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THE SIMULATION OF COMBINE HARVESTER PERFORMANCE AS AFFECTED BY BULK CROP PROPERTIES

By

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ABSTRACT

THE SIMULATION OF COMBINE HARVESTER PERFORMANCE AS AFFECTED BY BULK CROP PROPERTIES

By

Wilbur Thomas Mahoney, III

Physical changes in crop properties have been reported to affect the operational characteristics of combine harvesters. Performance, measured as mass other than grain (M.O.G.) feed rates at fixed grain loss levels, varies as a result of crop property changes (Stephens and Rabe, 1977). Combine performance may vary substantially during the course of a single day making comparisons of performance between combines in field tests difficult.

A research project was undertaken to determine the effect of bulk crop properties on combine performance. This thesis describes the collection and measurement of bulk crop properties, the correlation between property changes and combine performance, and the development of a combine simulation model based on bulk crop properties.

Fourteen bulk crop properties were collected for wheat and barley from 1980 through 1984. In addition, the performance of the cleaning component and the straw walker was also measured on a conventional type John Deere 6620 combine. Crop properties were measured on grain, chaff, and straw components of wheat and barley. The performance criteria was chaff feed rate at 0.5 percent cleaner grain loss and total M.O.G. (mass other than grain) feed rate at 1.0 percent walker grain loss.

Grain density, grain angle of repose, chaff density, chaff coefficient of friction, chaff compressibility modulus, grain:M.O.G. ratio, straw density, straw compressibility modulus, and straw coefficient of friction were shown to affect combine performance. In general, cleaner performance appeared to be three time more sensitive to crop changes than straw walker performance.

Cleaner performance and straw walker performance prediction equations were developed which explained 92.0 percent of the variation in cleaning performance and 30.0 percent of the variation of the performance in straw walker performance.

A computer simulation model was developed using crop property and combine performance data. The model predicted cleaner, walker, and overall processing performance as functions of ground speed, width of cut, crop yield, and a set of crop properties which vary in a stochastic manner. Implemented as an interactive program, the user specifies initial crop properties and variability. Each property is then simulated over a range of selected moisture conditions. The model can be used by students and test engineers to study the effects of crop properties on combine performance.

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TABLE OF CONTENTS

Page

LIST OF TABLES 8

LIST OF FIGURES . . . .

CHAPTER I: INTRODUCTION AND PROBLEM STATEMENT 1

1.1 Background 1
1.2 Problem Statement 2
1.3 Objectives 2

CHAPTER II: REVIEW OF LITERATURE 3

2.1 Introduction 3
2.2 Harvest Methods and Principles 3
2.3 Combine Performance 6
2.3.1 Performance Measurement 6
2.3.2 Factors Affecting Combine Performance 7
2.4 Threshing Cylinder Models 9
2.5 Straw Walker 11
2.6 Cleaner Models 13
2.7 System Research 14
2.7.1 Definition 14
2.7.2 System Models 14
2.7.3 Testing and Implementation 14
2.8 Crop Properties Research 15

CHAPTER III: COMBINE PERFORMANCE AND BULK CROP PROPERTY MEASUREMENT 17

3.1 Introduction 17
3.2 Combine Performance 18
3.3 Measuring Bulk Crop Properties 21
3.3.1 Material Collection and Crop Properties Measured . 21
3.3.2 Crop Component Moisture 21
3.3.3 Crop Bulk Density 22
3.3.4 Compressibility Modulus 27
3.3.5 Crop Friction 27
3.3.6 Particle Distribution 28
3.3.7 M.O.G. Ratios 31
3.3.8 Instrumentation 31

CHAPTER IV: CORRELATION OF CROP PROPERTIES TO COMBINE PERFORMANCE AND THE EFFECT OF MOISTURE ON CROP PROPERTIES 36

4.1 Introduction 36
4.2 Effect of Crop Properties on Cleaner Performance 46
4.2.1 Grain Angle of Repose 46
4.2.2 Grain Density 48

    4.2.3 Chaff Coefficient of Friction 48
    4.2.4 Chaff Density 49
    4.2.5 Chaff Compressibility Modulus 49
    4.2.6 Grain and Chaff Moisture 50
    4.2.7 Chaff Mean Length 50
    4.2.8 M.O.G. Ratios 51
  4.3 Effect of Crop Properties on Straw Walker Performance . . 51
    4.3.1 Grain Angle of Response 51
    4.3.2 Grain Density 52
    4.3.4 Straw Coefficient of Friction 52
    4.3.5 Remaining Straw Properties 53
  4.4 Conclusions 53
  4.5 Effect of Moisture on Crop Properties 54
    4.5.1 Introduction 54
    4.5.2 Grain Density 54
    4.5.3 Grain Angle of Repose 54
    4.5.4 Chaff Density 54
    4.5.5 Chaff Compressibility Modulus 56
    4.5.6 Chaff Coefficient of Friction 56
    4.5.7 Chaff Mean Length 56
    4.5.8 Straw Density 56
    4.5.9 Straw Compressibility Modulus 57
    4.5.10 Straw Coefficient of Friction 57
    4.5.11 Conclusions 57

CHAPTER V: PREDICTION MODELS 58

  5.0 Introduction 58
  5.1 Cleaner Prediction Equations 60
  5.2 Straw Walker Predictions Equations 65
  5.3 Conclusions 69

CHAPTER VI: CROP PROPERTY BASED COMBINE SIMULATION MODEL 74

  6.1 Introduction 74
  6.2 Objectives 74
  6.3 Model Concept 74
  6.4 Crop Property Simulation 76
  6.5 Feeding and Cutting 79
  6.6 Cleaning and Walker Loss 80
  6.7 Total Loss 84
  6.8 Random Variable Generation 84
  6.9 Simulation Results 84
  6.10 Conclusions 95

CHAPTER VII: SUMMARY AND CONCLUSIONS 96

  7.0 Summary 96
  7.1 Conclusions 96
    7.1.1 Affect of Crop Properties on Combine Performance . 97
    7.1.2 Combine Simulation 98
  7.2 Recommendations For Further Research 98

APPENDIX A: Crop Bulk Properties and Machine Performance Measurements Data Set 100

APPENDIX B: Scatter Plots of Combine Performance Versus Crop Properties 112

APPENDIX C: Scatter Plots of Crop Properties Versus Crop Moisture 129

APPENDIX D: Combine Simulation Model Source Code 140

APPENDIX E: Combine Simulation Interactive Session 154

BIBLIOGRAPHY 162

LIST OF TABLES

TABLE PAGE

1. Bulk crop property collection information listed by location, year, crop, test environment and machine measurements 23

2. Means and standard of property data and machine parameters listed by location and crop type 37

3. Measurement errors for each bulk crop property 38

4. Correlation of cleaner performance to crop properties listed by location and crop type 40

5. Correlation of straw walker performance to crop properties listed by location and crop type 41

6. Slopes of single variable regression equations which describe cleaner and straw walker performance as function crop properties 42

7. Property changes associated with a measurable change in cleaner performance and the probability of such a change 44

8. Property changes associated with a measurable change in straw walker performance and the probability of such a change 45

9. Unit change in cleaner properties to crop moisture listed per unit change in a crop property 55

10. Correlation of crop properties to crop moisture listed by location 55

11. Correlation prediction equation coefficients, adjusted R squares, and partial F ratios as determined by stepwise regression. Properties are listed as they entered the model . . 61

12. Cleaner prediction equation coefficients, adjusted R squares, and partial F ratios as determined by stepwise regression. Properties are listed as they entered the model . . 63

13. Effect of location on cleaner performance. The location effect was tested with covariate models using properties previously selected by stepwise regression 66

14. Straw walker prediction equation coefficients, adjusted R squares, and partial F ratios as determined by stepwise regression. Properties are listed as they entered the model . . . 67

15. Straw walker prediction equation coefficients, adjusted R squares, and partial F ratios as determined by stepwise regression. Properties are listed as they entered the model . . 68

16. Effect of location on cleaner performance. The location effect was tested with covariate models using properties previously selected by stepwise regression 72

17. Equation coefficients used to predict properties as functions of moisture. The data set used to develop the regression equations and statistics are also listed 82

18. Equations coefficients used to predict cleaner loss in simulation model. Partial F ratios are listed as generated by stepwise regression 83

19. Equation coefficients used to predict walker loss in simulation model. Partial F ratios are listed as generated by stepwise regression 83

20. Crop means and standard deviations used in the sensitivity analysis 87

21. Sensitivity analysis of simulated cleaner performance 89

22. Sensitivity analysis of simulated walker performance 90

23. Crop properties, crop yield, and machine parameters used simulation of cleaner and walker performance. The data is and actual barley data set 91

LIST OF FIGURES

FIGURES PAGE

1. Schematic of a combine harvester 5

2. Typical wheat cleaner performance curve 19

3. Typical wheat straw walker performance curve 20

4. Test stand used to measure density and compressibility modulus of chaff and straw 24

5. Typical graph of data from test stand used to measure density and compressibility modulus of chaff and straw . . . 26

6. Test stand used to measure chaff and straw coefficients of friction 29

7. Test stand used to measure grain angle of repose 30

8. Test stand used to sieve chaff into size components 32

9. Typical chaff size distribution curve 33

10. Electronic instrumentation used for crop property data collection 34

11. Predicted cleaner performance versus actual cleaner performance based on the entire data set 62

12. Predicted cleaner performance versus actual cleaner performance based on data gathered after 1981 64

13. Predicted straw walker performance versus actual straw walker performance based on entire data set 70

14. Predicted straw walker performance versus actual straw walker performance based on data gathered after 1981 71

15. Flow diagram of combine simulation model 75

16. Simulated cleaner performance versus actual cleaner performance 85

17. Simulated straw walker performance versus actual straw walker performance 86

18. Simulated cleaner performance curve and actual cleaner performance curve for North Dakota barley 92

19. Simulated straw walker performance curve and actual straw walker performance curve for North Dakota barley . . . 93

20. Simulated chaff feedrate at 0.5 percent grain loss and total M.O.G. feedrate at 1.0 percent grain loss versus grain moisture. Chaff properties variation was 5.0 percent and straw walker properties variation was 10.0 percent 94

21. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus grain density (kg/m^3) 112

22. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus grain angle of repose (degrees) 113

23. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff to M.O.G. ratio 114

24. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus grain to M.O.G. ratio 115

25. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff moisture (percent dry basis) 116

26. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff density (kg/m^3) 117

27. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff compressibility modulus (kPa) . . . 118

28. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff coefficient of friction 119

29. Scatter plot of chaff feedrate (t/h) at 0.5 percent grain loss versus chaff mean length (mm) 120

30. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus grain moisture (percent dry basis) 121

31. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus grain density (kg/m^3) 122

32. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus grain angle of repose (degrees) 123

33. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus straw moisture (percent dry basis) 124

34. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus grain to M.O.B. ratio 125

35. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus straw density (kg/m^3) 126

36. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus straw compressibility modulus (kPa) . . . 127

37. Scatter plot of M.O.G. feedrate (t/h) at 1.0 percent grain loss versus straw coefficient of friction 128

38. Scatter plot of Grain density (Kg/m^3) versus grain moisture (percent) 129

39. Scatter plot of grain angle of repose (degrees) versus grain moisture (percent) 130

40. Scatter plot of Grain to M.O.G. radio versus grain moisture (percent) 131

41. Scatter plot of chaff density (kg/m^3) versus chaff moisture (percent dry basis) 132

42. Scatter plot of chaff compressibility modulus (kPa) versus chaff moisture (percent dry basis) 133

43. Scatter plot of chaff coefficient of friction versus chaff moisture (percent dry basis) 134

44. Scatter plot of chaff mean length (mm) versus chaff moisture (percent dry basis) 135

45. Scatter plot of chaff to M.O.G. ration versus chaff moisture (percent dry basis) 136

46. Straw density (kg/m^3) versus straw moisture (percent dry basis) 137

47. Straw compressibility modulus (kPa) versus straw moisture (percent dry basis) 138

48. Straw coefficient of friction versus straw moisture (percent dry basis) 139

49. Example of cleaner loss curve displayed on screen by pressing the F3 function key 158

50. Example of Walker loss curve displayed on screen by pressing the F3 function key 159

51. Scatter plot displayed on screen by pressing F4 function key the option promotes the user for two crop properties or machine parameters 160

52. Example of simulation statistics displayed by pressing the F6 function key 161

CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

1.1 Background

Combine harvester performance varies throughout the harvesting period. Performance shifts often occur within the same harvest day. Stephens and Rabe (1977) reported performance decreased 30 percent in less than one week while conducting combine performance tests. During that week, grain moisture remained constant while straw moisture fell from 35 percent to 10 percent. Although the performance shift was not quantitatively explained much of the variation in performance was attributed to the change in straw moisture contrary to the popular belief that performance improves as straw moisture decreases. Research has been conducted to evaluate design changes or to compare machines in performance tests but little has been done to determine the effects of the crop parameters on combine performance.

Combine manufacturers conduct field and laboratory tests with prototype harvesters to determine if design changes significantly alter combine performance. Suspected crop property shifts often make comparisons between prototypes and production machines difficult. Presently, it is necessary to generate a performance curve for a production machine each time a prototype machine is operated to eliminate variability caused by the crop. Stephens and Rabe (1977) estimated 30-50 percent of testing time is spent generating the performance curve for the production machine.

Components are often tested with stored plant material in a laboratory setting. Performance of combines in field tests is not often duplicated using stored plant material in a laboratory setting. The failure to duplicate field tests has been attributed to changes in properties of the crop as a result of storage.

1.2 Problem Statement

The goal of field and laboratory testing is to produce valid and repeatable results. Changes in crop properties are thought to cause combine performance shifts. A method is needed to measure crop bulk properties and to explain the variation in combine performance as a function of crop properties. Ideally, a model of a combine harvester could be constructed such that production machine performance could be predicted thus minimizing the need for labor and cost intensive field performance curves.

1.3 Objectives

The purpose of this dissertation is to relate crop property changes to variations in combine harvester performance. The specific objectives are:

1) to identify and measure bulk crop property changes,
2) to correlate bulk crop property changes to combine harvester performance,
3) to predict losses as a function of crop properties, and
4) to develop a computer simulation of a combine harvester based on bulk crop property changes.

CHAPTER II

REVIEW OF LITERATURE

2.1 Introduction

Almost all seed and grain crops in the United States are harvested by combine harvesters. Conventional combines, those with a threshing component, straw walker, and cleaning component are the focus of this review. An overview of combine harvest methods, terminology, operating principles, and the factors reported to affect combine performance are presented.

2.2 Harvest Methods and Principles

Two primary harvest methods are used for harvesting small grain crops. Direct cutting, the most common harvest method, involves cutting the standing crop and processing in a continuous operation. Processing in this case refers to threshing, separation, and cleaning. Windrowing, another harvest method, is also used in some parts of the United States. The practice is common in the Northern United States and Western Canada. Although windrowing requires an extra operation, the practice facilitates curing in areas where drying conditions are variable. Generally, conventional combines are of two types: self-propelled and pull-type. Self-propelled combines can be further categorized by three machine types: level land, hillside, and sidehill machines. Level-land combines are intended for use on level or nearly level land. Hillside machines, as the name implies, are designed to allow combining on hillsides. Hillside machines are equipped with automatic leveling devices that allow the machine to remain horizontal while the cutting mechanism follows the contour of the ground. Hillside combines are designed to operate on maximum slopes of 30-45 percent. Sidehill combines are essentially level land combines with slightly altered components which do not allow the material distribution to overload a component. For example the cleaning unit is equipped with baffles to assure even material distribution. Pull-type combines are usually PTO driven versions of level land machines. Their widest application is in those areas that windrow small grains. They are less expensive and less maneuverable than self-propelled machines. Also, pull-type combines do not provide the continuous operator adjustment available on self-propelled combines.

Combines perform four basic operations during the harvesting process:

1. Cutting standing plants or picking up the windrow,
2. Threshing,
3. Separation, and
4. Cleaning.

A conventional combine is equipped with several components to accomplish the basic operations of harvesting (Figure 1).

When direct cutting standing plants a feeding and cutting mechanism called a header is employed. The mechanism's principle components are a reel, a sickle bar cutter, and a conveying system. As the combine moves into a standing crop, the reel momentarily holds the plant in place for cutting and then directs the crop rearward for conveying into the feeder house.

The threshing component of the cylinder-concave is comprised of a drum or cylinder partially enclosed by a concave or grate mounted perpendicular to the crop flow. The concave is slotted such that grain

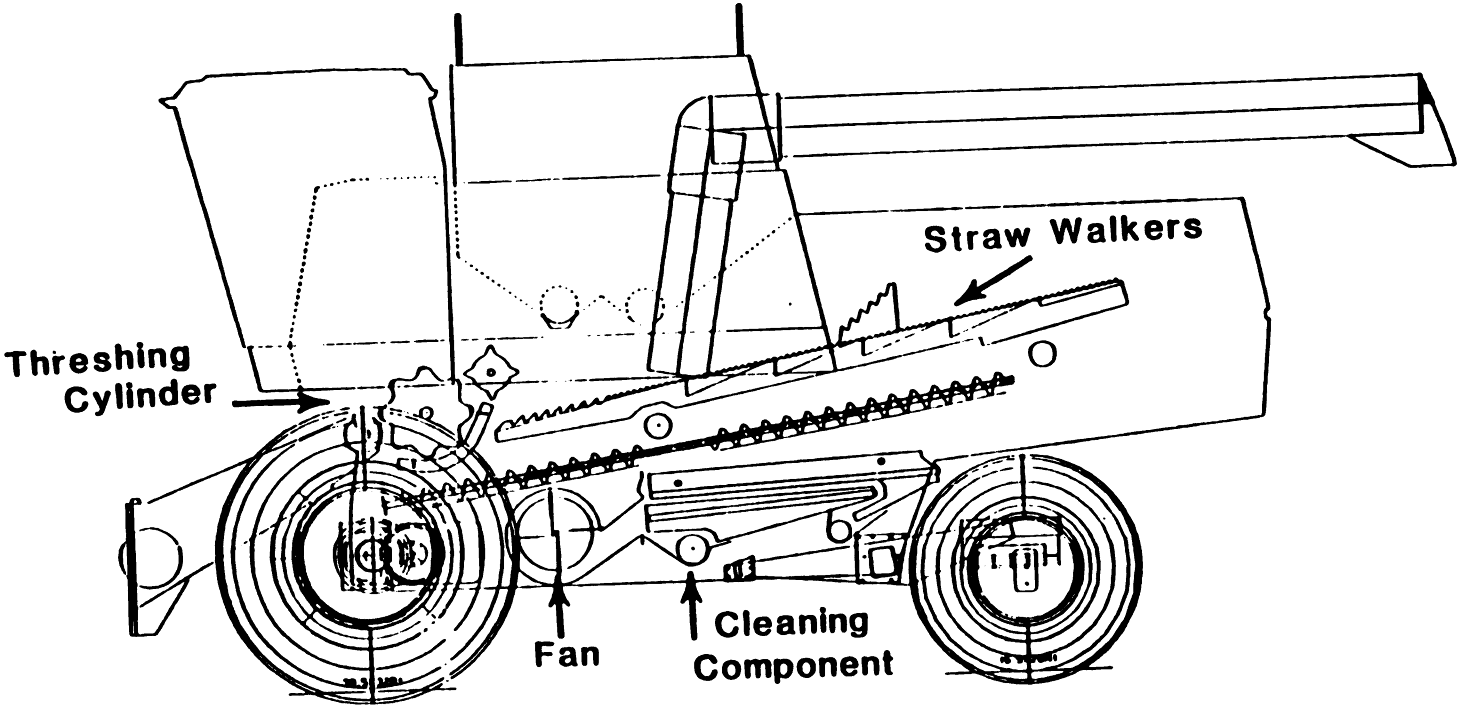

FIGURE 1

SCHEMATIC OF A COMBINE HARVESTER

may fall through it at separation. As the cylinder spins, crop is fed between the cylinder and concave. Rasping, squeezing, and impact between the revolving cylinder and stationary concave detach the grain from the plant.

The straw walker or rack is typically an oscillating bed which separates grain from straw as it agitates the crop material rearward. Grain and chaff fall through openings in the rack onto grain return pans which lead to the cleaning component. The remaining material, predominantly straw, is carried out of the machine by the straw walkers.

