model $D = b_0 + b_1S + b_2M_G$ Where S is Cylinder Speed in m sec^{-1} and M_G is % Grain Moisture Content.

Damage (D)		b_i	s.e.	R^2 Delete	Sig. Level	Regression Statistics
Total	b_0	14.44	4.67	.4842	.009	R^2 = .7025
Damage	b_1	0.64	0.17	.4002	.003	$\bar{R}^2$ = .6568
(D_t)	b_2	-1.08	0.26	.3023	.001	S.E. = 2.99
Splits	b_0	8.47	3.11	.33007	.017	R^2 = .5738
(D_s)	b_1	0.27	0.12	.37195	.028	$\bar{R}^2$ = .5082
	b_2	-0.58	0.17	.20186	.005	S.E. = 1.31
Checked	b_0	6.05	1.78	.63952	.005	R^2 = .8090
Bean	b_1	0.35	0.067	.39705	<.0005	$\bar{R}^2$ = .7796
(D_c)	b_2	-0.51	0.098	.41193	<.0005	S.E. = .76

The regression coefficients, their standard error R^2 deletes, R^2 and overall standard error of estimate for total damage, split and checked bean are shown in Table 6.5.

R^2_{cal} and $\bar{R}^2_{cal}$ for the exponential model were calculated after transforming the estimated value of the dependent variable from this model for total damage,

Table 6.5. Parameter Values and Regression Statistics for Sanilac Damage Model $D = \exp(b_0 + b_1 S + b_2 M_G)$ Where S is Cylinder Speed m.sec^{-1} and M_G is % Grain Moisture Content.

Damage		b_1	s.e.	R^2 Delete	Sig. Level	Regression Statistics
Total	b_0	3.56	.50	.514	<.0005	R^2 = .894, R^2_{cal} = .850
Damage	b_1	0.13	.02	.546	<.0005	$\bar{R}^2$ = .884, $\bar{R}^2_{cal}$ = .827
(D_t)	b_2	-0.23	.03	.353	<.0005	S.E.= .21, S.E.$_{cal}$= 1.41
Splits	b_0	2.89	0.8	.367	.003	R^2 = .685, R^2_{cal} = .644
(D_s)	b_1	0.09	0.03	.483	.013	$\bar{R}^2$ = .637, $\bar{R}^2_{cal}$ = .589
	b_2	-0.20	0.04	.202	.001	S.E.= .34, S.E.$_{cal}$= 1.21
Checked	b_0	3.16	.61	.800	<.0005	R^2 = .934, R^2_{cal} = .959
Bean	b_1	0.21	.02	.490	<.0005	$\bar{R}^2$ = .924, $\bar{R}^2_{cal}$ = .952
(D_c)	b_2	-0.33	.03	.443	<.0005	S.E.= .26, S.E.$_{cal}$= .35

split and check. These values of R^2_{cal} and $\bar{R}^2_{cal}$ are better then the linear model's R^2 and $\bar{R}^2$ value. The exponential model is associated with 90% of the variance in total damage, 68% of the variance in splits and 93% of the variance in checks, whereas the linear model is associated with only 70, 57 and 80% of the variance, respectively. Therefore we are accepting the exponential models given by equation (6.5) as being more representative. The minimum, maximum, mean and standard deviations for total damage, split and check are shown in Appendix C, Table 2.

The residuals of the linear and transformed exponential models are shown in Tables 6.6 through 6.8 for total damage, split and check. There is no marked difference in the nature of the residuals of the two models which again gives strength for accepting the exponential model based upon the much better R^2 values.

The high value of R^2 and low value of overall standard deviation indicate that damage to bean grain can be predicted quite accurately at any cylinder speed and grain moisture content. In the model the effect of cylinder speed is always positive. This means that increase in cylinder speed will increase damage. The moisture content coefficient is always negative indicating that increase in moisture content will decrease damage. Figures 6.3, 6.4 and 6.5 are based on the exponential model. They show the effect of grain moisture content on total damage, split and check for four different cylinder speeds.

Figures 6.6 and 6.7 show the measured value of splits for Sanilac and Seafarer varieties together with calculated values based on the exponential model for cylinder speeds of 10.16 and 15.24, respectively. The exponential model for splits looks to be close to

Table 6.6. Comparison of Residuals for Total Damage of Linear and Exponential Model. Residual from Exponential Model has been Transformed for Direct Comparison with Linear Model.

Grain Moisture Content	Model	Cylinder Speed m sec^{-1}			
		7.62	10.16	12.7	15.24
13.6	Linear	-.90	-2.12	.27	5.05
	Exponential	-.14	-1.2	.76	4.34
15.3	Linear	-.27	-1.38	-2.50	.39
	Exponential	-.08	- .57	-1.43	1.18
17.6	Linear	1.72	0.60	- .71	-.83
	Exponential	.5	.42	- .08	.32
18.5	Linear	1.99	0.87	- .64	-1.56
	Exponential	-.02	.06	- .53	-.62

the measured values of splits. Though the model somewhat overestimates at higher moisture contents, expecially at the 10.16 m.sec^{-1} cylinder speed, it underestimates at low moisture content when the cylinder speed is 15.24 m.sec^{-1}. These differences from measured value to calculated values are not significant. The split model represented by equation (6.5) may be used to predict the splits. The measured value for splits of Seafarer are also shown in Figures 6.6 and 6.7. The splits follow the same pattern as for Sanilac.

Table 6.7. Comparison of Residuals for Split of Linear and Exponential Model. Residual from Exponential Model has been Transformed for Direct Comparison with Linear Model.