The cleaning component, usually comprised of a chaffer sieve, a cleaning sieve, and a fan , is the final step in separation. Air directed on the mixture of grain, chaff, and broken straw carries the lighter debris out of the machine while the grain which is more dense falls through the sieves. The cleaned grain is then augured into the combine holding tank.

2.3 Combine Performance

2.3.1 Performance Measurement

Combine performance of the cleaner and the straw walker is commonly evaluated by measured processing grain loss. Loss can be described as percentage of grain lost, rate of loss, or amount of loss per unit of land area (Mailander et al, 1983). The most common performance criterion found in the literature is loss expressed as a percentage of grain available on a component for a specified time interval and is the criterion adopted by the Society of Agricultural Engineers (Agricultural Engineers Yearbook, 1983).

Header loss (loss at the feeding and cutting stage) is considered more difficult to measure than walker or cleaner loss. When measured, header loss is usually expressed in one of the three forms previously mentioned. Header loss is thought to account for most of the loss during combine harvesting and may vary from 0.5 to 2.0 percent (Ridenour et al,1968).

The cylinder-concave component can be evaluated in a number of ways. Percentage of grain lost is sometimes used. Perhaps the most common standard of cylinder-concave performance is efficiency. Cylinder-concave efficiency is defined as the percentage of grain separated through the concave. Grain damage is also a measure of performance but varies in importance. Grain damage is very important in crops that are harvested for seed because germination is affected. In grain harvested for consumption, damage is not as important because there is no incentive for high quality grain beyond minimum requirements (Mailander et al, 1983).

2.3.2 Factors That Affect Combine Performance

Combine performance is affected by many factors such as machine adjustments, crop conditions, and ground speed. ASAE standard S396T assumes that increased feedrate causes increased total processing loss as well as increased walker loss and cleaning loss. Grain processing loss has been described as an exponential function of feedrate (Kirk et al, 1977; Kumar and Goss, 1978; Friesen, 1966) while other researchers have used a linear function of feedrate raised to a power (Wrubleski, 1977; Reed et al, 1968; Audsley, 1979). Although the relationship between loss and feedrate are documented, values for the coefficients describing the relationship between feedrate and grain loss vary substantially. The discrepancy between coefficients of various equations based on similar machines suggests that factors other than feedrate affect grain loss. Researchers have examined the effects of machine design, machine adjustments, and to a lesser extent crop properties.

Cylinder speed and concave clearance have been shown to affect cylinder-concave performance when M.O.G. (mass other than grain) feedrate is constant (Vas and Harrison, 1964; Ridenour, 1968; Cooper, 1971; Bainer, Kepner, and Barger, 1980). Generally, faster cylinder speeds and more narrow concave settings are associated with higher threshing efficiency. Excessive cylinder speeds cause straw break up in some crops such that the cleaning component is loaded to a point that performance decreases. Goss et al (1958) and Vas and Harrison (1964) concluded that cylinder speed has a greater effect upon threshing efficiency and threshing loss than concave clearance. In addition to machine adjustments, orientation of the material entering the cylinder-concave has also been determined to affect separation efficiency (Arnold, 1964).

The straw walkers are also similarly affected by factors other than feedrate. Machine parameters are known to significantly affect walker performance. Walker crank speed and crank throw were investigated by Reed, Zoerb, and Bigsby (1974) as was straw walker length. In general, walker performance is optimum when the material is aggressively tossed upward and moved rearward. Goss (1958) and Reed, Zoerb, and Bigsby (1970) found grain to straw ratio to have a negative affect upon walker performance (higher grain loss). Straw length was found to be of little importance by Reed, Zoerb, and Bigsby (1970) in contrast to Huisman (1977). Huisman also found relative humidity and bulk density of straw to correlate with walker performance. He also reported that straw coefficient of friction, straw moisture, grain moisture, and modulus of elasticity to be poorly correlated with walker performance. Conversely, Nath (1982) found grain moisture to be an important factor relative to walker performance.

Nyborg, McColly, and Hinkle (1969) found reducing the grain to chaff ratio decreased cleaning shoe loss in some instances. Laboratory experiments have shown that shaker frequency, air flow characteristics and material entrance conditions affect cleaning performance (MacAulay and Lee, 1969; Rumble and Lee, 1970). Cylinder speed and concave clearance were reported to affect cleaning performance (Nath, Johnson, and Milliken, 1982). Other parameters such as chaffer opening, and cleaner slope also affect performance. In addition to feedrate and machine parameters, crop factors also affect cleaning performance. Nath, Johnson, and Milliken (1982) reported loss increased with increased grain moisture. Huynh (1982) reported increased moisture was responsible for increases in chaff coefficient of friction. Higher coefficients of friction resulted in faster conveying times over the component such that grain was not allowed to pass through the crop mat.

2.4 Threshing Cylinder Models

Nyborg, McColly, and Hinkle (1969) developed the following equation to describe cylinder loss in small grains:

$$TL = 4.76E\text{-}4\ (FR)^{1.5}\ G/S^{-1.69} \qquad [1]$$

where

TL = threshing loss (percent)

FR = M.O.G. feedrate (pounds per minute)

G/S = ratio of grain to M.O.G. feedrate.

The correlation coefficient for the equation was reported as 0.50. Fairbanks, Johnson, Schrock, and Nath (1979) described threshing loss in grain sorghum by the following equations:

$$TL = 10.35 - 4.76(CS) + 0.27\ 1(CC) \qquad [2]$$

$$TL = 3.46 + 0.217(M) - 0.261(CS) + 0.208(CC) \qquad [3]$$

where

TL = threshing loss (percent)

CS = cylinder speed (m/s)

CC = concave clearance (mm)

M = grain moisture (percent)

Correlation coefficients were reported as 0.49 and 0.71, respectively.

Nath, Johnson, and Milliken (1982) developed the following equation to predict threshing loss in grain sorghum:

$$TL = 9.105 + 0.144(M) + 0.150(S) + (0.111)(C)(2613(F^{2}) + 350.0 (FS)(10^{-4})) + (2578.0 (M2)(CS) + 16.0(MS^{2})(C2)10^{-4} \quad [4]$$

where

M = grain moisture (percent)

S = cylinder speed (m/s)

C = concave clearance (mm)

F = feedrate (kg/s)

The correlation coefficient for the model was 0.50.

Huisman (1983) proposed what he termed a "simplified model":

$$TL = TLF(FGT) \quad [5]$$

where

TL = threshing loss (kg/s)

TCF = threshing loss fraction

FGT = grain feedrate (kg/s)

Threshing loss fraction (TLF) is expressed as follows:

$$TLF = (1 - TSE)(0.025) \quad [6]$$

where

TSE = threshing separation efficiency

Huynh, Powell, and Siddall (1982) developed a stochastic model to describe the threshing and separation process in cereal grains. The time required for a kernel of grain to be threshed after entering the cylinder concave, the time required for a kernel to pass through the straw mat, and the time required for a kernel to pass through the concave grate were treated as random variables with characteristic distributions. They were able to determine the probability that a kernel would be threshed and separated before being carried out with the straw mat.

2.5 Straw Walker Models

Nyborg, McColly, and Hinkle (1969) proposed the following equation:

$$WL = 0.102\ (F)^{0.82}\ (G/S)^{-1.73} \quad [7]$$

where

WL = rack or walker loss (percent)

FR = feedrate (pounds per minute)

G/S = grain to straw ratio

The correlation coefficient for the model was 0.74.

Reed, Zoerb, and Bigsby (1970) used a slightly different approach than Nyborg, McColly, and Hinkle (1969) to model walker performance. Reed, Zoerb, and Bigsby (1970) concluded that wheat separation can be described by a decaying exponential function and developed an equation to predict walker length for specified separation efficiency. They proposed evaluating walker performance by the walker length required for a given efficiency. The equation:

$$L = \ln(100 - eff)/b \quad [8]$$

$$eff = \exp(-b * L) \quad [9]$$

where

L = length (m) of the walker

b = an empirically derived value dependent upon the grain feedrate, the M.O.G. feedrate, grain to M.O.G. ratio, crop factors, and walker design

Huisman, Heining, van Loo, and Bergman (1974) determined that a model incorporating M.O.G. feedrate, grain feedrate, and relative humidity best described walker loss. Other factors such as grain moisture, straw moisture, and stubble length were considered to be less significant. The equations:

$$WL = -11.96 + 1.40(FRS) + 1.64(\ln(RH) + 0.017(MCS) + \ln(MCG) + 3.2E{-}4(SL) + 0.021(FRG) \qquad [10]$$

where

WL = walker loss (kg/s)

FRS = straw feedrate (kg/s)

FRG = grain feedrate (kg/s)

RH = relative humidity (percent)

MCS = straw moisture (percent)

MCG = grain moisture (percent)

The model had a correlation coefficient of 0.91 and 0.77.

Nath, Johnson, and Milliken (1982) determined that walker loss in grain sorghum was a function of grain moisture, cylinder speed, cylinder-concave clearance, and feed rate. The correlation coefficient of the model was 0.51. The equation:

$$WL = 32.78 - 3.57(M) + 0.97(M^2) - 0.091(C) - 7.8\,(F)(0.00047(SC^2)) + 0.87 - (227.04(M)2(F) + 0.4\,(M^2)(SC) - 0.805(MSC)2)(10-4) \qquad [11]$$

where

M = grain moisture (percent)

S = cylinder speed (m/s)

C = concave clearance (mm)

F = M.O.G. feed rate (kg/s)

2.6 Cleaning Performance Models

Nyborg, McColly, and Hinkle (1969) proposed a model to describe cleaning loss in Canadian wheat. The equation:

$$CL = 0.116(FR)^{0.37}(G/S)^{-1.35} \quad [12]$$

where

CL = cleaning loss (pounds)

FR = feed rate (pounds/minute)

G/S = grain to straw ratio

Fairbanks, Johnson, Schrock, and Nath (1979) developed two models to predict cleaning losses in grain sorghum. The equations:

$$CL = 9.953 - 0.3382(MG) + 0.00069(MG^2) + 7.0(10-6)(CC^3) \quad [13]$$

$$CL = 7.507 + 0.358(CS) + 0.00547(MGCS) \quad [14]$$

where

CL = cleaning loss (percent)

MG = grain moisture (percent)

CC = concave clearance (mm)

CS = cylidner speed (m/s)

Huynh and Powell (1978) developed a probalistic model based upon two events: the migration of kernels through the chaffer openings, and crop dwell time on the cleaning component. The equation:

$$R = e^{-t/\tau} \quad [15]$$

where

R = the fraction of grain lost

t = the reciprocal of the mean time required for the grain to pass through the material mat

τ = the crop dwell time in the chaffer

2.7 Systems Research

2.7.1 Definition

Systems research is an analytical study of a system and its sub-systems. The method is a means to rationally quantify the parameters of a system and the inter-relationships of the parameters. Systems research activities can be categorized as system analysis and system synthesis. System analysis involves the separation of a system into fundamental components, while system synthesis utilizes the information gained from the analysis to observe or modify the existing system (Manetsch and Park, 1982).

2.7.2 System Models

Models are quantitative representations of a process (system). They are used to gain knowledge and convey information. Models are typically used for any or all of the following reasons:

1) economic considerations,
2) availability,
3) information.

There are two broad categories of models: deterministic and probabilistic. A deterministic model produces a repeatable set of outcomes while a probabilistic model introduces an element of uncertainty. The output from a probabilistic model varies if repeatedly provided with the same set of inputs while a deterministic model will yield the same values for a repeated set of inputs.

2.7.3 Testing and Implementation

After constructing a systems model, it is necessary to prove that the model is an adequate representation of the real process depicted. First the model must be verified. Verification is the process of checking the mathematical correctness of the expressions in the model. Second, the model is validated to compare the output to reality. In some cases, it is not possible to validate the model because:

1) the real world process may not exist, or

2) there may be to little information about the

the model as he operated the combine through the simulated field of corn which was projected on the screen. The simulation allowed engineers to gather data in a laboratory setting where there was more control of the experiment and less cost. Systems research is a technique to examine a complete system. Agricultural engineers and other researchers have successfully employed this methodology to study existing or future systems.

2.8 Crop Properties Research

The bulk of crop properties research has been related to material handling of fruits and vegetables and for processing of commercial food products.

> Mohsenin (1965) stated," certain physical characteristics and engineering properties of material (food and agricultural products) should constitute important engineering data. Despite ever increasing applications of machinery, little is known about the physical properties of materials which influence the efficiency of the machine and the quality of the product.

Early research was conducted by Zink (1935) to determine the specific gravity of seeds and by Oxley (1944) who reported bulk densities for various grains. Most early research was conducted to aid the development of seed sorting and cleaning. Research has been conducted to measure various aspects of many types of seed (Zoerb,1960; Harmond 1965; Kazarian and Hall, 1965; Garrett and Brooker, 1965; Brubaker and Pos, 1965; Chung and Converse, 1965; Zoerb, 1972;and Kusterman, 1984). Most testing of seed involved testing individual seeds and not bulk quantities.

Huisman (1977) investigated the effects of straw moisture content, bulk density of straw, straw modulus of elasticity, kinetic coefficient of straw on straw, and straw length distribution. In doing so, he developed several methods to measure the properties.

Straw bulk density was determined by placing a known volume of straw in a circular tub and loading the material to 120 Pa. The container was then shaken for one minute with a frequency of 33.1 cycles per second and an amplitude of 2.5 centimeters. The volume occupied by the straw was then used as the bulk density.

Modulus of elasticity was determined with a specially constructed instrumented test stand. Bundles of straw were subjected to a 3-point simple bending test from which the modulus of elasticity was derived. Coefficient of friction between straws was also determined by a specially constructed instrumented test stand. A straw stem was attached such that it was pulled across another similarly attached stem. The normal force was known and the frictional force was read directly from a force transducer.

CHAPTER III

COMBINE PERFORMANCE AND BULK CROP PROPERTY MEASUREMENT

3.1 Introduction

Measured combine performance is known to change significantly during repeated performance tests. Much of the variation in combine performance can be attributed to changes in crop conditions such that slight changes in crop conditions can cause significant changes in combine performance. Stephens and Rabe (1977) reported that cloud cover or overnight frost caused changes in the crop which resulted in significant performance changes. Also, laboratory tests conducted with stored crops often are not duplicated in field tests and this led researchers to believe that the properties of the stored crop had changed.

A research project was initiated to determine the effect of crop properties on combine performance. The results of the study have particular relevance for combine performance testing procedures. Prototype combine performance is evaluated by comparison to the performance of a production model combine. Typically, the performance of a production machine for a test day in the field is established first. Subsequent performance prototype tests are compared with this standard. The decision to establish a new standard of performance is not based on quantitative information but upon intuition and the time available. The information from this study will enable test engineers to determine when crop conditions have shifted such that performance is affected. Also, laboratory test results can be extrapolated for field conditions.

3.2 Combine Performance

The performance of two combine components was measured during the study: the cleaner and the straw walker as defined by ASAE Standard S343.1.

Performance measurement of each component was determined from loss curves which were generated with the bag catch method as described in ASAE Standard S396. In this method, the combine was operated at a predetermined ground speed and the material which exited the cleaner and the straw walker was caught in two separate bags and the time required to make the catch noted. The bags were then sieved to remove any grain. The amount of grain in each sample was recorded as percentage loss of the total grain processed during the the time the bags were open. Since the time required to collect the material was noted, the feedrate of the material on each component could be calculated. Material feedrates for the cleaner and the straw walker were recorded as the (MOG) feedrates expressed in metric tons per hour. The combine was operated at different ground speeds and the procedure repeated to include a range of feedrates. The performance for the walker or the cleaner was determined by plotting grain loss percentage versus the total MOG feedrate or chaff MOG feedrate (Figures 2 and 3). The relationship between grain loss and feedrate was found to best fit an exponential equation. Simple regressions of the natural logarithm of grain loss on feedrate were performed for each series of bag catches. One equation was calculated for the cleaner and one equation was calculated for the straw walker. The general form of the loss equation after the simple regression was:

$$\text{loss}' = a' + b * f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [16]$$

where

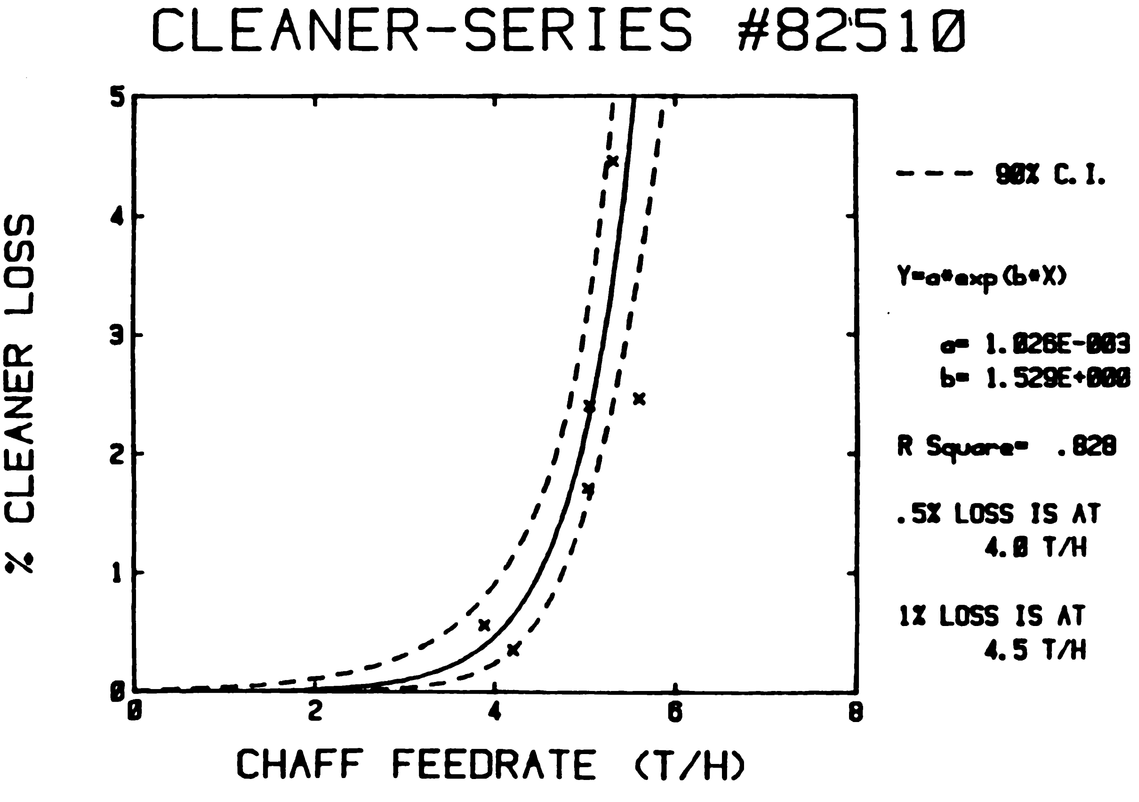

FIGURE 2

TYPICAL WHEAT CLEANER PERFORMANCE CURVE

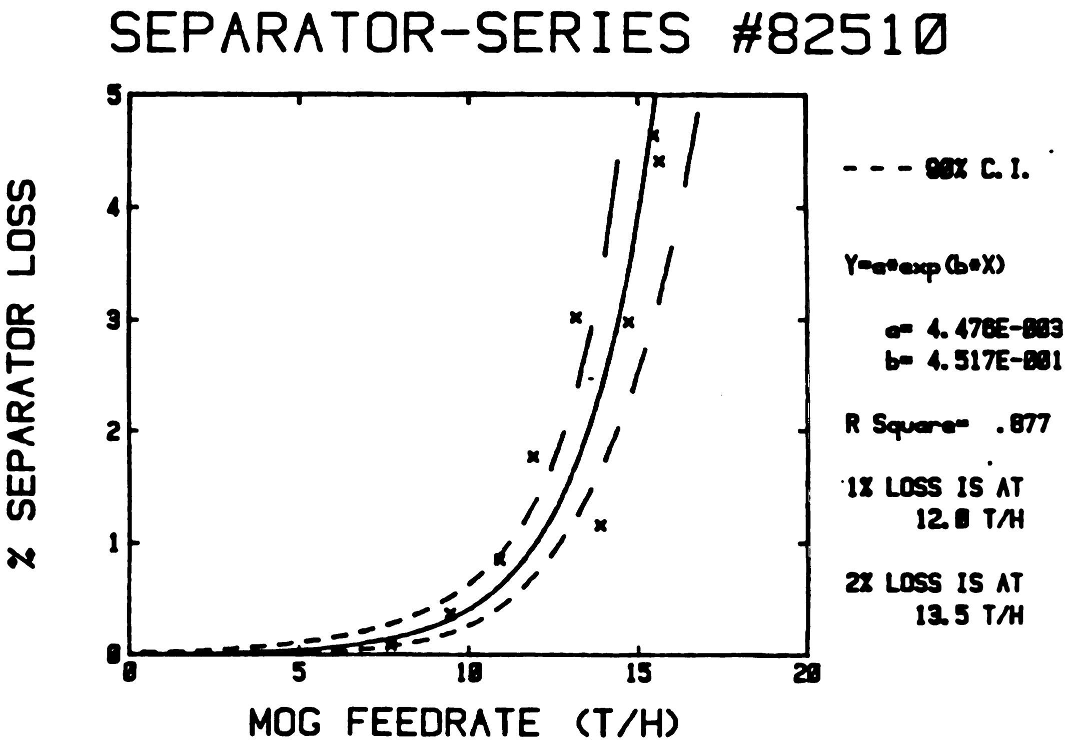

FIGURE 3

TYPICAL WHEAT STRAW WALKER PERFORMANCE CURVE loss'= natural log of grain loss (percent)

a' = natural log of regression coefficient

b = regression coefficient

f = chaff or M.O.G. feedrate (tons/hour)

The equation was further manipulated by taking the exponential of each term in Equation 16 to yield the following general form for cleaning loss or walker loss:

$$loss = a * \exp(b * f) \qquad [17]$$

where

loss = grain loss (percent)

a,b = regression coefficients

f = chaff or M.O.G. feedrate (tons/hour)

Cleaner performance was expressed as the chaff M.O.G. feedrate at 0.5 percent grain loss and straw walker performance was expressed as the total MOG feedrate at 1.0 percent grain loss as calculated from each respective equation. This method was used to determine the performance of components both in the field and in the laboratory. During laboratory testing, the crop material was placed on a conveyer belt and the feedrate was varied by altering the conveyer speed.

Performance data was gathered on two types of John Deere conventional harvesters, a 6620 combine, and a 8820 combine. All performance information was expressed in terms of a 6620 combine which is know to have two-thirds the capacity of an 8820 machine.

3.3 Measuring Bulk Crop Properties

3.3.1 Material Collection and Crop Properties Measured

Bulk samples of each crop component were collected from a production model combine harvester during generation of a loss curve. A sample of chaff MOG was collected from the a bag catch collected during the determination of each cleaner curve and a sample of walker MOG was collected during the determination of each walker curve. Grain was collected directly from the storage bin of the combine. Approximately 20 kilograms of grain was collected from the grain auger outlet in the storage bin during the generation of a loss curve and used in the determination of grain properties.

Twelve property measurements were performed upon the collected crop material without sorting or grading. They were grain moisture, grain density, grain angle of repose, chaff moisture, chaff density, chaff coefficient of friction, chaff mean length, chaff compressibility modulus, straw moisture, straw density, straw coefficient of friction, and straw compressibility modulus. In addition to loss curves, grain to MOG ratios and chaff to MOG ratios were measured (Table 1).

3.3.2 Crop Component Moisture

Grain moisture was determined with a John Deere portable moisture meter. The moisture contents of three to five grain sub-samples were determined and the mean moisture content calculated. Chaff and straw moistures (dry basis) were determined by oven drying samples using guidelines established by ASAE Standard S358.1.

3.3.3 Crop Bulk Density

Grain bulk density (kg/m^3) was determined by weighing a 1-litre sub-sample of grain which was collected from the grain tank. Three to five sub-sample densities were measured and averaged to obtain the final value for entry into the data set.

Chaff bulk density (kg/m^3) and straw bulk density (kg/m^3) were both determined using an automated test stand (Figure 4). Initially, chaff density was determined using a pexiglass cylinder loaded with 400.0

TABLE 1

BULK CROP PROPERTY COLLECTION INFORMATION LISTED BY LOCATION, YEAR, CROP, TEST ENVIRONMENT AND MACHINE MEASUREMENTS.

Location	Year	Crop	Test	Cleaner Curves	Walker Curves
Idaho	1980	Wheat, Barley	Field	22	21
Corchran, CA	1982	Wheat	Field	4	6
Fargo, ND	1982	Wheat	Field	3	4
Coal Valley, IL	1982	Wheat	Lab	0	10
Coal Valley, IL	1983	Wheat	Lab	3	0
Grand Forks, ND	1983	Wheat, Barley	Field	9	9
Coal Valley, IL	1984	Wheat	Lab	0	0
Coal Valley, IL	1984	Wheat	Field, Lab	0	6

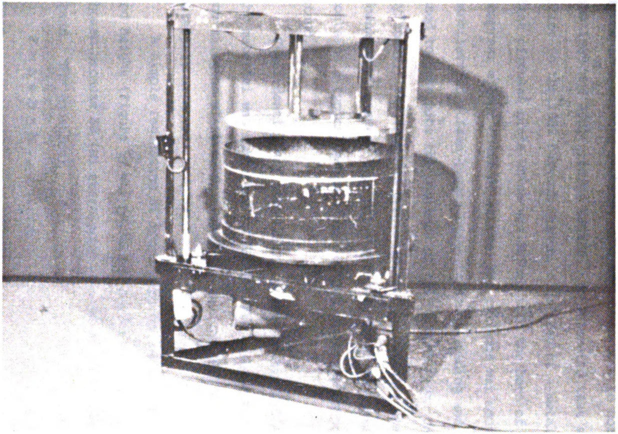

FIGURE 4

TEST STAND USED TO MEASURE DENSITY AND COMPRESSIBILITY MODULUS OF CHAFF AND STRAW grams of chaff. The cylinder was calibrated such that density was read directly from the side of the cylinder. A surface pressure of 280.0 (kPa) was used to compress the material for density determination because the pressure was thought to approximate the loading commonly found in a working combine. The stand was used to collect data during the 1980 and 1981 growing season. An automated test stand, constructed prior to the 1982 harvest season, consisted of a metal cylinder and a flat circular plate which was driven into the bore of the cylinder to compress either chaff or straw. The cylinder was mounted on three cantilevered strain gauged beams to sense loading and a potentiometer used to determine the distance of the plunger from the bottom of the cylinder. The crop was compressed as the circular plate was driven downward by a screw type drive attached to an electric motor. Figure 5 contains a typical graph of the output measurements produced by the test stand.

Chaff density and straw density were determined at the volume which the material was subjected to 280.0 (kPa). Three kilograms of chaff and one kilogram of straw were used for each respective test of crop material.

A simple regression of force over the range, 80.0 to 200.0 newtons and height (Figure 5) was performed for each sample. The range was chosen because 80 (N) corresponded to 280.0 (kPa) used in the previous stand. The equation:

$$F = a + b * h \qquad [18]$$

where

F = force exerted by the plunger

a,b = estimated regression coefficients

h = height (m) of the plunger from the bottom of the tub

was used to predict force for a given height and used in the calculation

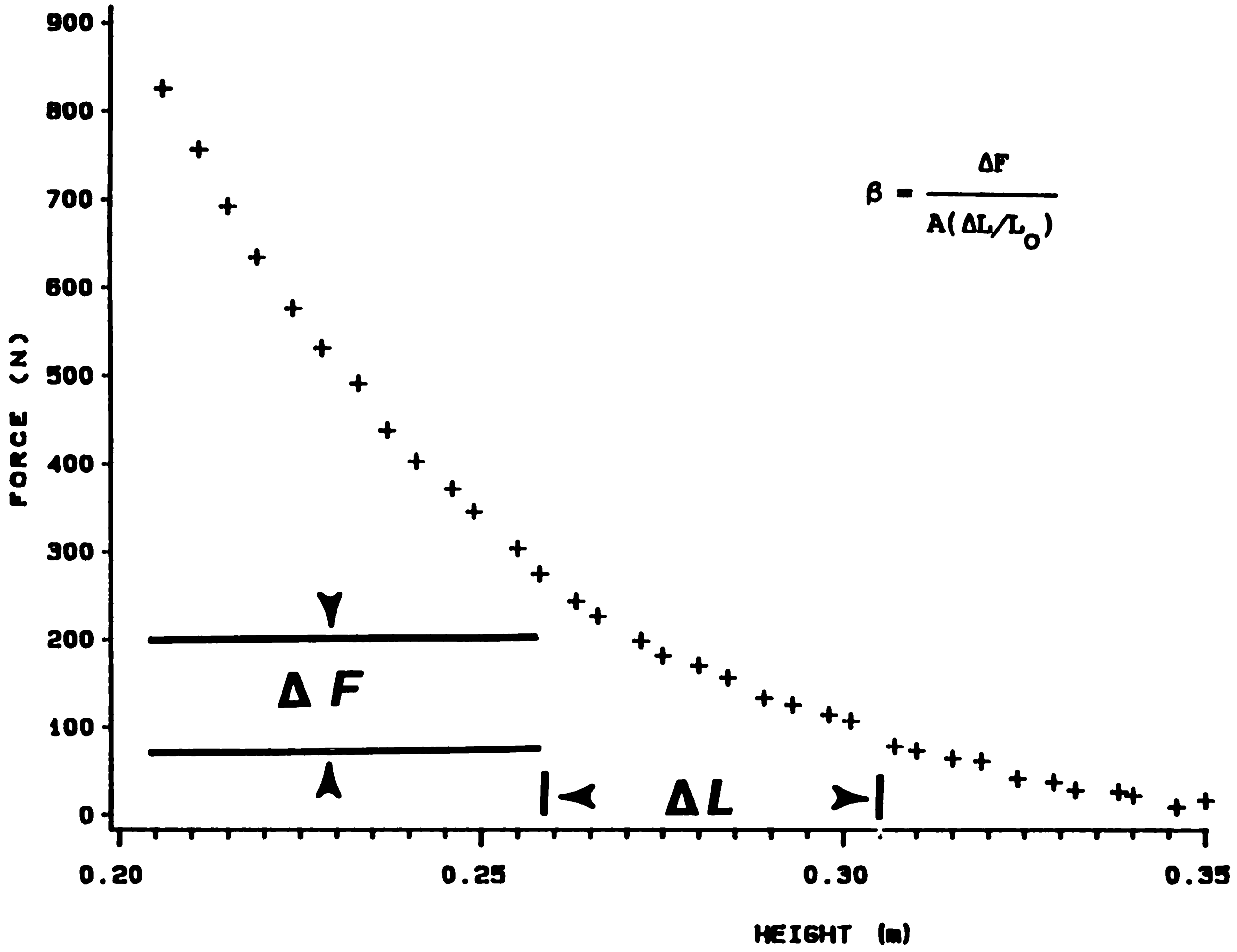

FIGURE 5

TYPICAL GRAPH OF DATA FROM TEST STAND USED TO MEASURE DENSITY AND COMPRESSIBILITY MODULUS OF CHAFF AND STRAW of bulk density and compressibility modulus of chaff and straw. The calculation of density for chaff or straw was performed using the known mass of material, the volume occupied at 280 (kPa), and the height at 280 (kPa) as calculated from Equation 18.

3.3.4 Compressibility Modulus

Compressibility modulus (kPa) is defined as:

$$\beta = \frac{\Delta\rho}{(\Delta V/V_o)} \quad \text{[19]}$$

where

$\Delta\rho$ = the change in applied pressure to the bulk sample

ΔV = the corresponding volumetric change and

V_o = the initial sample volume

As the circular plate descended, the volume of the crop material in the tub decreased while the area of the cylinder remained constant. The following calculating form of compressibility modulus was used:

$$\beta = \frac{\Delta F}{A(\Delta L/L_o)} \quad \text{[20]}$$

where

ΔF = the change in force(N)

A = the area(m) of the cylinder

ΔL = the corresponding change in height(m)

L_o = the initial height(m) of the sample

The change in force (ΔF) was predicted using Equation 18. As previously mentioned, the minimum value corresponds to the loading found in a combine. Two hundred newtons was chosen to standardize the fit and to provide the maximum number of linear points.

3.3.5 Crop Friction

Two types of friction measurements were conducted. The coefficient of friction between stainless steel and chaff or straw was determined as was the internal friction of grain on grain as related by angle of repose.

Chaff and straw coefficients of friction were measured with an automated stand (Figure 6). A sled was loaded with crop material and placed on a stainless steel surface which revolved when driven by an electric motor. The stand described by Hall and Husman (1981) was supplied by Deere and Company. An additional 1-kilogram weight was added to the sled. The sled was adjusted such that only crop material was in contact with the stainless steel surface. The sled was attached by a length of wire to a strain-gauged cantilevered beam. As the steel surface revolved, the frictional force was sensed by the can cantilevered beam. Since the normal force was known, the coefficient of friction was easily determined. The sampling procedure was conducted such that one revolution of the table was the duration of the test. Thirty-three coefficients of friction were averaged for a single value. Grain angle of repose as defined by Hall and Huisman (1981) was measured by placing a 1-litre sample of grain in a hollow cylinder (Figure 7). The cylinder was then slowly raised and the resulting cone height measured. The angle of repose was then determined knowing the volume and the height of the cone formed by the grain.

3.3.6 Particle Distribution

Chaff mean length was the only particle size measurement used. Measuring straw mean length was attempted by hand-counting a large straw sample. The measurement did not prove to be repeatable and required an excessive amount of time consequently, the determination of straw mean length was discontinued.

Chaff mean length is the mean particle size of a bulk chaff sample.

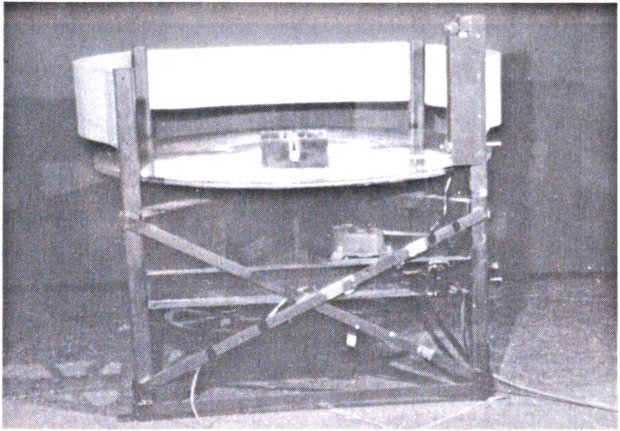

FIGURE 6

TEST STAND USED TO MEASURE CHAFF AND STRAW
COEFFICIENTS OF FRICTION

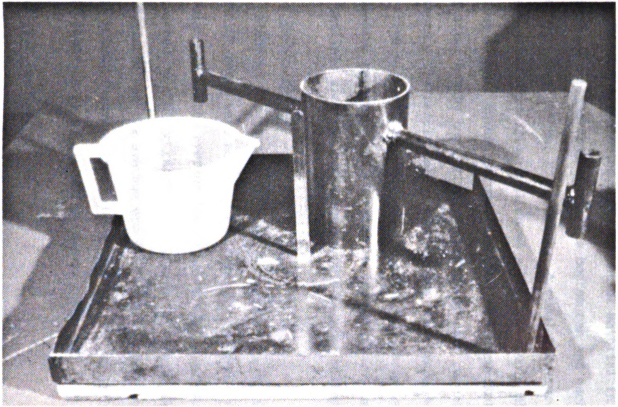

FIGURE 7

TEST STAND USED TO MEASURE GRAIN ANGLE OF REPOSE

A test stand constructed by Deere and Company was used to sort chaff into various sizes (Figure 8). Four sieves (19.03, 12.70, 6.35, 3.175 mm) were contained in a metal shaker box. A 1-kilogram sample was placed in the top of the box. The entire box was then driven by a crank mechanism for two minutes. The amount of material in each sieve was weighed as was the contents in the bottom pan and each weight expressed as a percentage of the total catch. A cumulative curve of percent catch versus sieve size (Figure 9) shows a typical sample distribution. Least squares linear regression was performed on the cumulative distribution data after taking the natural logarithm of each cumulative sieve contents. The resulting equation, where the independent variable was the sieve size of each tray and the dependent variable was the cumulative percentage of material in each tray, was used to calculate the particle size corresponding to 50.0 percent probability.

3.3.7 M.O.G. Ratios

Although not true crop properties, grain to M.O.G. ratio and chaff to M.O.G. ratio were measured by Deere and Company. Both ratios were calculated with the average feedrates of chaff, grain, and straw as determined by the bag catches for loss curve determination. Grain to M.O.G. ratio was the average grain feedrate (t/h) divided by the average total M.O.G. feedrate (t/h) while chaff to M.O.G. ratio was the average chaff feedrate (t/h) divided by the average total M.O.G. feedrate (t/h).

3.3.8 Instrumentation

A Hewelett Packard 85 computer, Hewelett Packard 3497 data acquisition unit, and two specially constructed John Deere signal conditioners were used to collect data from instrumented test stands (Figure 10). A K-tron electronic scale with digital read-out was used

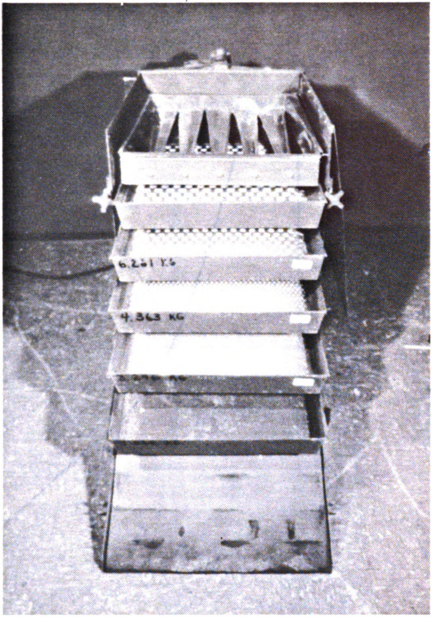

FIGURE 8

TEST STAND USED TO SIEVE CHAFF INTO SIZE COMPONENTS

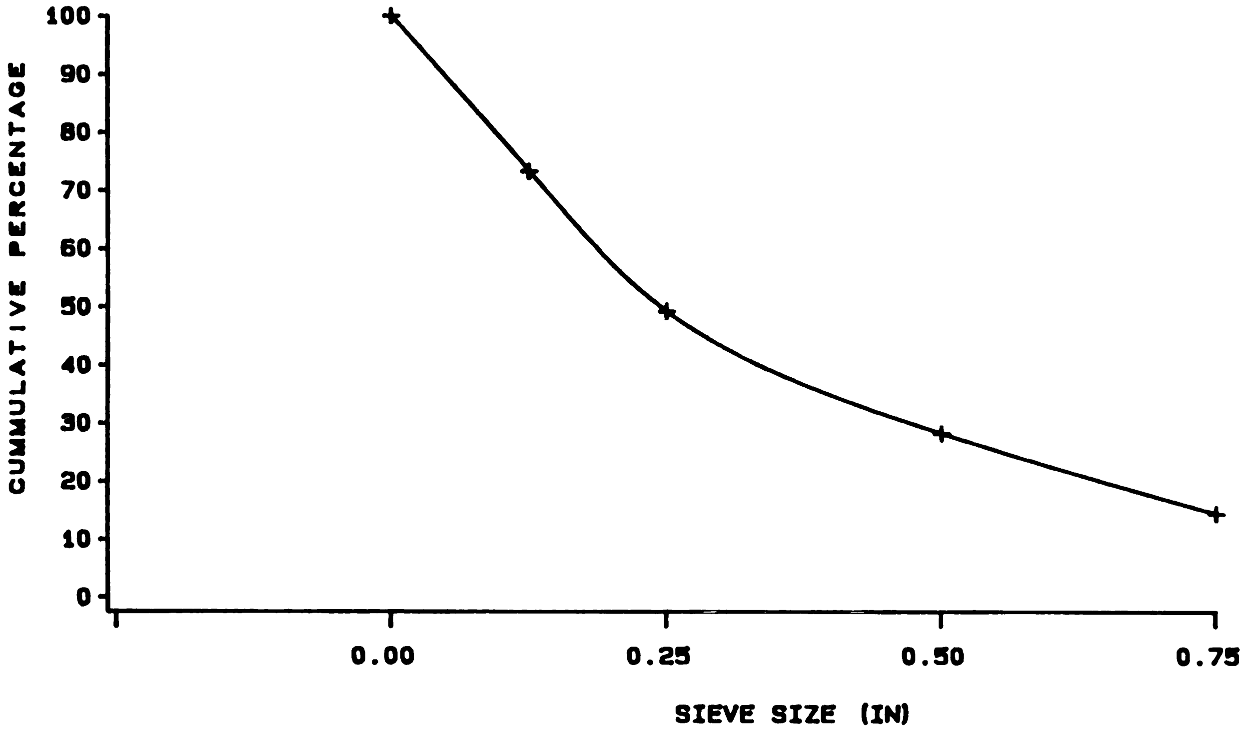

FIGURE 9

TYPICAL CHAFF SIZE DISTRIBUTION CURVE

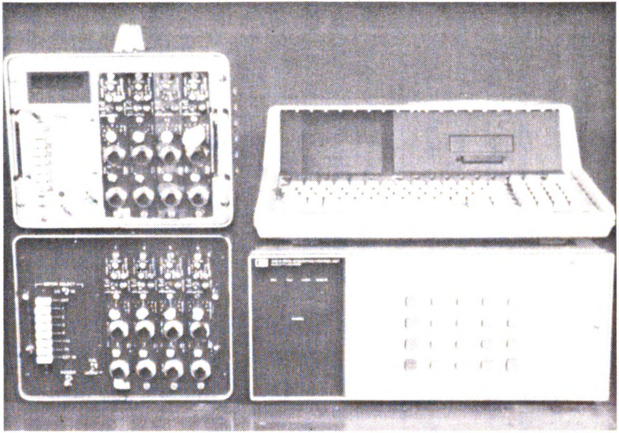

FIGURE 10

ELECTRONIC INSTRUMENTATION USED FOR
CROP PROPERTY DATA COLLECTION

to weigh crop material. The accuracy of the instrument was rated at plus or minus two grams.