Grain Moisture Content	Model	Cylinder Speed $m.sec^{-1}$ 7.62	10.16	12.7	15.24
13.6	Linear	-.41	-1.54	.73	3.30
	Exponential	0.0	-.98	1.28	3.67
15.3	Linear	-.33	-.71	-2.04	-.32
	Exponential	-.21	-.28	-1.41	.39
17.6	Linear	1.10	.53	-.16	-.69
	Exponential	.51	.39	.11	-.11
18.5	Linear	1.02	.44	-.14	-.77
	Exponential	.09	.01	-.12	-.36

The pod moisture content and predicted grain moisture content were used to develop Tables 6.9 and 6.10 for threshing loss and damage from the equations (5.17), (6.2) and (6.5). These tables can be used as a guide for selecting cylinder speeds in order to achieve maximum threshing and minimum damage. This will allow one to maximize economic return from the crop at the existing price structure.

Table 6.8. Comparison of Residuals for Check of Linear and Exponential Model. Residuals from Exponential Model has been Transformed for Direct Comparison with Linear Model.

Grain Moisture Content	Model	Cylinder Speed $m.sec^{-1}$			
		7.62	10.16	12.70	15.24
13.6	Linear	-.41	-1.54	.73	3.30
	Exponential	0.00	-.14	-.76	-.47
15.3	Linear	-.33	-.71	-2.04	-.32
	Exponential	.26	-.12	.06	.52
17.6	Linear	1.10	.52	-.16	-.69
	Exponential	.06	.16	-.02	-.54
18.5	Linear	1.02	.44	-.14	-.77
	Exponential	-.1	.16	-.25	-.05

Conclusion

Unthreshed loss models were determined for Seafarer and Sanilac varieties with 1974 data and were validated with 1973 data. The analysis indicated that 82 to 92% of the variance in unthreshed loss was accounted for in the linear model. Pod moisture content and cylinder speed were the major variables in the model. The two varieties Seafarer and Sanilac are different in threshing

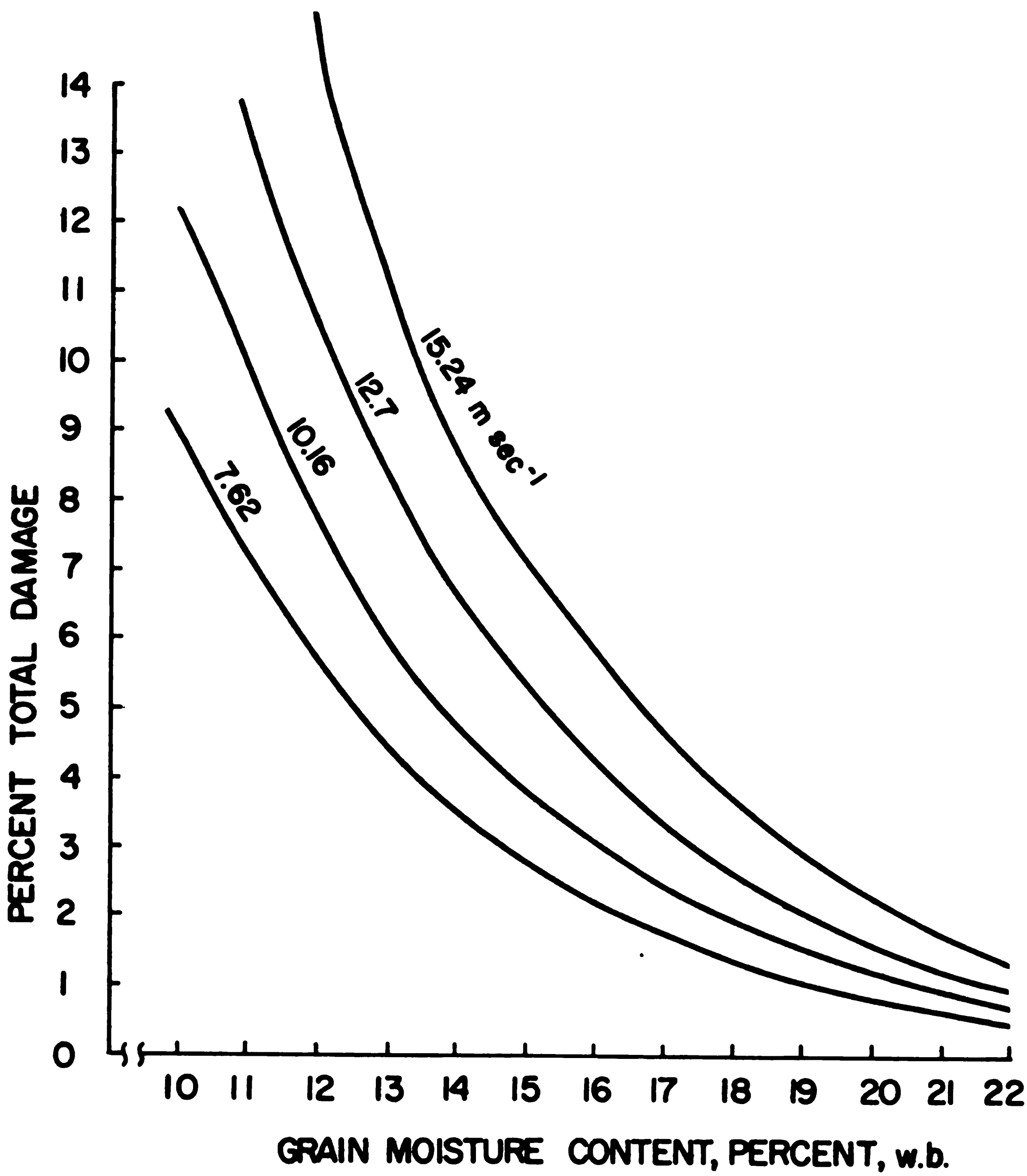

Figure 6.3. Effect of grain moisture content and cylinder speed upon percent total damage to Sanilac dry beans from the relationship shown in Table 6.5.