CHAPTER IV

CORRELATION OF CROP PROPERTIES TO COMBINE PERFORMANCE AND THE EFFECT OF MOISTURE ON CROP PROPERTIES

4.1 Introduction

This chapter is presented in two major sections. The first portion of the chapter addresses the effects of crop properties on cleaner and straw walker performance. The second portion of chapter discusses the influence of moisture on each crop property.

Several methods were employed to determine the effect of a crop property on cleaner or straw walker performance. An important distinction must be made in this chapter, the effect of each property on performance was analyzed singly. No attempt was made to control the influence of other properties on performance during the analysis of a single property. The objective was to provide a field engineer with a set of information which will enable him to determine when the performance of a combine component has measurably changed by monitoring a single property. To accomplish the objective it was necessary to determine the changes in each property associated with a measurable shift in performance.

The complete data set is located in Appendix A. Means and standard deviations of all the crop property and machine performance measurements are recorded by test location in Table 2 while measurement errors for each property were estimated and recorded in Table 3. The measurement errors are an estimation of the ability to measure each property. For example, grain angle of repose can be measured with an accuracy of 0.40 degrees. A property measurement was the average of several sub-sample measurements. In the case of grain angle of repose, several

TABLE 2

MEANS AND STANDARD DEVIATIONS OF PROPERTY DATA AND MACHINE PARAMETERS LISTED BY LOCATION AND CROP TYPE.

	All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo North Dakota (Wheat)	1982 Labora-tory (Wheat)	1983 Labora-tory (Wheat)	1983 Grand Forks, North Dakota (Barley)	1984 Labora-tory (Wheat)	1984 Labor-tory & Field at Coal Valley Illinois (Wheat)
Grain Moisture	14.28 (4.74)	12.68 (2.68)	13.28 (4.23)	9.29 (0.53)	12.82 (1.02)	14.81 (3.04)	15.91 (2.38)	12.24 (2.46)	10.50 (0.14)	17.91 (5.46)
Chaff Moisture	11.16 (4.04)	10.57 (3.99)	13.05 (5.04)	6.85 (4.14)	9.65 (3.64)	- -	12.89 (2.64)	9.82 (1.57)	10.20 (1.63)	- -
Straw Moisture	18.94 (15.24)	19.72 (9.15)	12.81 (4.34)	9.10 (1.82)	18.12 (15.43)	15.69 (5.32)	- -	15.41 (4.28)	10.30 -	26.2 (21.9)
Grain Density	772.0 (75.0)	693.0 (29.0)	849.0 (35.0)	885.0 (41.0)	800.0 (22.0)	809.0 (19.3)	786.0 (15.7)	645.0 (32.0)	825.0 (7.0)	751.0 (32.0)
Chaff Density	42.4 (7.0)	42.2 (4.5)	47.4 (4.6)	53.4 (8.9)	39.8 (6.8)	- -	43.0 (4.9)	42.4 (4.8)	40.35 (1.3)	- -
Straw Density	16.3 (3.3)	14.9 (2.0)	16.5 (3.1)	19.0 (2.9)	14.7 (2.6)	17.1 (2.3)	- -	15.3 (2.3)	15.6 -	16.0 (4.0)
Chaff Mean Length	7.69 (2.34)	10.66 (1.91)	11.30 (1.08)	8.27 (2.17)	6.99 (0.90)	- -	10.31 (0.93)	5.22 (1.32)	5.39 (0.88)	9.63 (1.08)
Chaff Compressibility Modulus	4.55 (1.97)	- -	- -	7.60 (2.34)	6.94 (1.25)	- -	4.45 (0.37)	3.56 (0.16)	3.85 (0.01)	- -
Straw Compressibility Modulus	2.07 (0.42)	- -	- -	2.21 (0.34)	2.70 (0.50)	1.69 (0.14)	- -	1.89 (0.24)	2.07 -	2.06 (0.37)
Grain Angle of Repose	22.4 (2.7)	24.1 (1.0)	22.8 (2.8)	20.5 (1.6)	22.1 (1.5)	23.1 (1.7)	24.9 (2.7)	25.0 (0.4)	21.0 (1.6)	21.0 (3.2)
Chaff Coefficient of Friction	0.329 (0.048)	0.268 (0.029)	0.360 (0.040)	0.274 (0.009)	0.333 (0.039)	- -	0.309 (0.017)	0.366 (0.027)	0.345 (0.013)	- -

* Mean
** ( ) Standard Deviations

TABLE 2 continued

	All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo North Dakota (Wheat)	1982 Labora-tory (Wheat)	1983 Labora-tory (Wheat)	1983 Grand Forks, North Dakota (Barley)	1984 Labora-tory (Wheat)	1984 Labor-tory & Field at Coal Valley Illinois (Wheat)
Straw Coefficient of Friction	0.339	0.354	0.355	0.272	0.320	0.303	-	0.361	0.278	0.360
	(0.050)	(0.029)	(0.029)	(0.019)	(0.04)	(0.021)	-	(0.041)	-	(0.054)
Grain to M.O.G. Ratio	1.73	-	-	1.39	0.84	-	0.58	1.57	1.01	-
	(0.64)	-	-	(0.89)	(0.13)	-	(0.22)	(0.15)	(1.20)	-
Chaff to M.O.G. Ratio	0.35	-	-	0.43	0.38	-	0.20	0.34	0.24	-
	(0.10)	-	-	(0.08)	(0.07)	-	(0.06)	(0.06)	(0.06)	-
Cleaner Feedrate at 0.05 Percent Cleaner Loss	1.74	1.16	1.63	4.00	3.13	-	2.03	1.16	2.20	-
	(0.99)	(0.42)	(0.50)	(0.16)	(0.15)	-	(0.49)	(0.22)	-	-
Total M.O.G. Feedrate At 1.0 Percent Walker Loss	7.37	4.28	5.92	9.57	14.07	7.21	-	6.81	9.05	9.63
	(2.92)	(0.77)	(2.04)	(2.88)	(0.80)	(0.98)	-	(0.51)	(0.78)	(1.08)

TABLE 3

MEASUREMENT ERRORS FOR EACH BULK CROP PROPERTY.

Property	Measurement error
Grain Moisture (%)	0.18
Chaff Moisture (%)	0.40
Straw Moisture (%)	1.20
Grain Density (kg/m^3)	9.5
Chaff Density (kg/m^3)	1.6
Straw Density (kg/m^3)	1.0
Chaff Compressibility Modulus (kPa)	0.42
Straw Compressibility Modulus (kPa)	0.38
Grain Angle of Repose (degrees)	0.40
Chaff Coefficient of Friction	0.015
Straw Coefficient of Friction	0.025
Chaff Mean Length (mm)	0.5

sub-samples of grain were drawn and the grain angle of repose of each sub-sample determined. The mean and standard deviation of the sub-sample measurements was then calculated and recorded as the grain angle of repose of the sample. The error of measurement was estimated by calculating the mean of all the standard deviations for each property sample.

The correlation of crop properties to the performance of the cleaner and the walker was performed (Tables 4 and 5) but the correlations did not explain the property change required before a measurable performance shift occurred. Scatter plots of cleaner and walker performance versus each crop property are located in Appendix B. Single variable equations derived from simple regressions were generated to express performance as a function of properties for both the cleaner and the straw walker. The slope of each equation (Table 6) was evaluated to determine the property change associated with a 1-ton/hour feedrate performance increase. For example, the slope of the equation which described cleaning performance as a function of grain angle of repose was -0.34 (ton/hour)/(degree). The reciprocal of the slope was 2.95 (degree)/(ton/hour). In other words, based on the relationship between chaff feedrate at 0.5 percent grain loss and grain angle of repose, a 2.95 degree property change produced a 1-ton/hour change in chaff feedrate.

A 10.0 percent performance shift was thought to be the minimum detectable difference in combine performance as opposed to a 1-ton/hour change in feedrate which was equivalent to a 42.0 percent change in cleaner performance and a 13.5 percent change in walker performance. In fact, a 20.0 percent shift may be a more realistic figure.

It was desired to determine what property changes were required to

TABLE 4

CORRELATION OF CLEANER PERFORMANCE TO CROP PROPERTIES LISTED BY LOCATION AND CROP TYPE.

		All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo, North Dakota (Wheat)	1983 Laboratory (Wheat)	1983 Grand forks, North Dakota (Wheat)
Grain Moisture	*	-0.34	-0.73	-0.17	0.71	-0.57	-0.67	0.35
	**	41	9	13	13	4	3	9
	***	0.014	0.012	0.28	0.144	0.308	0.267	0.351
Grain Density		0.69	0.71	0.15	0.19	1.00	0.96	0.87
		41	9	13	4	3	3	9
		0.001	0.015	0.307	0.407	0.001	0.094	0.002
Grain Angle of Repose		-0.75	-0.73	-0.30	-0.07	0.19	-0.59	-0.90
		41	9	13	4	3	3	9
		0.001	0.012	0.157	0.465	0.439	0.328	0.000
Chaff Moisture		-0.35	-0.66	-0.07	0.26	0.96	-0.52	-0.18
		41	9	13	4	3	3	9
		0.013	0.027	0.416	0.37	0.09	0.328	0.640
Chaff Density		-	-0.88	0.13	-0.73	-0.96	0.77	-0.37
		-	9	12	4	3	3	9
		-	0.001	0.33	0.135	0.087	0.218	0.322
Chaff Compressibility Modulus		0.85	-	-	-0.02	0.36	-0.24	0.614
		19	-	-	4	3	3	9
		0.001	-	-	0.488	0.384	0.42	0.078
Chaff Coefficient of Friction		-0.68	-0.34	0.24	-0.77	-0.73	-0.87	-0.36
		41	9	13	4	3	3	9
		0.001	0.189	0.21	0.113	0.238	0.167	0.342
Chaff Mean Length		-0.37	-0.01	0.69	0.28	-0.94	-0.76	-0.09
		41	9	13	4	3	3	9
		0.009	0.486	0.005	0.362	0.107	0.224	0.817
Grain to M.O.G. Ratio		-0.19	-	-	0.73	0.67	-0.93	-0.52
		19	-	-	4	3	3	9
		0.213	-	-	0.133	0.265	0.121	0.151

* Correlation Coefficient
** Observations
*** Significance Level

TABLE 4 continued

	All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo, North Dakota (Wheat)	1983 Laboratory (Wheat)	1983 Grand forks, North Dakota (Wheat)
*Chaff to M.O.G. Ratio	0.58	-	-	0.69	0.91	-0.20	-0.05
	19	-	-	4	3	3	9
	0.016	-	-	0.154	0.142	0.436	0.904

TABLE 5

CORRELATION OF STRAW WALKER PERFORMANCE TO CROP PROPERTIES LISTED BY LOCATION AND CROP TYPE.

		All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo, North Dakota (Wheat)	1982 Laboratory (Wheat)	1983 Grand Forks, North Dakota (Wheat)	1984 Laboratory & Field at Coal Valley Illinois
Grain Moisture	*	-0.06	-0.27	-0.02	0.56	0.96	-0.27	-0.21	-0.66
	**	56	9	12	6	4	10	9	8
	***	0.338	0.244	0.479	0.123	0.018	0.018	0.585	0.78
Grain Density		0.38	0.25	-0.22	-0.27	-0.77	0.26	0.79	0.87
		55	9	12	6	4	10	9	5
		0.002	0.260	0.24	0.305	0.113	0.230	0.012	0.028
Grain Angle		-0.44	-0.47	0.44	-0.46	0.06	-0.32	-0.91	-0.49
		55	9	12	6	4	10	9	5
		0.001	0.099	0.075	0.182	0.471	0.185	0.006	0.227
Straw Moisture		0.07	0.60	0.10	-0.40	0.77	-0.47	-	-0.55
		55	9	12	6	4	10	-	6
		0.306	0.045	0.379	0.214	0.112	0.085	-	0.126
Straw Density		0.09	-0.13	-0.43	0.50	0.91	-0.66	-0.16	-0.37
		55	9	11	6	4	10	9	6
		0.473	0.365	0.091	0.157	0.044	0.018	0.713	0.232
Straw Compressibility Modulus		0.43	-	-	-0.78	-0.87	0.40	0.10	0.09
		34	-	-	6	4	10	9	6
		0.005	-	-	0.033	0.066	0.126	0.820	0.435
Straw Coefficient Friction		-0.41	0.21	-0.54	0.34	0.04	-0.42	-0.50	0.09
		55	9	12	6	4	10	9	6
		0.001	0.295	0.03	0.255	0.480	0.113	0.21	0.432
Grain to M.O.G. Ratio		-0.38	-	-	0.36	-0.17	-	-0.53	-
		19	-	-	6	4	-	9	-
		0.052	-	-	0.243	0.413	-	0.140	-

* Correlation Coefficient

** Observations

*** Significance Level

TABLE 5 continued

	All Data	1980 Idaho (Wheat)	1980 Idaho (Barley)	1982 Corchran, California (Wheat)	1982 Fargo, North Dakota (Wheat)	1982 Laboratory (Wheat)	1983 Grand Forks, North Dakota (Wheat)	1984 Laboratory & Field at Coal Valley Illinois
Chaff to M.O.G. Ratio	0.46	-	-	0.83	-0.70	-	-	-
	19	-	-	6	4	-	-	-
	0.024	-	-	0.02	0.149	-	-	-

TABLE 6

SLOPES OF SINGLE VARIABLE REGRESSION EQUATIONS WHICH DESCRIBE CLEANER AND STRAW WALKER PERFORMANCE AS FUNCTIONS OF CROP PROPERTIES.

	Cleaner	Straw Walker
Grain Density	-0.008	0.013
Grain Angle of Repose	-0.340	-0.054
Chaff Coefficient of Friction	-15.300	-
Straw Coefficient of Friction	-	-29.200
Chaff Density	0.06	-
Straw Density	-	0.010
Chaff Compressibility	0.40	-
Straw Compressibility	-	2.900
Chaff Mean Length	-0.150	-
Grain Moisture	-0.090	-
Straw Moisture	-	0.010
Grain to M.O.G Ratio	0.52	-3.16
Chaff to M.O.G Ratio	6.54	-

observe a measurable shift in performance. Reference points were required to establish a basis for determining the chaff feedrate and total M.O.G. feedrate equivalent to a 20.0 percent shift in cleaner and walker performance. The overall performance means for cleaner and walker performance were used. The mean performance for the cleaner was 1.77 (tons/hour) chaff feedrate at 0.5 percent grain loss and 7.37 (tons/hour) total M.O.G. feedrate at 1.0 percent grain loss for the walker (Table 2). A 20.0 percent performance shift was equal to 0.35 (tons/hour) for the cleaner and 1.47(tons/hour) for the walker. Property changes required to cause a 20.0 percent shift in performance from the overall mean were calculated by multiplying the 20.0 percent feedrate by the inverse slope from each equation. For example, using data from Table 6, the property change for grain angle of repose was 1.04 degrees, or 2.95 (degrees)/(tons/hour) multiplied by 0.35 (tons/hour).

Probabilities were calculated to express the likelihood of observing a property change which would result in a measurable performance shift. The results of the these calculations for cleaner performance and walker performance are shown in Tables 7 and 8.

A large sample of properties data was assumed such that the standard normal tables were used to determine the associated probabilities. The required change in each property which caused a measurable change in performance was normalized using each respective overall data set standard deviation (Table 2) and the probability determined from statistical tables. For example, "Z" values for the standard normal curve were calculated for grain angle of repose by dividing 1.04 degrees (Table 6) times 2.0, the property change required for a measurable shift in cleaner performance, by 2.7 degrees (Table 2),

TABLE 7

PROPERTY CHANGES ASSOCIATED WITH A MEASURABLE CHANGE IN CLEANER PERFORMANCE AND THE PROBABILITY OF SUCH A CHANGE.

	Change in Property Required for 20 Percent Performance Shift	Probability of Property Change Associated with 20 Percent Performance Shift
Grain Density	47.0 (kg/m^3)	21.0
Grain Angle of Repose	1.04 (degrees)	44.0
Chaff Coefficient of Friction	0.025	30.0
Chaff Density	5.6 (kg/m^3)	13.0
Chaff Compressibility Modulus	0.9 (kPa)	37.0
Grain Moisture	3.2 (%)	18.0
Chaff Mean Length	2.3 (mm)	5.0
Chaff Moisture	4.0 (%)	5.0
Grain to M.O.G. Ratio	0.7	5.0
Chaff to M.O.G. Ratio	0.05	3.0

TABLE 8

PROPERTY CHANGE ASSOCIATED WITH A MEASURABLE CHANGE IN STRAW WALKER PERFORMANCE AND THE PROBABILITY OF SUCH A CHANGE.

	Change in Property Required for 20 Percent Performance Shift	Probability of Property Change Associated with 20 Percent Performance Shift
Grain Density	113.0 (kg/m^3)	< 1.0
Grain Angle of Repose	2.7 (degrees)	5.0
Straw Coefficient of Friction	0.040	11.0
Straw Modulus	0.5 (kPa)	2.0
Grain Moisture	32.0 (%)	0
Straw Moisture	77.0 (%)	0
Straw Density	150.0 (kg/m^3)	0
Grain to M.O.G. Ratio	0.46	15.0

the standard deviation of grain angle of repose for the entire data set. The resulting "Z" value, 0.77, describes a standardized distance from the mean of grain angle of repose which lies at 0.0. The "Z" value corresponds to an area under the curve for values of grain angle of repose which lie outside plus or minus 1.04 degrees from the mean of grain angle of repose. The area under the curve which is approximately 44.0 percent is the percentage of grain angle of repose values in the sample which were plus or minus 1.04 degrees from the mean value. This percentage is also the sample probability that a grain angle of repose is plus or minus 1.04 degrees from the mean.

Table 9 lists the performance to property ratios for the cleaner and the straw walker. The ratio of change in performance to change in each a property is an indicator of the relative importance of each crop property. The ratios were calculated by dividing 20.0 percent (measurable machine shift) by the change in property (Tables 6 and 7) expressed as percentage of the property mean. For example, the percentage change in grain angle of repose from the mean value of grain angle of repose is 1.04 (Table 2) divided by 22.4 (Table 2) multiplied by 100 percent which equals 4.6 percent. The ratio (change in performance/change in property) is 4.3 (Table 9) or 20.0 percent divided by 4.6 percent. The ratio indicates how responsive performance was to corresponding property changes.

4.2 Effect of Crop Properties on Cleaner Performance

4.2.1 Grain Angle of Repose

Grain angle of repose was negatively correlated with cleaning performance. As a correlation of -0.75 (Table 4) indicates, performance tended to improve as grain angle of repose decreased. It appears that grain was less likely to pass through the chaff mat as the angle of

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TABLE 9

UNIT CHANGE IN CLEANER PERFORMANCE AND WALKER PERFORMANCE FOR A UNIT CHANGE IN A CROP PROPERTY.

	Ratio of Cleaner Performance to Property Change	Ratio of Straw Walker Performance to Property Change
Grain Density	3.3	1.4
Grain Angle of Repose	4.3	1.7
Chaff Coefficient of Friction	2.8	-
Straw Coefficient of Friction	-	1.4
Chaff Density	1.4	-
Straw Density	-	0.0
Chaff Mean Length	0.8	-
Grain Moisture	0.9	0.1
Chaff Moisture	0.6	-
Straw Moisture	-	0.0
Grain to M.O.G. Ratio	0.5	0.7
Chaff to M.O.G. Ratio	1.3	-

repose increased.

Cleaner performance appeared to be most sensitive to changes in grain angle of repose based upon a calculated performance to property ratio of 4.3 (Table 9). A 1.04 degree change was required to observe a measurable change in cleaning performance (Table 7) while the likelihood of observing such a property change was 44.0 percent. The ability to measure a 1.04 degree change was well within the accuracy of measurement (Table 3) as the mean sample variation was 0.44 degrees.

4.2.2 Grain Density

Grain density (kg/m^3) was positively correlated with cleaning performance based on a correlation coefficient of 0.69 (Table 4). Cleaner performance increased 3.3 times for every corresponding increase in grain density (Table 9). A 43.0 (kg/m^3) change in grain density was required to detect a measurable shift in cleaner performance. The probability of such a property change was 21.0 percent. The required property change was well within the sampling variation of 9.5 (kg/m^3) (Table 3).

4.2.3 Chaff Coefficient of Friction

Chaff friction was inversely related to cleaning performance. A correlation of -0.68 indicates a strong relationship to cleaning performance (Table 4). Higher levels of chaff friction tended to impede movement of the chaff mat across the cleaner and probably impeded the flow of grain through the chaff mat.

Cleaning performance had a performance to property ratio of 2.8 with chaff friction (Table 9) which indicates the cleaner is relatively sensitive to changes in chaff coefficient of friction. A friction change of 0.025 was required to observe a measurable performance shift while the probability of a measurable property shift was 30.0 percent (Table 7). The property change was readily detected based upon a sampling variation of 0.015 (Table 3).

4.2.4 Chaff Density

Chaff density (kg/m^3) was positively related to cleaner performance based on a correlation coefficient of 0.36 (Table 4). This was not the expected result. It was believed that higher chaff densities, having less pore space, would be more difficult to clean. The decrease in voids was thought to inhibit grain movement through the chaff mat. The cleaner was sensitive to changes in chaff density as evidenced by a performance to property ratio of 1.40 (Table 9). A 5.62 (kg/m^3) change in chaff density was required to observe a measurable performance change (Table 7). The probability of observing a significant property shift was 11.0 percent (Table 7). Based on accuracy of measurement data, it was possible to detect shifts in chaff density.

4.2.5 Chaff Compressibility Modulus

Chaff compressibility modulus (kPa) was positively correlated with cleaner performance. The correlation coefficient was 0.85 (Table 4). The relationship seems intuitively correct because chaff with larger modulus values indicates resistance to volumetric change. Chaff which was resistive to volumetric change would likely have more pore space while being cleaned. A performance to property ratio of 1.0 indicates that a 20.0 percent performance shift required a 20.0 percent property shift (Table 9). An 0.90 (kPa) change in compressibility modulus was required to observe a measurable performance shift (Table 7) while the probability of observing a property shift was 37.0 percent. The accuracy of measurement for chaff compressibility modulus was 0.42 (kPa) which was well within the change required (Table 3) to detect a measurable property change.

4.2.6 Grain and Chaff Moisture

Grain moisture appeared to have a negative effect upon cleaner performance based on a correlation coefficient of -0.31 while chaff moisture had little if any effect on cleaning performance based on a correlation of -0.03 (Table 4). The performance to property ratios for grain moisture and chaff moisture were 0.90 and 0.60, respectively (Table 9). A 3.2 percent shift in grain moisture and 4.0 percent shift in chaff moisture were required to observe a measurable performance shift (Table 7). The probability of observing a significant grain moisture shift was 18.0 percent and 5.0 percent for chaff moisture (Table 7). Both property changes are measurable based upon sampling accuracy. The mean variation for grain moisture was 0.24 percent and 0.40 percent for chaff moisture (Table 3).

4.2.7 Chaff Mean Length

Chaff mean length (mm) was inversely related with performance. The correlation between cleaner performance and chaff mean length is -0.37 (Table 4). A higher mean length was a indication of more loading on the cleaning component and decreased performance. The performance to property ratio for chaff length was 0.80 (Table 9). A change of 2.33 (mm) was required to observe a measurable property shift (Table 7). The probability of observing a significant property shift was 5.0 percent (Table 7) while the mean sample variation for chaff mean length was 0.52 (mm) (Table 3).

4.2.8 M.O.G. Ratios

Grain to M.O.G. ratio had a minimal effect upon cleaner performance as indicated by the low correlation of -0.19 (Table 4). Based on the poor correlation, the effect of grain to M.O.G. ratio on cleaner performance appears inconclusive.

Chaff to M.O.G. was more highly correlated to cleaner performance than was grain to M.O.G. ratio based on a correlation of 0.58. Cleaner performance tended to increase as chaff to M.O.G. ratio increased. A change of 0.05 in the chaff to M.O.G. ratio resulted in a 20.0 percent change in cleaner performance. The likelihood of observing a measurable change in cleaner performance as a result of a shift in chaff to M.O.G. ratio was 32.0 percent.

4.3 Effect of Crop Properties on Straw Walker Performance

4.3.1 Grain Angle of Repose

Grain angle of repose (degrees) affected walker performance in much the same manner as cleaner performance. The correlation between grain angle of repose and walker performance was -0.44 (Table 5). As grain angle of repose increased, performance tended to decrease. Grain with larger values of angle of repose appeared to be less likely to pass through the straw mat.

The performance to property ratio for grain angle of repose and walker performance was 1.7 (Table 9). A 2.77 degree change in angle of repose was required to observe a measurable shift in walker performance. The probability of observing a property change was 5.0 percent (Table 8). The sample accuracy for angle of repose was 0.44 degrees (Table 3).

4.3.2 Grain Density

Grain density (kg/m^3) was positively correlated with walker performance as evidenced by a correlation coefficient of 0.38 (Table 5). Larger grain densities were associated with better grain movement through the straw mat.

A performance to property ratio of 1.4 indicated the influence of grain density on walker performance relative to the other properties (Table 9). A 113.0 (kg/m^3) change in grain density was required to observe a measurable performance shift (Table 8). The probability of observing such a property shift was less than 1.0 percent (Table 8). The sample accuracy was 9.5 (kg/m^3) (Table 3).

4.3.3 Straw Coefficient of Friction

Straw coefficient of friction was inversely related to walker performance. The correlation coefficient between straw friction and walker performance was -0.41 (Table 5). As the coefficient of friction increased, the movement of straw across the walker was reduced as was capacity.

The performance to property ratio for straw friction was 1.4 (Table 9). A 0.04 change in straw friction was required to observe a measurable change in walker performance (Table 7). The probability of observing a property change which corresponded to a measurable machine shift was 11.0 percent. Since the sample accuracy was 0.25, a property shift was measurable (Table 3).

4.3.4. Straw Compressibility Modulus

Straw compressibility modulus (kPa) was positively related to walker performance. The correlation coefficient was 0.43 (Table 5). Straw with higher modulus values tended to resist compaction and maintained its porosity.

The performance to property ratio for compressibility modulus was 0.80 (Table 9). A 0.51 (kPa) change in compressibility was required to detect a measurable performance shift (Table 8). The probability of observing a property change which corresponded to a measurable performance shift was 2.0 percent. The sampling accuracy was 0.38 (kPa) (Table 3).

4.3.5 Remaining Straw Properties

The remainder of the walker performance related properties appeared to have little affect on performance. Grain moisture, straw moisture, straw density, and grain to M.O.G. all appeared to have a negligible affect on performance. All were poorly correlated and required extreme property changes to alter performance.

4.4 Conclusions

Cleaning performance was more sensitive to crop changes than walker performance and more properties were directly related to cleaning performance. In addition, property changes associated with measurable performance shifts were less for cleaning performance than for walker performance. For example, a 1.0 degree change (Table 7) in grain angle of repose was required for a measurable shift in cleaning performance while a 2.7 degree change (Table 8) in grain angle of repose was required for a measurable change in walker performance. Overall, the cleaner was approximately three times more sensitive to changes in crop properties than the straw walker based on the ratio of percentage performance change to percentage property change required for a measurable performance shift (Table 6). In general, the ratios were approximately three times greater for the cleaner than the straw walker.

4.5 Effect of Moisture on Crop Properties

4.5.1 Introduction

Moisture affects crop properties in a predictable fashion. Many combine operators base field adjustments on crop moisture. Grain moisture is the most common criterion due to ease of measurement and near instantaneous determination using an electronic moisture tester. Table 10 shows the correlation between each crop property and moisture. Specifically, grain properties are correlated to grain moisture, chaff properties to chaff moisture, and straw properties to straw moisture. Scatter plots of each crop plotted as a function of its component moisture are located in Appendix C.

4.5.2 Grain Density

Grain density tended to decrease as grain moisture increased. The overall data set correlation was -0.33. The correlation between grain density and grain moisture for wheat using data from the Coal Valley, Illinois data set was -0.57 (Table 10). This data set was thought to be most representative of field conditions due to the number of observations, wide moisture range, and maturity level of the crop.

4.5.3 Grain Angle of Repose

Grain angle of repose decreased with associated increases in grain moisture as evidenced by a correlation 0.42 for the entire data set (Table 10). Once again, the Coal Valley, Illinois data set illustrates the relationship for a single crop. The correlation for Coal Valley was 0.80.

4.5.4 Chaff Density

Chaff density did not correlate well with chaff moisture. The correlation coefficient was 0.0, however the relationship between chaff

TABLE 10

CORRELATION OF CROP PROPERTIES TO CROP MOISTURE LISTED BY LOCATION.

		All Data	1980 Idaho Wheat	1980 Idaho Barley	1982 California Wheat	1982 North Dakota Wheat	1982 Coal Valley Wheat	1982 Coal Valley	1983 North Dakota Wheat	1984 Coal Valley Wheat	1984 Valley Wheat (Field)
Grain Density	*	-0.33	-0.80	-0.12	0.33	0.56	-0.97	-0.85	-0.53	-	-0.57
	**	95	10	13	11	7	10	4	10	-	30
	***	0.001	0.003	0.347	0.347	0.092	0.001	0.077	0.058	-	0.001
Grain Angle of Repose		0.42	0.92	-0.19	-0.74	0.52	0.96	0.94	0.24	-	0.79
		95	10	13	11	7	10	4	10	-	30
		0.001	0.001	0.268	0.005	0.117	0.001	0.029	0.255	-	0.001
Chaff Density		0.21	0.51	0.64	0.03	0.80	-	0.36	0.65	0.21	-
		59	10	13	11	7	-	4	10	38	-
		0.055	0.065	0.009	0.469	0.016	-	0.317	0.022	0.096	-
Chaff Compressibility Modulus		-0.46	-	-	-0.41	0.71	-	0.96	0.36	-0.21	-
		70	-	-	11	7	-	4	10	38	-
		0.001	-	-	0.106	0.037	-	0.020	0.152	0.101	-
Chaff Coefficient of Friction		0.48	0.48	0.68	-0.37	0.71	-	0.66	0.34	0.74	-
		93	10	13	11	7	-	4	10	38	-
		0.001	0.082	0.005	0.130	0.036	-	0.16	0.167	0.001	-
Chaff Mean Length		0.31	0.60	-0.10	0.19	-0.70	-	0.82	-0.17	-	0.83
		55	10	13	11	7	-	4	9	-	30
		0.011	0.033	0.373	0.286	0.041	-	0.089	0.334	-	0.001
Straw Density		0.44	-0.34	0.52	-0.10	0.03	-0.11	-	-0.17	-	0.83
		88	10	12	11	7	10	-	9	-	30
		0.001	0.166	0.044	0.387	0.474	0.376	-	0.334	-	0.001
Straw Compressibility Modulus		-0.34	-	-	-0.09	-0.63	-0.81	-	-0.32	-	-0.51
		66	-	-	11	7	10	-	9	-	30
		0.003	-	-	0.411	0.065	0.002	-	0.206	-	0.002

* Correlation Coefficient
** Observations
*** Significance Level

TABLE 10 continued

	All Data	1980 Idaho Wheat	1980 Idaho Barley	1982 California Wheat	1982 North Dakota Wheat	1982 Coal Valley Wheat	1982 Coal Valley	1983 North Dakota Wheat	1984 Coal Valley Wheat	1984 Valley Wheat (Field)
Straw Coefficient of Friction	0.56	0.31	0.07	0.26	-0.05	0.86	-	0.68	-	0.66
	90	10	13	11	7	10	-	9	-	30
	0.001	0.190	0.404	0.229	0.460	0.001	-	0.023	-	0.001

Note: Grain properties are correlated with grain moisture
Chaff properties are correlated with chaff moisture
Straw properties are correlated with straw moisture

density and chaff moisture is generally positive for location sub-sets (Table 10). Chaff density appeared to increase with corresponding increases in chaff moisture. For example, increasing moisture causes crop material to loose its resiliency and compress more easily.

4.5.5 Chaff Compressibility Modulus

Chaff compressibility modulus tended to decrease as moisture increased as indicated by a correlation of -0.46 for the entire data set (Table 10). As chaff became less moist, more pressure was required to change a volume of chaff.

4.5.6 Chaff Coefficient of Friction

Chaff coefficient of friction tended to increase as chaff moisture increased. This effect was evidenced by the overall data set correlation coefficient of 0.49 and the various location sub-set correlations (Table 10).

4.5.7 Chaff Mean Length

Chaff mean length tended to increase as chaff moisture increased based on the correlation of the overall data set (Table 10). The correlations of the location sub-sets do not support the theory that chaff length increases as moisture increases. It was theorized that wet crop material was less likely to break than dry material.

4.5.8 Straw Density

Straw density appeared to increase as straw moisture increased based on an overall data set correlation of 0.44 (Table 10). The correlation between straw density and straw moisture was strongest for the Coal Valley, Illinois data set. The sub-set data was most indicative of the true relationship because Coal Valley was the only test location where the crop was harvested at less than optimal conditions.

4.5.9 Straw Compressibility Modulus

Straw compressibility modulus tended to decrease as straw moisture increased. An overall correlation coefficient of -0.34 supported the relationship. Examination of the relationships for the various sub-sets (Table 10) also tended to support an inverse relationship. Like chaff, as the material became drier, it became more resistive to changes in volume.

4.5.10 Straw Coefficient of Friction

Straw coefficient of friction tended to increase with increased moisture. The overall correlation coefficient of 0.56 indicated a positive relationship between friction and moisture (Table 10).

4.5.11 Conclusions

Although the relationships between properties were subject to considerable variability, there appeared to be discernible trends in most cases. Data from selected test sites appeared to be more representative of the true relationships than the relationships derived from the entire data set. The test program was conducted such that the machines were tested in a narrow range of conditions at a given location. While the moisture range may have been similar at different locations, the properties and the performance of the machines was vastly different. For example, the grain moisture at two sites is 12.0 percent but the crop properties are not the same nor is the performance of the machine. The overall data were useful but it should be noted that the variation in moisture was controlled by the nature of the testing program.

CHAPTER V

PREDICTION MODELS

5.0 Introduction

Stepwise linear regression analysis was performed on the property data sets to develop predictive equations for the cleaner and the straw walker. The Statistical Package for the Social Sciences (SPSS) was used on the the Michigan State University Control Data Cyber 750 mainframe computer. Crop properties were chosen for the analysis such that cleaner performance was expressed as a function of grain and chaff properties. Only grain and straw properties were used to describe straw walker performance. It was assumed that the cleaner was affected by grain and chaff properties while the walker was affected by grain and straw properties and not chaff properties.

During the course of the experiment, several types of data transformations were performed on the data set before stepwise regression analysis was used. The transformations included logarithmic transformations properties, properties raised to powers, and properties expressed as mulitplicative combinations of one another. Models of the following general form explained the most variation in cleaning and walker performance:

$$y_i = b_o + b_1 x_{1i} \cdot\cdot\ b_k x_{ik}\ e_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [21]$$

where

y_i = M.O.G. feedrate (t/h) at a fixed grain loss

b_j = estimated regression coefficients

x_i = crop properties

e_i = error not accounted for by the model

i = 1,2, ..., n observations

$j = 1,2, \ldots, k$ independent variables

Equation 21 can be manipulated in to a power equation by expressing each term as an exponential:

$y_i = b_o * x_{1i}b_1 \ldots x_{ni}b_n$.................. [22]

where

y_i = M.O.G. feedrate (t/h) at a fixed grain loss

b_j = estimated regression coefficients

x_i = crop properties

$i = 1,2, \ldots, n$ observations

$j = 1,2, \ldots, k$ independent variables

Covariate models of cleaner and straw walker performance were analysed after stepwise regression was used to develop predictive equations for the cleaner and the straw walker. This was done to determine if location effects contributed to the explaination of combine performance after the effects due to crop properties was removed. Equation (21) was revised to add the classification variable, location. The general covariate model was:

$x_{ij} = L_i + b_1x_{ij} \ldots + b_nx_{ij}$................................[23]

where

y_{ij} = M.O.G. feedrate (t/h) at a fixed grain loss

L_i = fixed effects (test sites)

b_j = estimated regression coefficients

x_{ij} = crop properties

e_{ij} = error not accounted for by the model

$i = 1,2, \ldots n$ treatments (test sites)

$j = 1,2, \ldots k$ observations

5.1 Cleaner Prediction Equations

The entire set of chaff and grain properties were used for possible inclusion using the stepwise regression process. The most possible observations was insured by including all the cleaning data. The criteria for inclusion or exclusion from the resulting equation was chosen such that a 0.10 level of significance was maintained. Table 11 contains coefficients, constants, adjusted R square values, and number of observations used to develop the prediction equation. Figure 11, a scatter plot of predicted cleaner capacity versus observed cleaner capacity was constructed to graphically depict the overall correlation of the equation.

Grain angle of repose, chaff coefficient of friction, chaff density, and chaff mean length were selected in the that order to describe 72.0 percent of the variation in cleaning performance. Each variable entered the equation at the 10.0 percent level of significance.

In the previously described analysis, the maximum number of observations was made available for stepwise regression. Chaff compressibility modulus was not collected with the instrumented test stand until the 1982 growing season. Including chaff compressibility modulus in the analysis would not have allowed the maximum number of observations for the analysis because missing value option used by the statistical package would discard any data record with missing observations. The more recently collected properties were included in the analysis at the expense of twenty-two observations.

Table 12 lists the prediction equation coefficients, number of observations used in the stepwise regression, F ratios for each variable as they entered the model, and adjusted R squares as each variable entered the model. Figure 12 shows observed cleaner performance plotted

TABLE 11

CLEANER PREDICTION EQUATION COEFFICIENTS, ADJUSTED R-SQUARES, AND PARTIAL F-RATIOS AS DERIVED BY STEPWISE REGRESSION. PROPERTIES ARE LISTED AS THEY ENTERED THE MODEL.

Property	Coefficient	Adjusted R-Square	Partial F-Value
Grain Angle of Repose	-1.901	0.55	26.5
Chaff Coefficient of Friction	0.897	0.69	6.7
Grain Density	1.603	0.71	7.4
Chaff Mean Length	-0.241	0.73	3.4
Constant	0.010		

NOTE: The model was developed using the entire data set consisting of 41 observations.