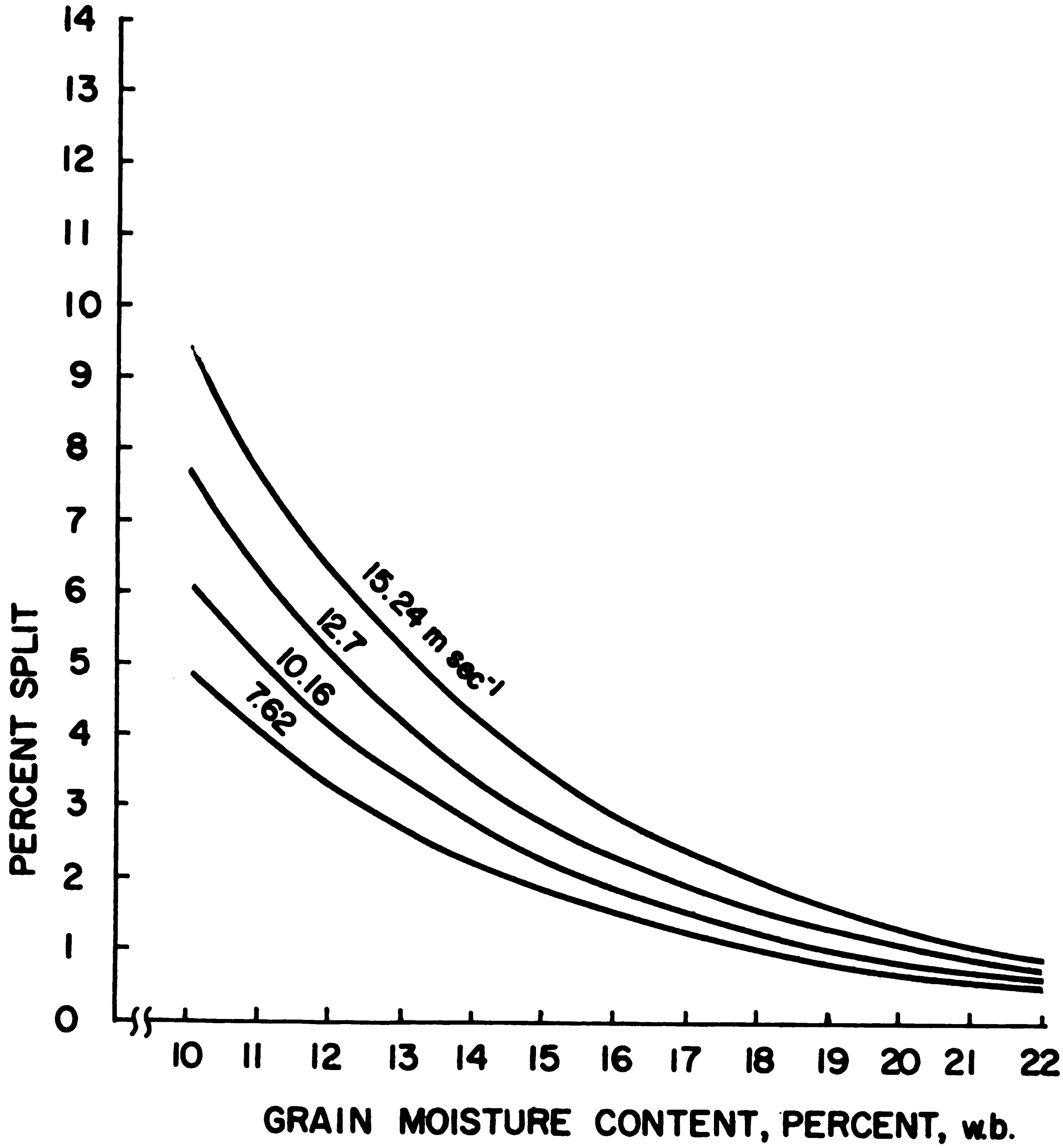

Figure 6.4. Effect of grain moisture content and cylinder speed upon percent splits in Sanilac dry beans from the relationship shown in Table 6.5.