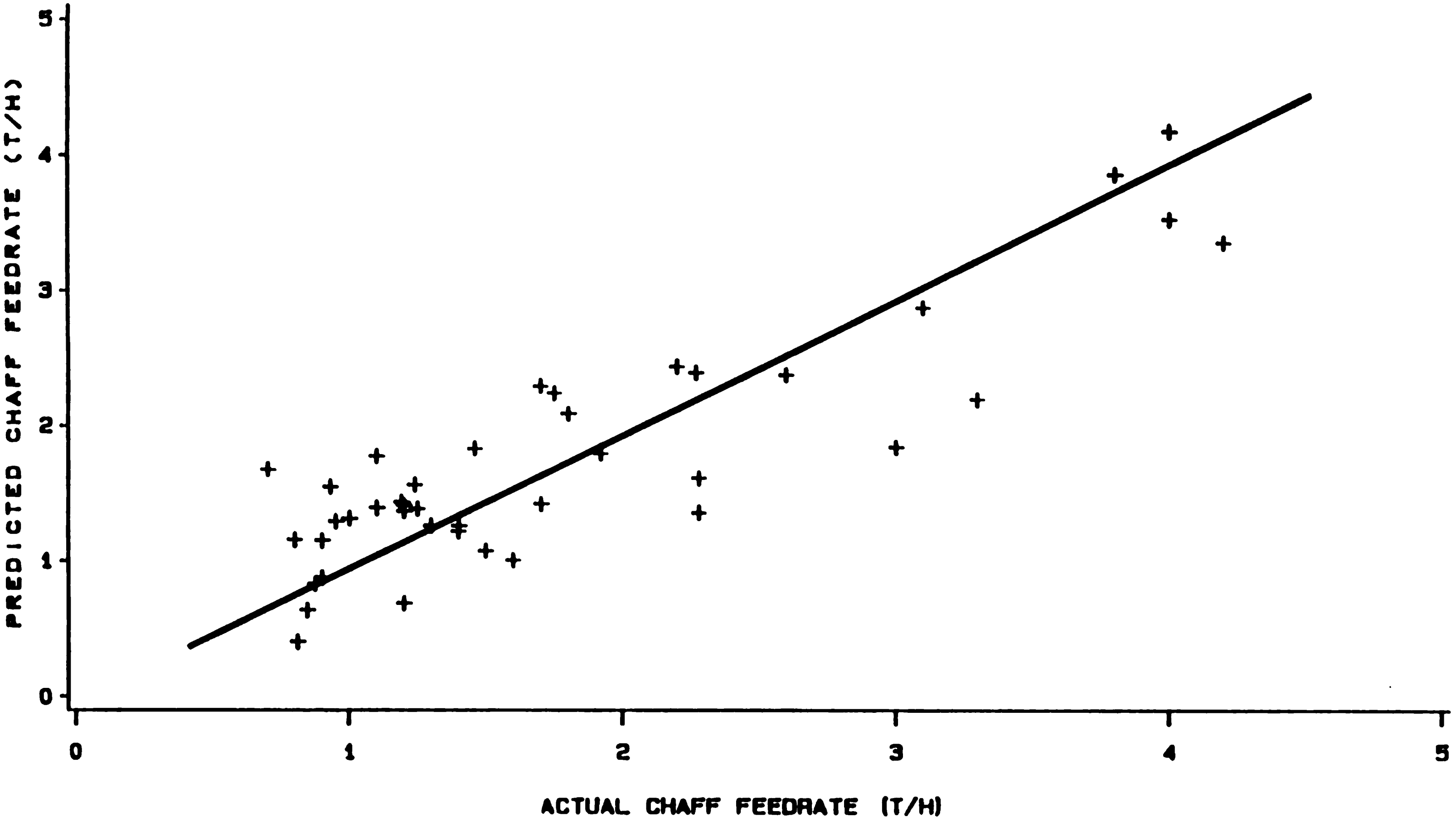

FIGURE 11

PREDICTED CLEANER PERFORMANCE VERSUS ACTUAL CLEANER PERFORMANCE BASED ON RELATIONSHIPS DERIVED FROM THE ENTIRE DATA

TABLE 12

CLEANER PREDICTION EQUATION COEFFICIENTS, ADJUSTED R-SQUARES, AND PARTIAL F-RATIOS AS DERIVED BY STEPWISE REGRESSION. PROPERTIES ARE LISTED AS THEY ENTERED THE MODEL.

Variable	Coefficient	Adjusted R-Square	Partial F-Value
Grain Density	2.951	0.84	35.4
Chaff Compressibility Modulus	0.392	0.89	6.1
Chaff Mean Length	-0.293	0.92	3.31
Constant	5.828 E-9		

NOTE: The model was developed using data gathered after 1981 consisting of 23 observations.

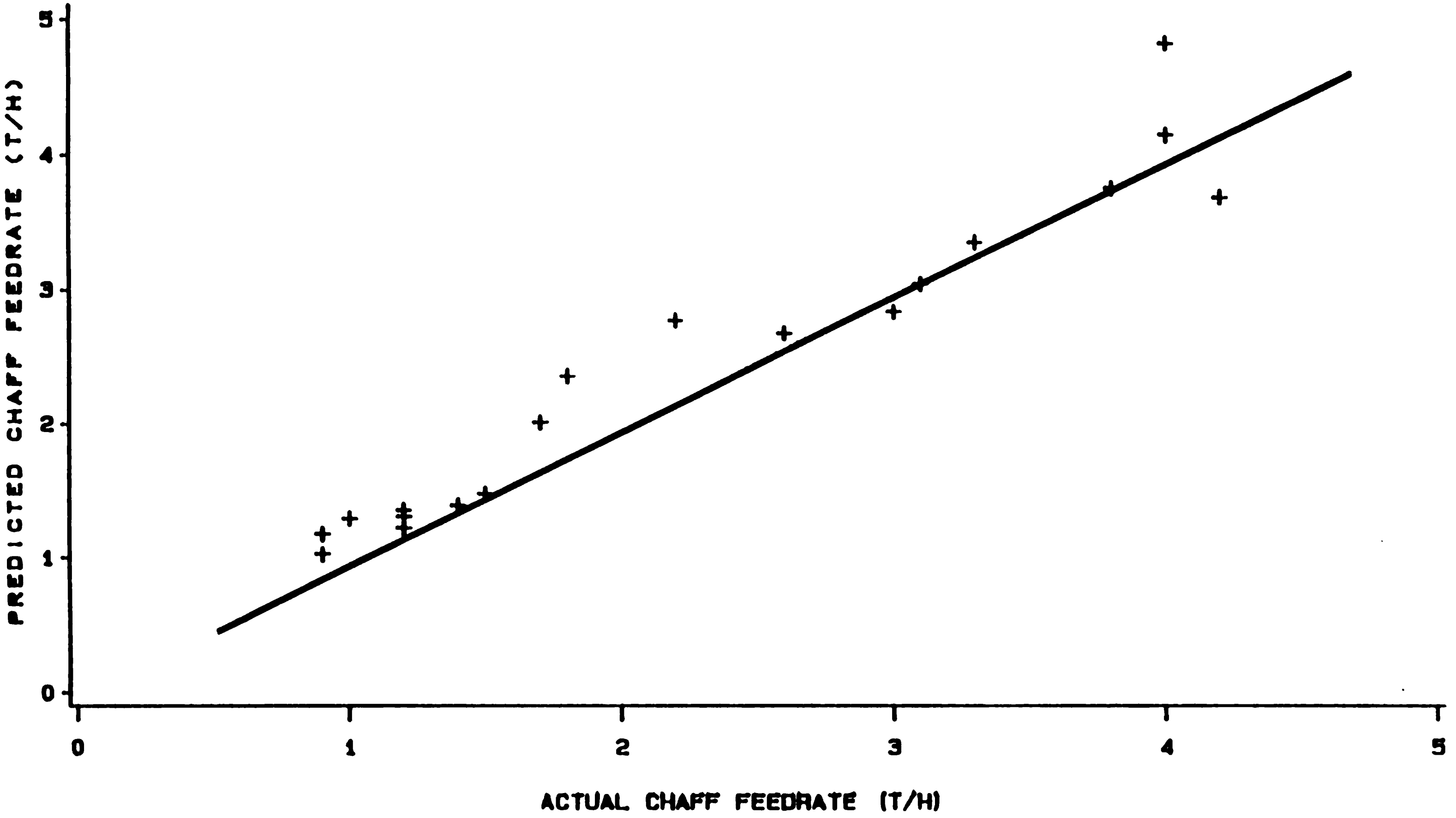

FIGURE 12

PREDICTED CLEANER PERFORMANCE VERSUS ACTUAL CLEANER PERFORMANCE BASED ON RELATIONSHIPS DERIVED USING DATA GATHERED AFTER 1981 against the predicted data using the equation of Table 12. Grain density, chaff compressibility modulus, chaff mean length, and chaff coefficient of friction were used to explain 92.0 percent of variation in cleaning performance. As before, the 10.0 percent level of significance was used to include or exclude a variable from the model. Grain properties were selected as the primary variable in both analyses. Although 92.0 percent of the variation in the data set was explained when compressibility modulus was included, the set contained less than half the number of original observations. Also, the larger data set represented a wider range of crop conditions and combine performance. The additional variability explained by including location effects in a covariate model which included grain angle of repose, chaff coefficient of friction, chaff density, and chaff mean length was 2.0 percent (Table 13). Location effects explained an additional 3.0 percent of the variation in cleaning performance in the model which included grain density, chaff compressibility modulus, chaff mean length, and chaff coefficient of friction (Table 13).

5.2 Straw Walker Prediction Equations

As with the cleaner analysis, stepwise regression was performed on various sets of straw and grain property data using transformed and untransformed data. When transformed, the variables were expressed logarithically, raised to powers, and combined multiplicatively with one another. Straw walker performance was best described by a power relationship as illustrated by Equation 22.

Results of stepwise regressions on straw and grain data are shown in Tables 14 and 15. A set of properties data was selected such that the most possible observations were available for inclusion in the

TABLE 13

EFFECT OF LOCATION ON CLEANER PERFORMANCE.
THE LOCATION EFFECT WAS TESTED WITH COVARIATE MODELS USING PROPERTIES PREVIOUSLY SELECTED BY STEPWISE REGRESSION.

Based on the Entire Data Set

Source of Variation	Partial F-Ratio	R-Square	PR > F
Location	5.0	0.02	0.003

Based on Data Collected After 1981

Source of Variation	Partial F-Ratio	R-Square	PR > F
Location	16.6	0.03	0.0001

TABLE 14

STRAW WALKER PREDICTION EQUATION, ADJUSTED R-SQUARES AND PARTIAL F-RATIOS AS DERIVED BY STEPWISE REGRESSION. PROPERTIES ARE LISTED AS THEY ENTERED THE MODEL.

Property	Coefficient	Adjusted R-Square	Partial F-Ratio
Straw Coefficient of Friction	-1.081	0.21	13.8
Grain Angle of Repose	-1.216	0.30	6.87
Constant	90.378		

NOTE: The model was developed using the entire data set consisting of 54 observations.

TABLE 15

STRAW WALKER PREDICTION EQUATION, ADJUSTED R-SQUARES, PARTIAL F-RATIOS AS DERIVED BY STEPWISE REGRESSION. PROPERTIES ARE LISTED AS THEY ENTERED THE MODEL.

Property	Coefficient	Adjusted R-Square	Partial F-Ratio
Grain Angle of Repose	-0.629	0.18	3.28
Straw Density	-0.629	0.21	5.77
Grain Density	0.824	0.30	4.52
Constant			

NOTE: The model was based on data gathered after 1981 consisting of 33 observations.

equation. This resulted in an equation based on 54 observations. Straw coefficient of friction and grain angle of repose entered in the equation at the 10.0 percent level of significance. The equation explained 30.0 percent of the variation in straw walker performance.

Another regression analysis was performed on a properties data set which included straw compressibility modulus. The addition of straw compressibility modulus reduced the number of observations in data set because the property was not measured prior to 1982. The resulting equation based on 33 observations explained 30.0 percent of the variation in straw walker performance. Grain angle of repose, straw density, and grain density were selected using the stepwise procedure.

Scatter plots of predicted straw walker performance versus observed straw walker performance are presented in Figures 13 and 14.

Location effects explained an additonal 27.0 percent in straw walker performance in a model which included straw friction and grain angle of repose (Table 16). Location effects were also significant in a model which contained straw compressibility modulus, straw density, and grain density. An additional 28.0 percent variation in straw walker was accounted for by the addition of location effects to the model (Table 16).

5.3 Conclusions

Cleaner performance can be predicted by grain angle of repose, chaff friction, chaff compressibility modulus, chaff mean length, and grain density. Straw walker performance can best be predicted by straw coefficient of friction, straw compressibility modulus, straw density, and grain angle of repose. Ninety-two percent of variation in cleaning

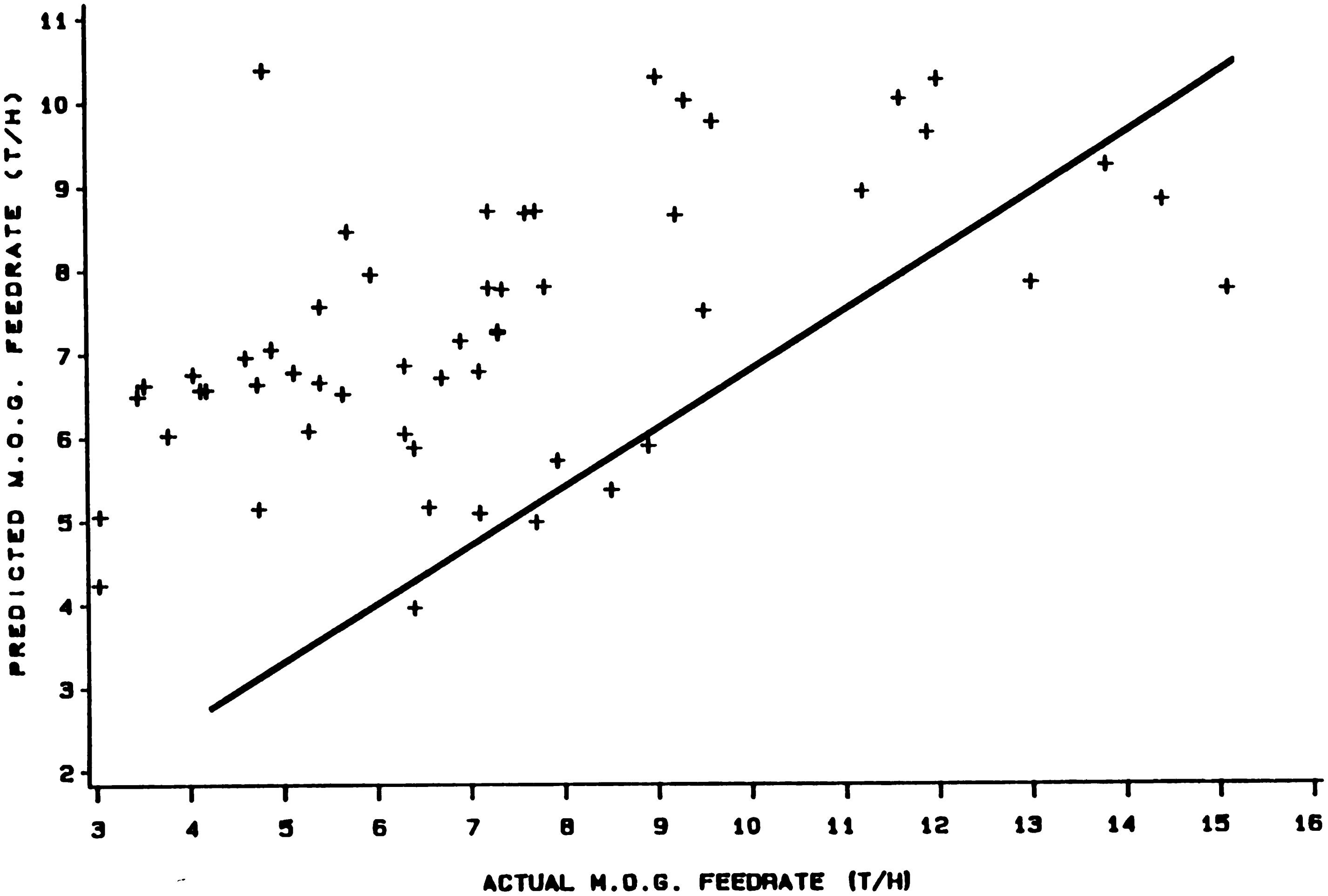

FIGURE 13

PREDICTED STRAW WALKER PERFORMANCE VERSUS
ACTUAL STRAW WALKER PERFORMANCE BASED ON RELATIONSHIPS
DERIVED USING THE ENTIRE DATA SET

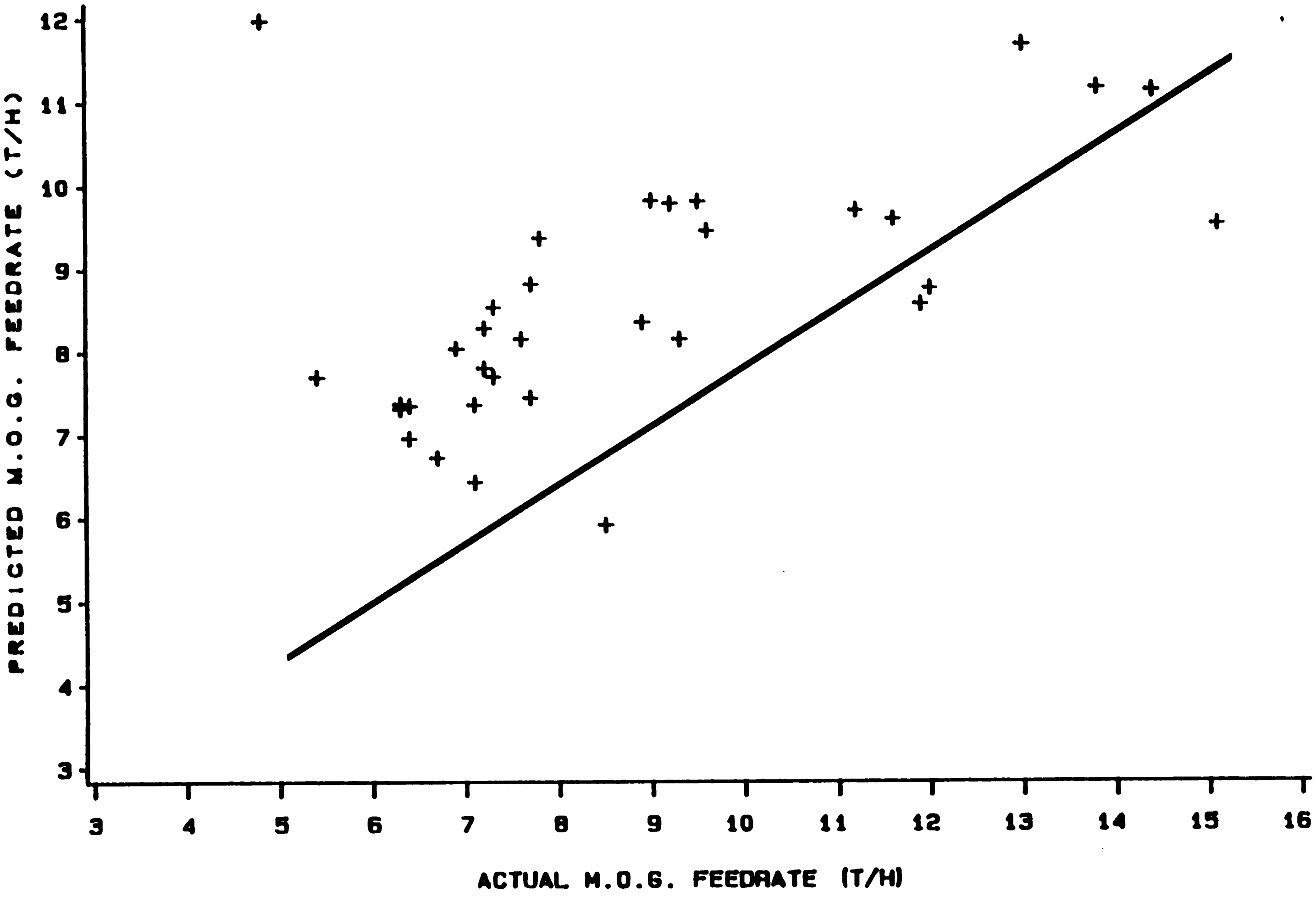

FIGURE 14

PREDICTED STRAW WALKER PERFORMANCE VERSUS
ACTUAL STRAW WALKER PERFORMANCE BASED ON RELATIONSHIPS
DERIVED USING DATA GATHERED AFTER 1981

TABLE 16

EFFECT OF LOCATION ON STRAW WALKER PERFORMANCE.
THE LOCATION WAS TESTED WITH A COVARIATE MODEL USING
PROPERTIES PREVIOUSLY SELECTED BY STEPWISE REGRESSION.

Based on the Entire Data Set

Source of Variation	Partial F-Ratio	R-Square	PR > F
Location	16.6	0.27	0.0001

Based on Data Collected After 1981

Source of Variation	Partial F-Ratio	R-Square	PR > F
Location	20.4	0.28	0.0001

performance was explained while only 30.0 percent of variation in walker performance was explained by the properties data. Location effects explained an additional 3.0 percent variation in cleaner performance and an additional 30.0 percent variation in walker performance.

CHAPTER VI

CROP PROPERTY BASED COMBINE SIMULATION MODEL

6.1 Introduction

A computer simulation model of a John Deere 6620 combine harvester is presented. The model, which was implemented in the Basic programming language on an IBM compatible micro computer will predict grain loss as a function of ground speed, yield, width of cut, and crop parameters. The program listing is found in Appendix D while examples of the program output and instructions for use are located in Appendix E.

6.2 Objectives

The objectives of the model were to:

1. Predict grain loss on the major components of the combine as a function of ground speed, yield, width of cut, and crop bulk property
2. Graphically show the relationship between crop changes and combine performance.

6.3 Model Concept

Figure 15 is a flow diagram of the combine simulation model. The flow of material can be traced from component to component. The user inputs to model are: grain moisture, chaff moisture, straw moisture, grain density, grain angle of repose, chaff mean length, chaff coefficient of friction, straw density, straw compressibility modulus, crop yield, grain to M.O.G. ratio, and chaff to M.O.G. ratio. Model outputs are: cleaning loss, walker loss, and total loss.

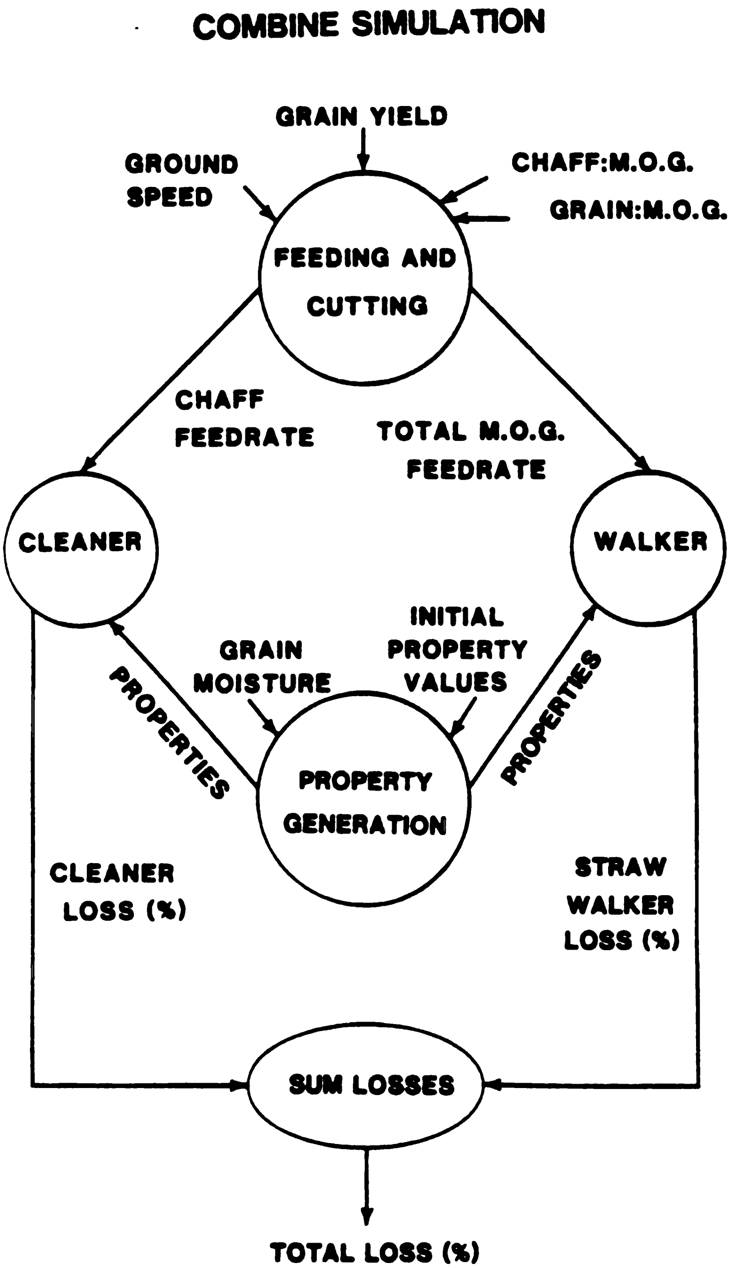

FIGURE 15

FLOW DIAGRAM OF COMBINE SIMULATION MODEL

6.4 Crop Propterty Simulation

The user can describe the properties used to model the crop or select a set of parameters for a give geographic location. The user may also specify various moisture levels for a give crop and/or select crop property data from actual test locations (California wheat, North Dakota wheat, and North Dakota barley) types for simulation.

Crop properties were assumed to be functions of crop type, and environment (weather and soil fertility). It was also assumed that the bulk properties for a given location were functions of moisture at crop maturity.

Equations were derived to express all crop properties in the model as functions of moisture. Specifically, chaff coefficient of friction was expressed as a function of chaff moisture while straw density was expressed as a function of straw moisture.

It was further assumed that crop component moistures can be expressed as functions of one another. Since grain moisture is the most common measurement performed by farmers and test personnel, it was decided to express chaff and straw moisture as functions of grain moisture.

Relationships were derived by regression to predict properties as functions of moisture. The relationships were assumed to be of forms raised to powers. Coefficients for each equation, R squares, F values, and the data used to develop each equation are listed in Table 17.

Crop property data was analyzed by location, by crop type and as a complete data set. Numerous equations to predict a property as a function of moisture were generated by using subsets. The criteria used to select an equation was: best R square and widest range of data. Simply using the entire data set to develop predictive equations was not

TABLE 17

EQUATION COEFFICIENTS USED TO PREDICT PROPERTIES AS FUNCTIONS OF MOISTURE. THE DATA SET USED TO DEVELOP THE REGRESSION EQUATIONS AND STATISTICS ARE ALSO LISTED.

Dependent Variable	Independent Variable	Equation Coefficient a	Equation Coefficient b	Data Set	Calculated F-Ratio	R-Square	Observations
Grain Angle of Repose	Grain Moisture	5.784	0.454	1984 Coal Valley (Summer)	57.5	0.66	30
Grain Density	Grain Moisture	965.0	-0.0088	1984 Coal Valley (Summer)	13.7	0.30	30
Chaff Moisture	Grain Moisture	0.764	1.102	All Data	17.9	0.23	87
Chaff Density	Chaff Moisture	22.838	0.247	1982 North Dakota	4.0	0.33	7
Chaff Coefficient of Friction	Chaff Moisture	0.122	0.379	1984 Coal Valley (Spring)	40.1	0.51	38
Chaff Mean Length	Chaff Moisture	7.639	0.155	1980 Idaho (Wheat)	4.6	0.29	10
Straw Moisture	Grain Moisture	1.479	0.896	All Data	28.8	0.25	86
Straw Density	Straw Moisture	8.129	0.220	1984 Coal Valley (Summer)	18.6	0.38	30
Straw Coefficient of Friction	Straw Moisture	0.235	0.141	1984 Coal Valley (Summer)	20.2	0.39	30

* Equation: Property = $a * \text{moisture}^b$

used because the effects of moisture were controlled by the machine testing method.

Single variable equations used to predict crop changes as functions of moisture were assumed to be representative for any small grain type. However, a typical grain density at 12.0 percent moisture in California wheat is 900 Kg/m^3 while a typical grain density for North Dakota barley is 700 kg/m^3 at the same moisture content. The equation derived from Illinois wheat data is not an adequate predictor of California wheat or North Dakota barley unless the equation is adjusted.

The following example illustrates the method used to adjust an equation. The equation which describes grain density as a function of grain moisture is based upon data gathered at the Coal Valley, Illinois, test site during the summer of 1984. If it is desired to predict the change in grain density for a simulation of North Dakota barley, the equation must be adjusted to predict the North Dakota condition. Grain density at 12 percent grain moisture as predicted by the equation is 868.0 (kg/m^3). Based on prior personal experience, grain density for barley averaged 645.0 (kg/m^3). These values are used to illustrate the adjustment.

The equation which describes grain density as a function of grain moisture, found in Table 17, must be altered as follows:

1. Linearize the equation,
2. Substitute the value of the property,
3. Substitute the value for moisture,
4. Solve for coefficient "a",
5. Convert equation to power form.

The equation in its power form as shown in Table 17 is:

$$\text{Gden} = 965.0 \exp^{(-0.0088(\text{Gmost}))} \qquad [24]$$

where

Gden = grain density (kg/m^3)

965.0 = estimated regression coefficient

-0.0088 = estimated regression coefficient

Gmost = grain moisture (percent)

The linearized equation, obtained by taking the natural logarithm of each side of the equation, is:

$$Ln(Gden) = Ln(965.0) + (-0.0088(Gmost)) \qquad [25]$$

A new coefficient can be solved for after substituting the new values of grain angle of repose and grain moisture. The resulting equation is:

$$Gden = 717.0 \exp^{(-0.0088(Gmost))} \qquad [25]$$

Typically, the values used to adjust the equation are selected as those that correspond to the optimum performance of the machine for a particular crop.

6.5 Feeding and Cutting

The feeding and cutting component of the simulation model was developed using assumptions that feedrate is:

1. a function of width of cut,
2. a function of ground speed,
3. a function of yield.

The equation used to simulate feedrate is:

$$FR = SP(YD)WD(1/GMOG)(0.00329) \qquad [26]$$

where

FR = M.O.G. feedrate (t/h)

SP = ground speed (miles/hour)

Wd = cutting width (feet)

GMOG = grain to M.O.G. ratio

0.00329 = unit factor

The chaff feedrate was determined by the following equation:

$CF = CMOG(FR)$ .... [27]

where

CF = chaff feedrate (t/h)

$CMOG$ = chaff to M.O.G ratio

FR = M.O.G feedrate (t/h)

6.6 Cleaning and Walker Loss

Inputs to the cleaning component and straw walker component in the model were crop properties, chaff feedrate, and total M.O.G. feedrate. In order to predict losses on each component, it was necessary to develop relationships which described cleaning and walker loss as a function of feedrates and crop properties.

The performance curves (Figures 2 and 3) which describe percentage of grain lost versus feedrate were developed using logarithmically transformed grain loss in a linear regression on feedrate. The form of the relationship was:

$Loss = a * \exp^{((b)(FR))}$ .... [28]

where

$Loss$ = percentage of grain lost

a = estimated regression coefficient

b = estimated regression coefficient

FR = M.O.G feedrate (t/h)

Relationships were developed using multiple regression to describe cleaning and straw walker performance as functions of the performance curve regression coefficients. For example, a regression analysis using the "a" coefficients of all cleaning performance curves as the dependent variable and grain and chaff properties as the independent variables was performed. The resulting equation described the intercept as a function of properties. Likewise, a similar regression was performed on the "b" coefficients of all cleaner curves. Both the intercept and the slope of a cleaner curve can be predicted as functions of crop properties. Loss for any feedrate can then be predicted. Equations of the following form were produced:

$$a_{ij} = b_o x_{i1}^{b_1} x_{i2}^{b_2} \ldots x_{ik}^{b_k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [29]$$

$$b_{ij} = b_o x_{i1}^{b_1} x_{i2}^{b_2} \ldots x_{ik}^{b_k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [30]$$

where

b_{ij} = estimated regression coefficients

X_i = crop properties

i = 1,2, ..., n observations

j = 1,2, ..., k independent variables

Straw walker equations of the same form were also produced. The coefficients and statistics for the cleaner and walker loss equations used in the model are found in Tables 18 and 19.

The equations enabled the prediction of grain loss as a function of crop properties and feedrate. For a unique set of crop properties, a unique performance curve was described based on the predicted cofficients. Cleaner loss was calculated in the model using the chaff feedrate (FR) from the feeding and cutting component (Eq. 27) the following form:

$$\text{cleaning loss} = a_c \exp^{((b_c(CF))} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [31]$$

Straw walker loss was calculated using the total M.O.G. feedrate (FR) from the feeding and cutting component (Eq. 26) in an equation of the following form:

$$\text{walker loss} = a_s \exp^{((b_s(FR))} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [32]$$

TABLE 18

EQUATION COEFFICIENTS USED TO PREDICT CLEANER LOSS IN SIMULATION MODEL. PARTIAL F-RATIOS ARE LISTED AS GENERATED BY STEPWISE REGRESSION.

'a' Coefficient Statistics

Property	Equation Coefficients	Partial F-Ratio
Grain Angle of Repose	3.76	18.1
Chaff Mean Length	3.31	3.7
Chaff Coefficient of Friction	9.0	9.26
Constant	3.34 E+6	

NOTE: Model based on 23 observations. Adjusted R-square is 0.64.

'b' Coefficient Statistics

Property	Equation Coefficients	Partial F-Ratio
Grain Density	-5.03	7.01
Chaff Coefficient of Friction	-3.41	6.09
Constant	9.18 E-12	

NOTE: Model based on 23 observations. Adjusted R-square is 0.32.

*Grain Loss = $a*\exp^{(b*\text{chaff feedrate})}$

TABLE 19

EQUATION COEFFICIENTS USED TO PREDICT WALKER LOSS IN SIMULATION MODEL. PARTIAL F-RATIOS ARE LISTED AS GENERATED BY STEPWISE REGRESSION.

'a' Term Statistics

Property	quation Coefficients	Partial F-Ratio as Variable Entered Model
Grain Density	4.44	15.1
Constant	1.80 E-15	

NOTE: Model based on 34 observations. Adjusted R-square is 0.34.

'b' Term Statistics

Property	Equation Coefficients	Partial F-Ratio as Variable Entered Model
Grain Density	-2.24	16.1
Straw Modulus	-0.67	2.1
Straw Density	0.61	2.6
Constant	0.46 E+3	

NOTE: Model based on 34 observations. Adjusted R-square is 0.29.

*Loss = $a*\mathrm{exp}^{(b*\text{total M.O.G. feedrate})}$

6.7 Total Loss

Total losses can be calculated by adding the loss from the walker and the cleaner for each simulated groundspeed.

6.8 Random Variable Generation

A random variable generator was implemented to introduce variation into the model. Specifically, crop yield and the crop properties were treated as random variables in the simulation.

The inverse transformation method with piecewise piecewise approximation was used to code the Gaussian generator as described by (Manetsch and Park, 1985). Inputs to the generator to provide a normal distribution were the value of each property and variation expressed as a percent of the property.

6.9 Simulation Results

The relationships in the model have been checked for mathematical correctness. The model can be validated by plotting predicted feedrates versus actual feedrates used to develop the initial equations. Figure 16 shows the relationship of simulated chaff feedrates at 0.5 percent cleaner loss versus actual chaff feedrates at 0.5 percent cleaner loss. An R square of 0.62 was calculated. Figure 17 shows the relationship of simulated total M.O.G. feedrate at 1.0 percent walker loss to total M.O.G. feedrate at 1.0 percent walker loss. The simulated values explained 70.0 percent of the variation in walker performance. A sensitivity analysis using the data in Table 20 was performed by holding all but one of the properties at its mean level while varying one property from a value equal to plus one standard deviation to minus one standard deviation from its mean value. The change in performance was expressed as the percentage change from the predicted performance

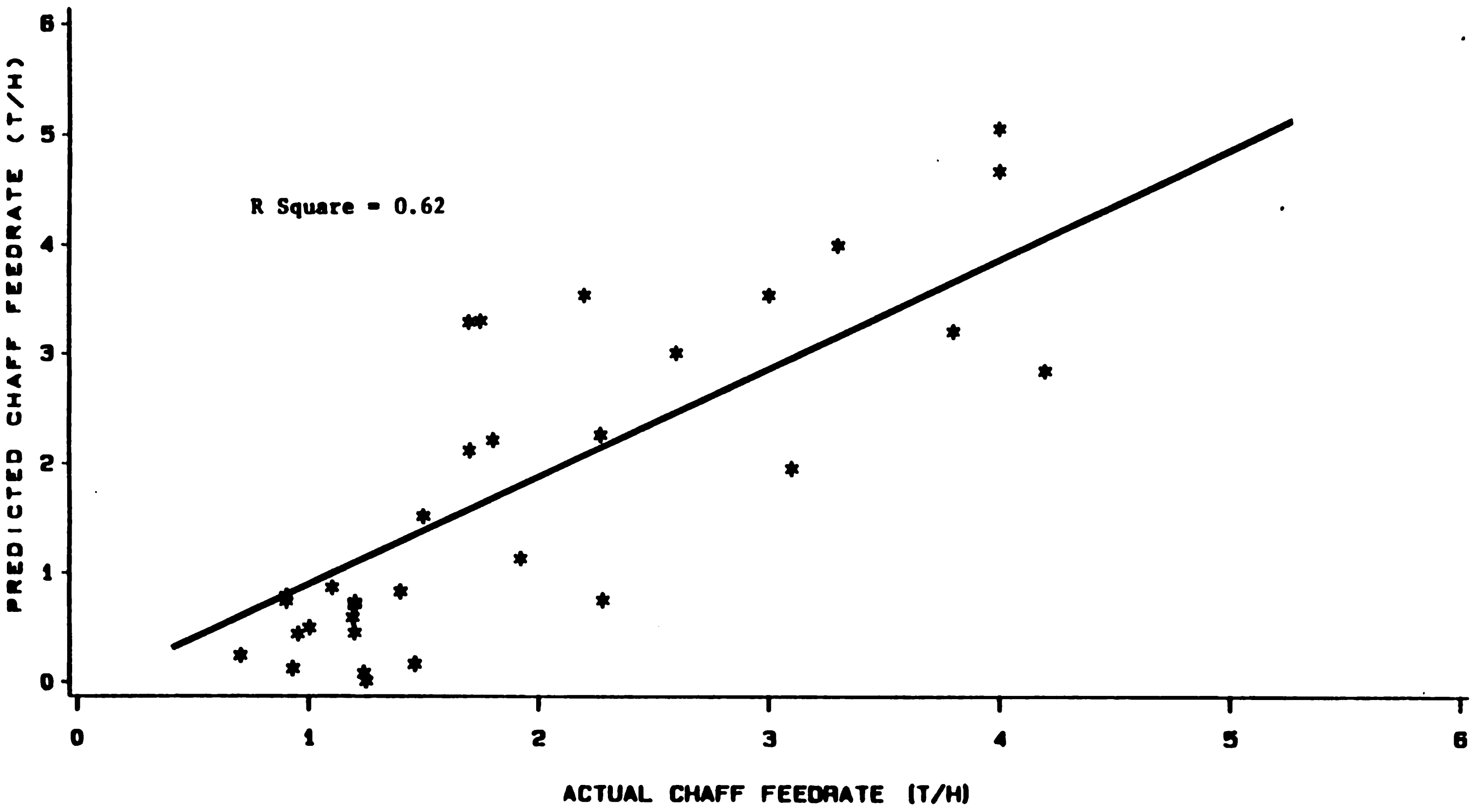

FIGURE 16

SIMULATED CLEANER PERFORMANCE VERSUS ACTUAL CLEANER PERFORMANCE

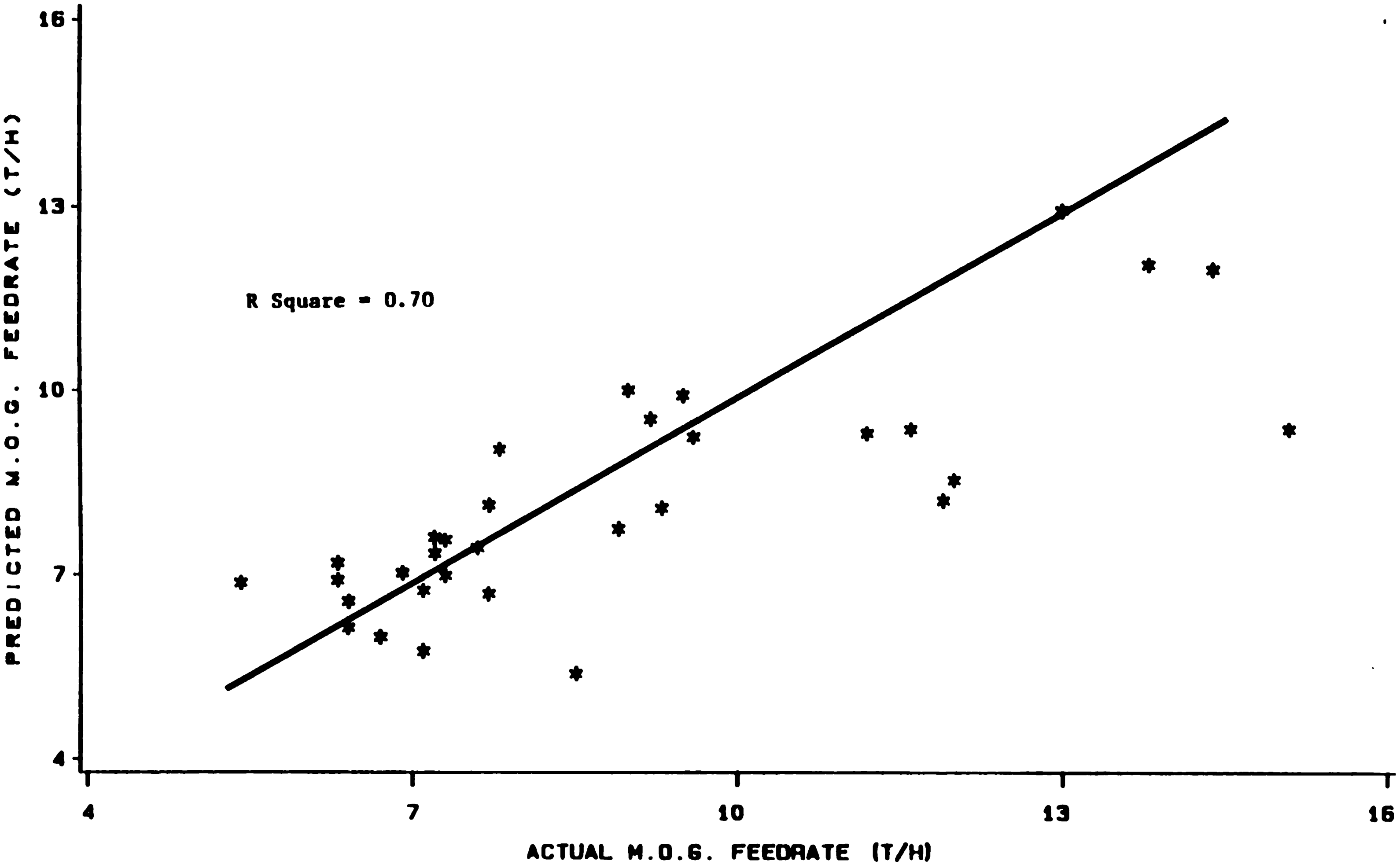

FIGURE 17

SIMULATED STRAW WALKER PERFORMANCE VERSUS ACTUAL STRAW WALKER PERFORMANCE

TABLE 20

CROP PROPERTY MEANS AND STANDARD DEVIATIONS USED IN SENSITIVITY ANALYSIS.