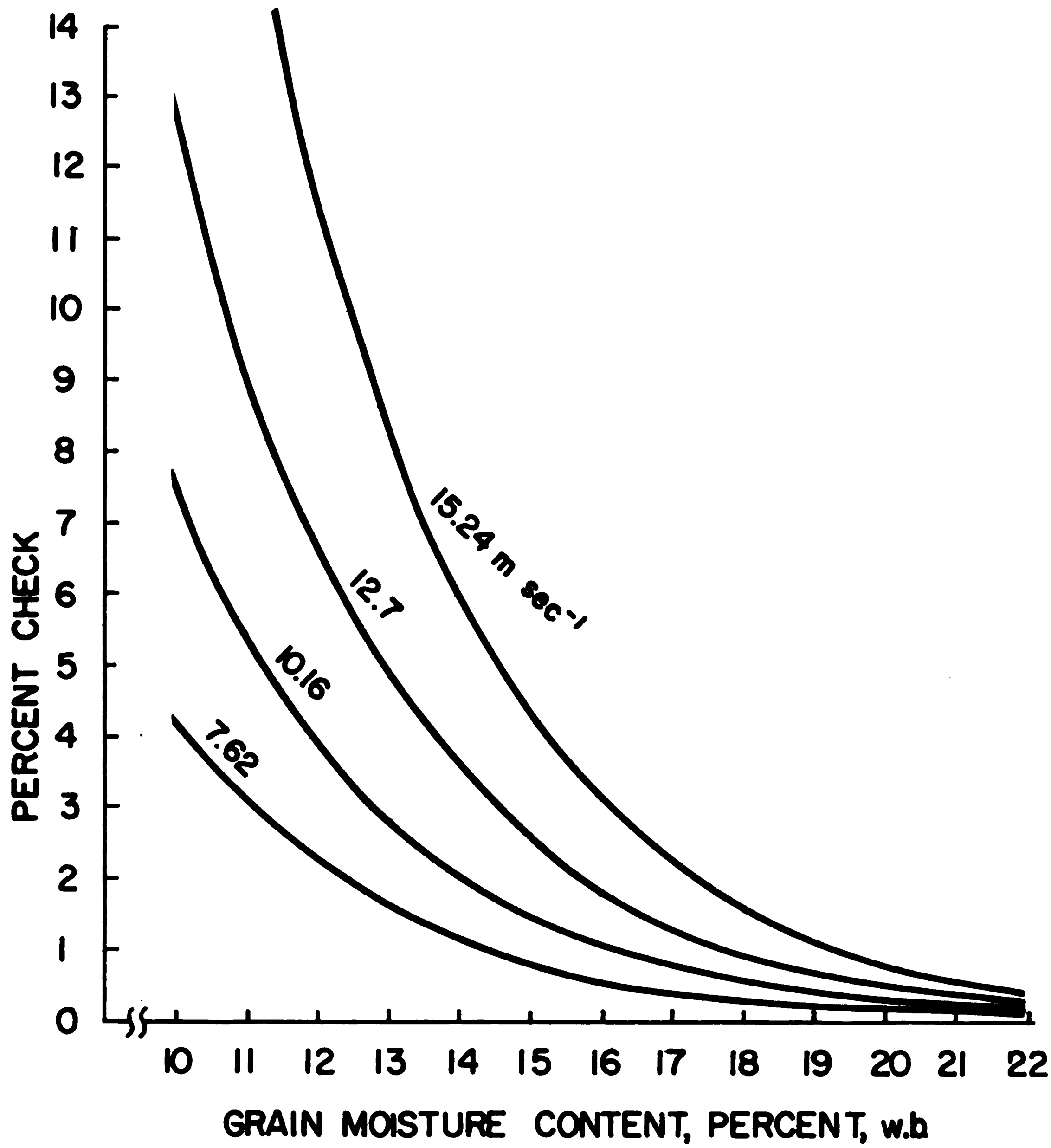

Figure 6.5. Effect of grain moisture content and cylinder speed upon percent checked bean in Sanilac dry beans from the relationship shown in Table 6.5.

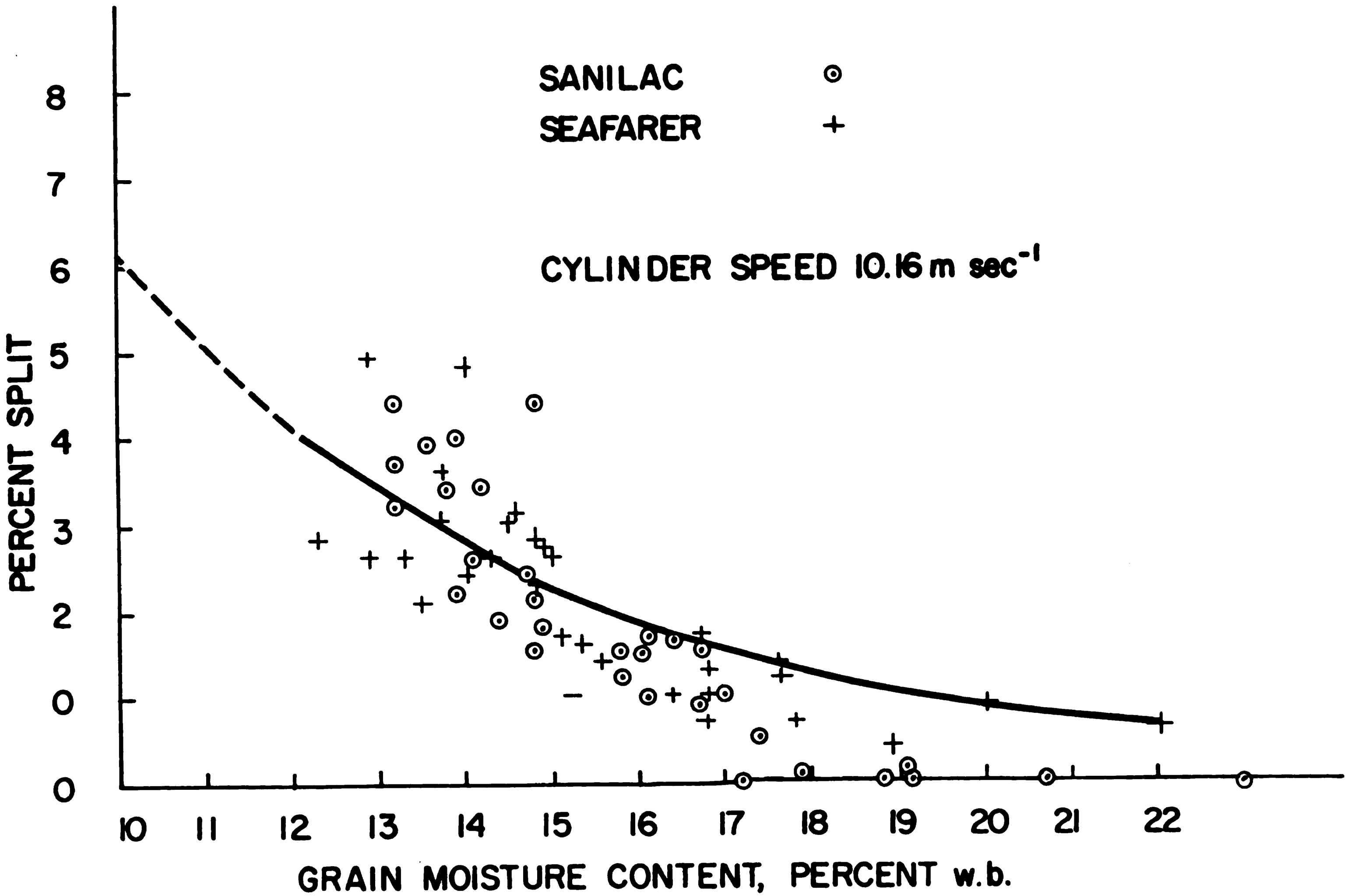

Figure 6.6. Percentage of splits Seafarer and Sanilac dry beans in 1974 versus percent grain moisture content for a cylinder speed of 10.16 m.sec^{-1}. The line is calculated from the relationship shown in Table 6.5.

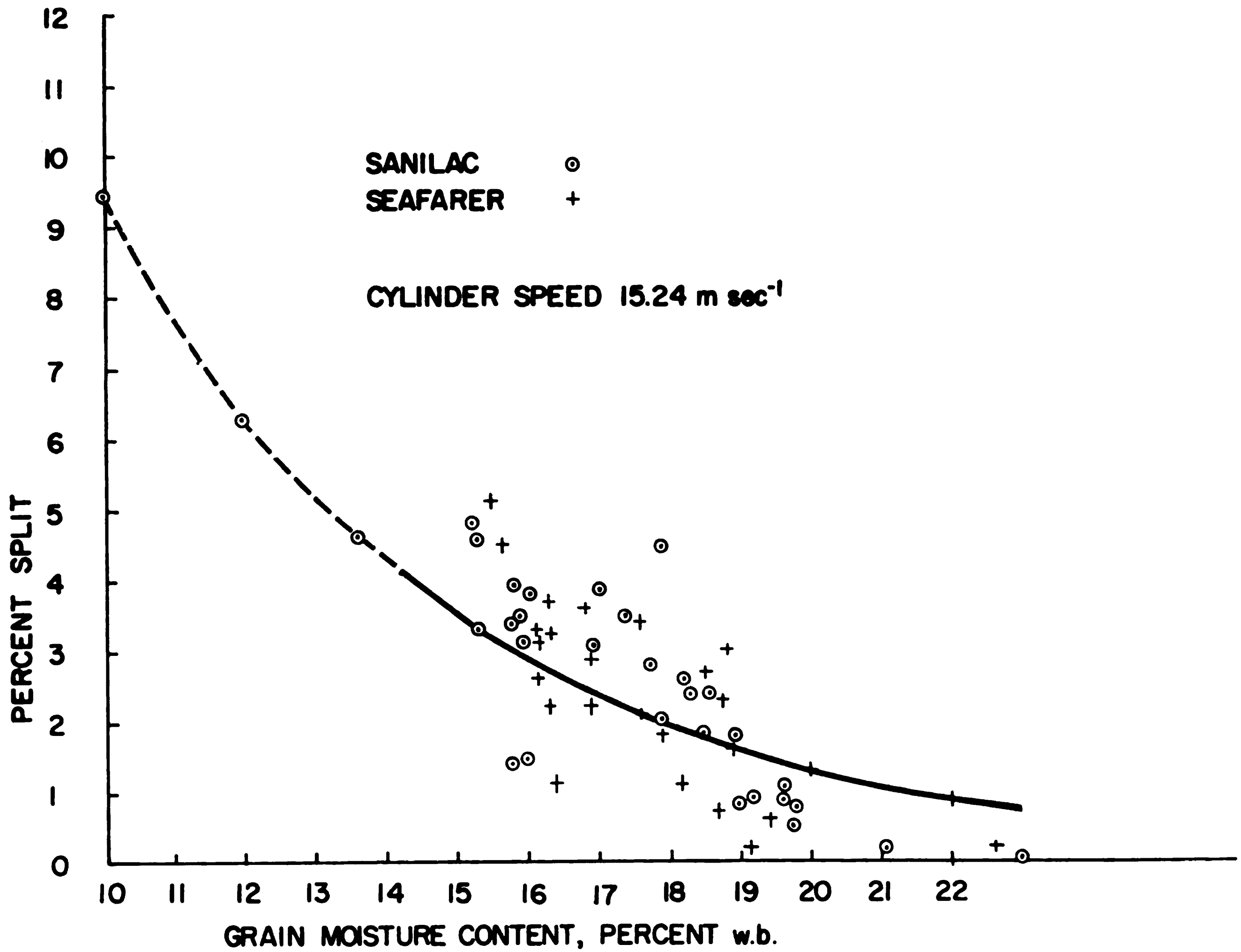

Figure 6.7. Percentage splits Seafarer and Sanilac dry beans in 1974 versus grain moisture content for a cylinder speed of 15.24 $m.sec^{-1}$. The line is calculated from the relationship shown in Table 6.5.

Table 6.9. Threshing Loss and Damage at Different Speeds and Moisture Contents of Seafarer Dry Beans.

Pod Moisture Content	Predicted Grain Moisture Content	Cylinder Speed m sec^{-1} 7.62		10.16		12.7		15.24	
		Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage
12.0	14.9		3.08	0.00	4.29		5.97	0.0	8.3
12.2	15.0		3.01	.64	4.18		5.82	.21	8.1
12.4	15.11		2.93	1.32	4.08		5.68	.38	7.9
12.6	15.21		2.86	1.99	3.98		5.54	.55	7.71
12.8	15.32		2.79	2.67	3.88		5.4	.72	7.52
13.0	15.43		2.72	3.34	3.79		5.27	.89	7.33
13.2	15.54		2.66	4.01	3.7		5.14	1.06	7.15
13.4	15.65		2.59	4.69	3.6		5.01	1.23	6.98
13.6	15.75		2.53	5.36	3.52		4.89	1.4	6.81
13.8	15.86		2.47	6.04	3.43		4.77	1.57	6.64
14.0	15.97		2.41	6.71	3.35		4.65	1.74	6.48
14.2	16.08		2.35	7.38	3.26		4.54	1.91	6.32
14.4	16.19		2.29	8.06	3.18		4.43	2.08	6.16
14.6	16.29		2.23	8.73	3.11		4.32	2.25	6.01
14.8	16.4		2.18	9.41	3.03		4.22	2.42	5.86
15.0	16.51		2.12	10.08	2.96		4.11	2.59	5.72
15.2	16.62		2.07	10.75	2.88		4.01	2.76	5.58
15.4	16.73		2.02	11.43	2.81		3.91	2.93	5.44
15.6	18.83		1.97	12.1	2.74		3.82	3.1	5.31
15.8	16.94		1.92	12.78	2.68		3.72	3.27	5.18
16.0	17.05		1.88	13.45	2.61		3.63	3.44	5.05

Table 6.9. (Continued)

Pod Moisture Content	Predicted Grain Moisture Content	Cylinder Speed m sec^{-1}							
		7.62		10.16		12.7		15.24	
		Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage
16.2	17.16		1.83	14.12	2.55		3.54	3.61	4.93
16.4	17.27		1.79	14.8	2.48		3.45	3.78	4.81
16.6	17.37		1.74	15.47	2.42		3.37	3.95	4.69
16.8	17.48		1.7	16.15	2.36		3.29	4.12	4.57
17.0	17.59		1.66	16.82	2.31		3.21	4.29	4.46
17.2	17.70		1.62	17.50	2.26		3.13	4.46	4.35
17.4	17.81		1.58	18.18	2.21		3.05	4.63	4.23
17.6	17.92		1.54	18.66	2.16		2.97	4.80	4.12
17.8	18.03		1.50	19.34	2.11		2.85	4.97	4.00
18.0	18.14		1.46	20.02	2.06		2.81	5.14	3.89

Table 6.10. Threshing Loss and Damage at Different Speeds and Moisture Contents of Sanilac Dry Bean.

Pod Moisture Content	Predicted Grain Moisture Content	Cylinder Speed m sec^{-1}							
		7.62		10.16		12.7		15.24	
		Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage
12.0	14.88		3.17	.13	4.3		5.97	0.0	8.32
12.2	14.99		3.01	.58	4.19		5.83	0.0	8.11
12.4	15.11		2.93	1.04	4.08		5.68	.12	7.9
12.6	15.22		2.86	1.49	3.97		5.53	.28	7.69
12.8	15.34		2.78	1.95	3.87		5.39	.43	7.49
13.0	15.45		2.71	2.4	3.77		5.25	.58	7.30
13.2	15.56		2.64	2.85	3.67		5.11	.73	7.11
13.4	15.68		2.57	3.31	3.58		4.98	.88	6.93
13.6	15.79		2.51	3.76	3.49		4.85	1.04	6.75
13.8	15.91		2.44	4.22	3.4		4.72	1.19	6.57
14.0	16.02		2.38	4.67	3.31		4.60	1.34	6.4
14.2	16.13		2.32	5.12	3.22		4.48	1.49	6.22
14.4	16.25		2.26	5.58	3.14		4.37	1.64	6.07
14.6	16.36		2.20	6.03	3.06		4.25	1.80	5.92
14.8	16.48		2.14	6.49	2.98		4.14	1.95	5.76
15.0	16.59		2.09	6.94	2.9		4.04	2.10	5.62
15.2	16.70		2.03	7.39	2.83		3.93	2.25	5.47
15.4	16.82		1.98	7.85	2.75		3.83	2.4	5.33
15.6	16.93		1.93	8.3	2.68		3.73	2.56	5.19
15.8	17.05		1.88	8.76	2.61		3.63	2.71	5.06
16.0	17.16		1.83	9.21	2.54		3.54	2.86	4.93

Table 6.10. (Continued)

Pod Moisture Content	Predicted Grain Moisture Content	Cylinder Speed m sec^{-1}							
		7.62		10.16		12.7		15.24	
		Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage	Threshing Loss	Damage
16.2	17.27		1.78	9.66	2.48		3.45	3.01	4.8
16.4	17.34		1.74	10.12	2.41		3.36	3.16	4.67
16.6	17.50		1.69	10.57	2.35		3.27	3.32	4.55
16.8	17.62		1.65	11.03	2.29		3.19	3.47	4.43
17.0	17.73		1.60	11.48	2.23		3.11	3.62	4.32
17.2	17.84		1.56	11.93	2.17		3.03	3.77	4.21
17.4	17.96		1.51	12.09	2.11		2.95	3.92	4.10
17.6	18.07		1.47	12.55	2.05		2.87	4.07	3.99
17.8	18.18		1.42	13.00	1.99		2.79	4.22	3.88
18.0	18.30		1.37	13.46	1.93		2.71	4.37	3.77

characteristics with Seafarer being harder to thresh than Sanilac.

Linear and exponential models of damage were developed for Sanilac dry beans relating grain moisture content and cylinder speed to grain damage. The coefficient of determination for the linear model was 70%, whereas for the exponential model it was 89%. This indicates that the exponential model describes bean damage better than the linear model.

VII. USE OF THE MODEL

When describing actual use of the models several things must be considered, such as limitations on equipment, time, cost, etc. The models discussed previously have been verified only for two varieties of navy beans commonly grown in Michigan.

The results from the models can be used as a guide in determining such things as harvesting maturity, drying rate, change in pod and grain moisture content, unthreshed loss in the field, and damage. The role of the decision maker in the decision process is of the greatest importance in achieving a successful transition between models and reality to optimize harvesting efficiency.

The drying and wetting models may be used for simulation of work no work combine harvesting hours provided we have the required data. Some variables are readily available. Some will need to be established. At present dew duration data are not readily available in the form we used. A relationship among soil temperature, air temperature and dew point may indicate dew occurrence and solar radiation during the morning hours might help in determining the end of dew hours. With these variables cumulative dew hours may be estimated.

The current study on drying, threshing loss and damage was done only during the daylight hours (9-5) when pod moisture content is decreasing more rapidly than grain moisture content. A study will be required to determine the threshing effectiveness at different cylinder speeds while pod moisture content is increasing rapidly during evening hours. At this time grain moisture content will be increasing less rapidly than pod moisture content.

In the present models the carryover effect of rain on the next day's moisture content, and soil tractability were not considered. Tractability models developed for corn by Tulu (1973) and Holtman (1975), Department of Agricultural Engineering, Michigan State University, East Lansing, may be applicable to bean conditions. The effect of rainfall on the rise of pod and grain moisture content of beans also has to be established. A relationship between weather variations and combine harvesting hours during the entire day can then be established.

The unthreshed loss and damage models can be summarized in table or chart form for use by extension personnel and farmers. These models may be used in forecasting from expected weather conditions the number of hours available for harvesting on succeeding day. This information can be given to farmers through the public media or through direct contact of extension personnel.

The model can also be used to examine the implications for design and development work which could lead to improved equipment performance. Minimizing the threshing losses could affect total cost of bean production. The models can be used by plant breeders in their attempts to increase grain development period. They should also take care to develop varieties to withstand mechanical threshing with only a minimum of damage.

VIII. SUMMARY AND CONCLUSION

Two varieties of navy beans, Seafarer and Sanilac, were planted at East Lansing, Michigan, on two different dates in 1973 and three different dates in 1974 to observe bean phenological stages and to determine harvesting operation parameters. To supplement our field observations, crop development data were obtained from farmers in the bean-growing areas of Michigan.

Navy bean phenological stages and the beginning of harvesting time can be estimated by using a growing degree day unit system. During 1974, Seafarer required 90 days to achieve harvesting maturity, whereas 79 days were needed during 1973 to accumulate an average of 926 GDD (°C) each year. Similarly for Sanilac, 97 days were required in 1974 and only 81 days in 1973 to accumulate an average 958 GDD units (°C) each year. From this we conclude that growing degree day unit is a better technique for predicting physiological development and harvesting maturity than are calendar days. The counties' results indicated that Seafarer required 967 GDD whereas Sanilac 1003 GDD.

Navy bean pod and grain moisture content varies in response to diurnal changes in environmental conditions. Pod and grain moisture content along with concurrent weather were used to formulate the rate of change of moisture content models for Seafarer and Sanilac varieties. The multiple coefficient of determination (R^2) for pod drying rates were 71 and 75% for Sanilac and Seafarer varieties, respectively, when using initial pod moisture content (%), rate of change of temperature ($°C\ t^{-1}$) and difference between pod and grain moisture content (%) as independent variables. The analysis indicated that coefficients of the difference between pod and grain moisture term was identical in both varieties. Comparison of the measured rate of change of pod moisture content during 1973 with predicted pod moisture content showed that they corresponded well.

The coefficient of determination (R^2) for rate of change of grain drying models was 12% for Sanilac and 28% for Seafarer when using the same variables as for pod drying. These models indicate that rate of change of grain moisture of navy beans is not dependent directly on environmental variables used in this study.

Since pod and grain moisture content follow to some extent identical patterns during a large part of the day, a linear relationship was developed between them from 1974 data. The model was validated with 1973 data and the predicted values showed good agreement with observed values of grain moisture content. A detailed study will be required to determine exactly how the bean dries within the pod.

Exponential relationships were found between rise in moisture content overnight and the number of hours of dew. Residual analysis indicated that these models were giving misleading results. Therefore linear models were developed which may be used to predict rise in moisture content overnight. These models, however, are valid only for dew duration of 6 to 12 hours.

Harvesting operation models were developed for Seafarer and Sanilac varieties. The threshing loss model included percent pod moisture content and cylinder speed $m.sec^{-1}$ as major variables. The models indicated varietal differences in threshing behavior with Seafarer harder to thresh than Sanilac.

A damage model developed for Sanilac included percent grain moisture content and cylinder speed ($m.sec^{-1}$) as major variables.

On the basis of these models it can be said that maximum threshing can be achieved if pod moisture content is 13% or lower and damage can be minimized if the grain moisture content is in the range of 18-20%. Periodic adjustment of the combine is required during harvesting in order to reduce the percentage of unthreshed beans when pods are moist and tough and/or to minimize cracking when bean moisture content is low. Since the models indicate that varietal differences exist, new varieties introduced will require testing to determine threshability, damage, and drying behavior.

The damage and threshing dependence on cylinder speed require the machine designer to develop methods for easy monitoring and adjustment of cylinder speed. This will allow the machine operator to reduce both field loss of and damage to the final product.

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APPENDICES

APPENDIX A

Table 1. MSU Growing Degree Day Units for the Year 1973.

Date of Planting	Emergence			Flowering: Beginning		Flowering: Maximum		Flowering: End		M.C. 50%		M.L. 20%		Harvesting	
		Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD
June 8	Seafarer	5	68.3	35	411.8	44	511.9	54	637.5	67	796.7	73	862.5	80	934.4
	Sanilac	5	68.3	39	450.0	46	536.1	58	680.5	70	826.9	76	882.2	82	866.0
June 25	Seafarer	6	62.1	35	416.7	45	542.5	51	610.3	67	799.1	71	857.2	77	912.5
	Sanilac	6	62.1	39	461.4	48	580.6	56	666.4	68	814.7	73	881.6	79	929.1
Ave. of both plantings	Seafarer	5	65.2	35	414.3	44.5	527.2	52.5	623.9	67	797.9	72	859.9	78.5	923.5
	Sanilac	6	65.2	39	455.7	47	558.4	57	673.9	69	820.8	74.5	881.9	80.5	947.6

Table 2. MSU Growing Degree Day Units for the Year 1974.

Date of Planting	Variety	Emergence		Flowering						50% Moisture Control		20% Moisture Content		Harvesting	
				Beginning		Maximum		End							
		Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD	Day	GDD
June 10	Seafarer	9	55.9	39	407.1	48	505.3	61	637.2	75	802.2	83	876.2	92	936.9
	Sanilac	9	55.9	42	435.5	52	544.7	65	684.7	85	884.6	87	983.8	100	1004.0
June 20	Seafarer	7	54.1	37	437.8	45	507.6	56	627.0	72	803.5	80	847.7	83	921.9
	Sanilac	7	54.1	41	469.5	49	547.8	60	670.0	78	832.4	86	910.8	92	955.0
June 28	Seafarer	7	88.3	37	445.1	45	533.1	55	647.8	75	820.5	83	883.0	91	924.7
	Sanilac	7	88.3	40	473.4	48	564.5	58	680.6	81	866.9	88	904.7	98	945.0
Ave. of three Plantings	Seafarer	7.7	66.1	37.7	430.0	46	515.3	57.3	637.3	-	808.7	82	869.0	90.3	927.8
	Sanilac	7.7	66.1	41.0	459.5	49.7	552.3	61.0	678.4	-	861.3	90.3	932.8	96.6	968.0

Table 3. Counties Average Growing Degree Day Units for Years 1972, 1973 and 1974.

Variety	Emergence			Flowering			Harvesting		
	No. of Obs.	Mean	Std.	No. of Obs.	Mean	Std.	No.of Obs.	Mean	Std.
YEAR 1972									
Seafarer	53	58.8	11.29	53	459.8	67.07	53	994.5	71.04
Sanilac	19	56.0	9.31	22	480.1	67.34	22	1039.7	41.13
YEAR 1973									
Seafarer	82	56.6	7.63	80	447.7	24.28	90	950.7	33.98
Sanilac	41	64.6	9.27	41	464.5	25.6	50	987.0	45.3
YEAR 1974									
Seafarer	153	63.4	14.55	160	447.1	41.69	185	955.2	56.02
Sanilac	51	61.0	14.4	60	475.7	37.58	60	981.0	42.93

APPENDIX B

Table 1. Minimum, Maximum, Mean and Standard Deviations of Variables in Pod Drying Model for Seafarer and Sanilac Varieties.

Variety	Variable	Minimum Value	Max. Value	Mean	Standard Deviation
	M_P	10.5	37.0	17.87	5.43
	M_G	12.3	28.0	18.07	3.60
	M_P	-4.4	- .05	-1.35	1.10
Seafarer	M_G	-2.07	.4	- .50	0.38
	$\frac{\Delta T}{\Delta t}$	- .85	3.73	.93	.93
	$M_{(P-G)}$	-5.9	9.5	-.208	3.25
	M_P	11.0	31.6	17.67	4.96
	M_G	12.5	25.6	18.1	3.45
	M_P	-4.93	- .05	-1.21	1.02
	M_G	-2.45	.65	- .45	.32
	$\frac{\Delta T}{\Delta t}$	-2.44	4.07	.89	1.06
	$M_{(P-G)}$	-5.2	7.8	- .45	2.90

APPENDIX C

Table 1. Minimum, Maximum, Mean and Standard Deviations of Variables in Unthreshed Model for Seafarer and Sanilac Varieties.

Variety	Cylinder Speed m sec^{-1}	Variable	Minimum Value	Maximum Value	Mean	Standard Deviation
Seafarer	10.16	M_p	10.50	25.3	14.06	3.29
		Unthreshed Loss	0.00	51.600	6.96	11.71
	15.24	M_p	11.30	26.5	16.42	4.00
		Unthreshed Loss	0.00	14.00	3.93	3.58
Sanilac	10.16	M_p	10.80	24.90	14.2	3.47
		Unthreshed Loss	0.00	37.20	5.25	8.41
	15.24	M_p	10.10	24.80	16.96	3.95
		Unthreshed Loss	0.60	13.40	3.77	3.31

Table 2. Minimum, Maximum, Mean and Standard Deviation in Damage for Sanilac Variety.

Variable	Minimum	Maximum	Mean	Standard Deviation
Total Damage	1.3	14.5	4.16	3.39
Split	1.0	8.3	2.38	1.83
Check	.15	6.2	1.77	1.61
Grain Moisture Content	13.6	18.5	16.25	1.99
Cylinder Speed in m sec^{-1}	7.62	15.24	11.43	2.93
Log (Damage)	.26	2.67	1.21	.63
Log (Split)	-0.0	2.12	.68	.56
Log check	-1.9	1.82	.20	.95

VITA

Bachchan Singh was born in the Village of Nari-Pacha-deora, District Ghazipur, Uttar Pradesh, India, on July 4, 1938, to Sahadeo and Rama Devi Singh. His early years were spent in his village. He did his high school in 1954 from Nandgunj, Ghazipur; I. Sc. (Ag.) in 1956 from Udai Pratap College Varanasi; B. Sc. (Ag.) in 1958 from Institute of Agricultural Sciences, (Govt. Agri. College), Kanpur and B. Sci. (Agri) Engineering in 1961 from Agricultural Institute, Allahabad.

From 1961 to 1964, Mr. Singh was employed by the Department of Agriculture, Uttar Pradesh, to teach Agricultural Engineering to B. Sc. (Ag) students.

In 1965, he enrolled at the University of Guelph, Ontario, Canada, to study Farm Machinery under Dr. W. K. Bilanski and was granted the Master of Science Degree in 1966.

From 1967 to 1971, Mr. Singh was on the staff of the G. B. Pant University of Agriculture and Technology, Pantnagar, India. Since that time Mr. Singh has been sponsored by G. B. Pant University of Agriculture and Technology under the AID program for higher studies leading to the Ph.D. degree under Dr. Dale E. Linvill.

Bachchan was married to Gulbas on June 8, 1957, at Imilia, Varanasi. They are the parents of three daughters, Suneeta, born September 26, 1961; Neena, born November 14, 1967; Nishi, born August 10, 1969; and a son Neeraj, born on January 19, 1972.