	Mean	Standard Deviation
Grain Moisture (%)	12.0	-
Grain Density (kg/m^3)	775.0	75.0
Grain Angle of Repose (degrees)	22.4	2.7
Chaff Moisture (%)	11.2	4.0
Chaff Mean Length (mm)	7.7	2.3
Chaff Coefficient of Friction	0.33	0.05
Straw Moisture (%)	18.0	2.5
Straw Compressibility Modulus (kPa)	2.1	0.4
Straw Density (kg/m^3)	16.3	3.3

determined by the mean property values. The percentage change in performance was divided by the percentage change in the property to produce a dimensionless number to evaluate each property in the loss equations.

Based on the sensitivity analysis using data from Table 21, the cleaner was most affected by changes in grain density and least affected by changes in grain angle of repose (Table 21). The straw walker was most affected by straw density and least affected by grain density (Table 22). Cleaning performance and walker performance curves were generated by the model using actual data from test runs in North Dakota barley (Table 23). Figures 18 and 19 are scatter plots from an actual field test. The best fit line for the actual data is shown as is the simulated performance curve. The cleaning capacity at 0.5 percent grain was loss was 1.50 (t/h) while the predicted capacity was 1.47 (t/h). Actual walker capacity at 1.0 percent loss was 7.10 (t/h) compared to a predicted feedrate of 6.70 (t/h). Both simulated curves were generated with no crop variation. Chaff and grain property variation of 5.0 percent or less tendeds to produce the most realistic cleaner performance data while straw and grain property variation of 5.0 to 10.0 percent tended performance.

Figure 20 shows the relationship of cleaning and walker performance to grain moisture as predicted by the model. Inputs from Table 23 were used as initial property values to simulate performance for six different moisture contents. The initial or reference grain moisture selected was 12.0 percent. Crop variation for cleaner properties was 5.0 percent and crop variation for straw walker properties was 10.0 percent. As expected, the general trend in both cases was a decrease in performance as grain moisture increased.

TABLE 21

SENSITIVITY ANALYSIS OF SIMULATED CLEANER PERFORMANCE.

	Percentage Change in Property*	Percentage Change in Performance	Ratio of Performance Change to Property Change
Grain Density	42.0	210.0	5.1
Chaff Mean Length	121.0	133.0	1.1
Chaff Coefficient of Friction	44.0	58.0	0.8
Grain Angle of Repose	423.0	62.0	0.2

*Properties varied plus or minus two standard deviations from mean.

TABLE 22

SENSITIVITY ANALYSIS OF SIMULATED STRAW WALKER PERFORMANCE.

	Percentage Change in Property*	Percentage Change in Performance	Ratio of Performance Change to Property Change
Straw Density	40.0	51.0	1.3
Straw Modulus	81.0	55.0	0.7
Grain Density	210.0	48.0	0.2

*Properties varied plus or minus two standard deviations from mean.

TABLE 23

CROP PROPERTIES, CROP YIELD, AND MACHINE PARAMETERS USED FOR SIMULATION OF CLEANER AND WALKER PERFORMANCE. THE DATA IS AN ACTUAL BARLEY DATA SET.

Yield (bu/ac)	75.0
Grain to M.O.G. Ratio	1.5
Chaff to M.O.G. Ratio	0.3
Grain Moisture (%)	12.0
Chaff Moisture (%)	12.0
Straw Moisture (%)	15.0
Grain Density (kg/m^3)	630.0
Grain Angle of Repose (degrees)	24.3
Chaff Coefficient of Friction	0.390
Chaff Mean Length (mm)	5.5
Straw Density (kg/m^3)	16.0
Straw Compressibility Modulus (kPa)	1.8
Chaff Feedrate at 0.5 Percent Cleaner Loss	1.5
Total M.O.G. Feedrate at 1.0 Percent Walker Loss	7.1

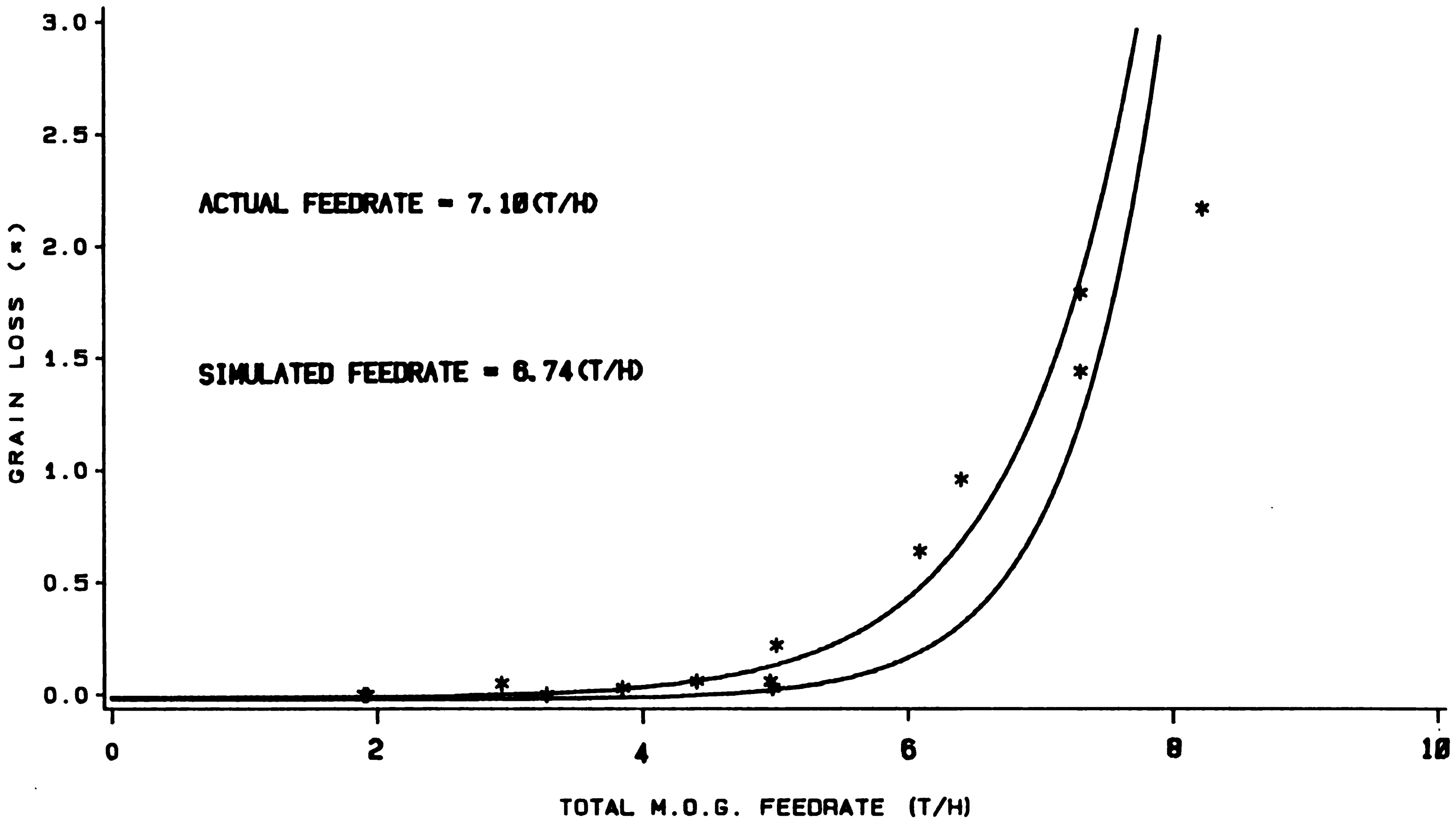

FIGURE 18

SIMULATED CLEANER PERFORMANCE CURVE AND ACTUAL PERFORMANCE CURVE
FOR NORTH DAKOTA BARLEY

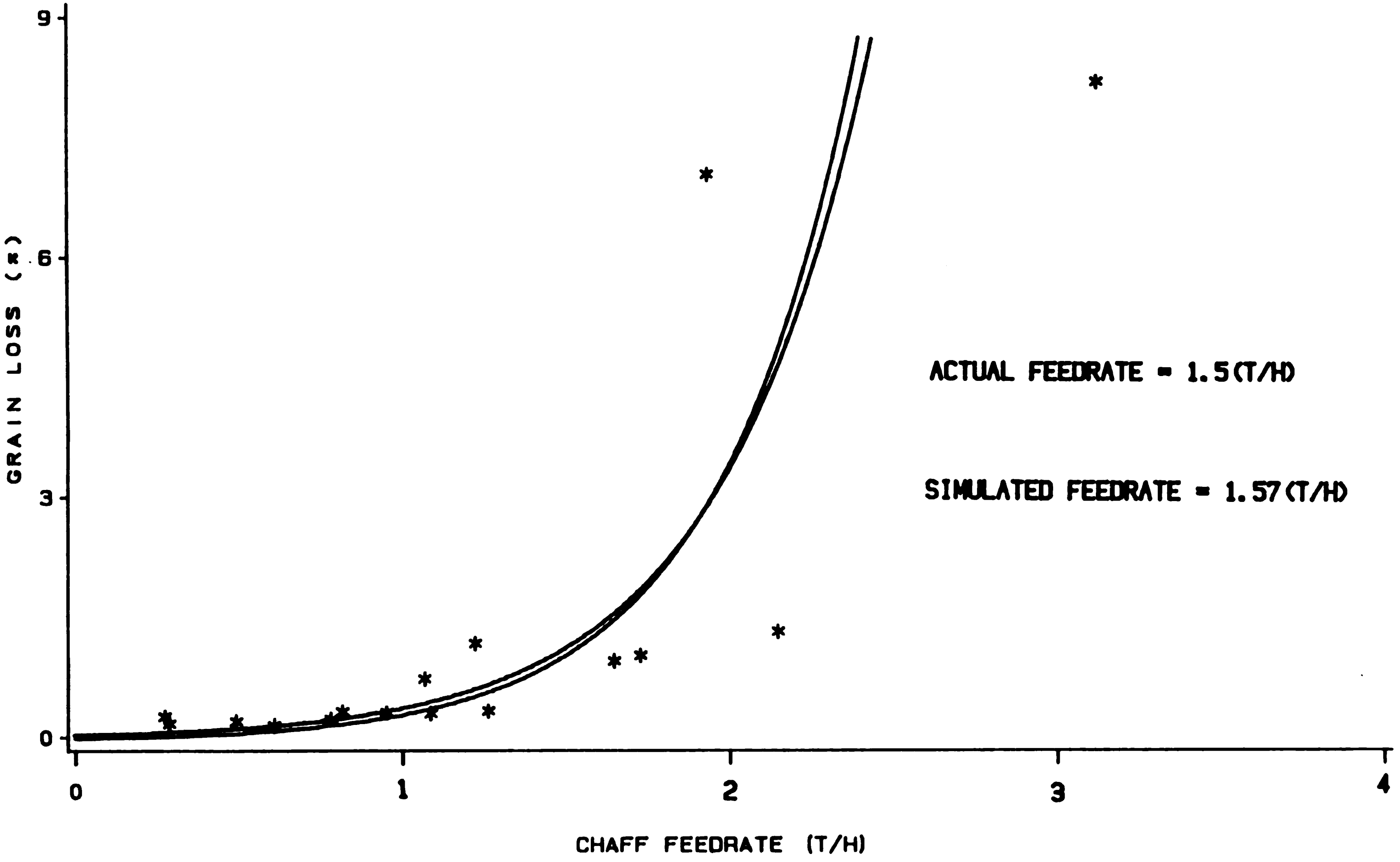

FIGURE 19

SIMULATED STRAW WALKER PERFORMANCE CURVE
AND ACTUAL STRAW WALKER PERFORMANCE CURVE
FOR NORTH DAKOTA BARLEY

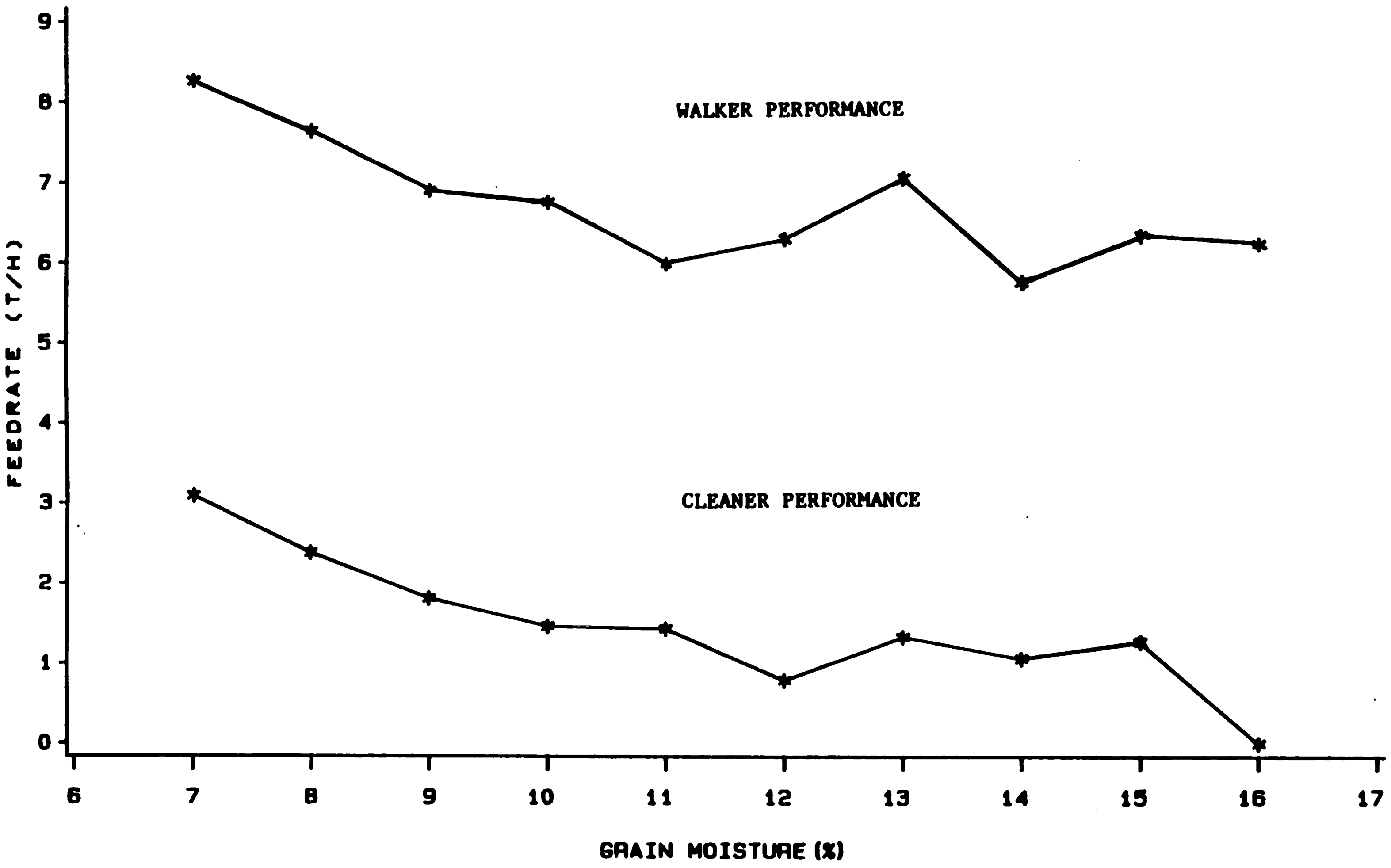

FIGURE 20

SIMULATED CHAFF FEEDRATE AT 0.5 PERCENT GRAIN LOSS
AND TOTAL M.O.G. FEEDRATE AT 1.0 PERCENT GRAIN LOSS VERSUS GRAIN MOISTURE.
CHAFF PROPERTIES VARIED BY 5.0 PERCENT AND
STRAW WALKER PROPERTIES VARIED BY 10.0 PERCENT

6.9 Conclusions

The crop property based simulation model can predict trends in cleaning performance and in straw walker performance. Compared to actual data, the model explained 62.0 percent of the variation in cleaner performance and 70.0 percent of the variation in straw walker.

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.0 Summary

Fourteen bulk crop properties of wheat and barley were measured and correlated to cleaner and straw walker performance of a John Deere model 6620 combine harvester. Data was collected from 1980 through 1984 by Michigan State University and John Deere Harvester Works personnel. Crop properties are known to affect the performance of combines in field tests. Stephens and Rabe (1977) reported the affects of weather upon crop properties and the subsequent change in combine performance. Traditionally, crop moisture information has been used to make decisions such as when to harvest and when to make decisions concerning machine adjustments. Little was quantitatively known about the effect of properties on combine performance. Moisture content of grain, chaff, and straw have been shown to explain some of the variation in performance, but models dependent solely on moisture are site specific and fail to fully describe the physical complexities for a small grain crop.

The primary objective of the study was to relate changes in crop properties to changes in combine performance. This information was of particular interest to John Deere Harvester Works engineers for use during field tests of prototype combines. The information also establishes the groundwork for a controller which senses changes in one or several crop properties and makes machine adjustments in an operating combine. Performance changes were influenced by changes in grain, chaff, and straw bulk properties.

The properties which displayed the most effect on performance were grain angle of repose, grain density, chaff coefficient of friction and straw coefficient of friction. In this study, moisture was found to have a minimal effect upon combine performance which was probably due to the narrow range of moisture examined. Most variation in crop properties was due to location differences and variety.

A combine simulation model was constructed based on the crop property data gathered during the study. A computer model was implemented on an IBM compatible micro-computer using the BASIC programming language. The model predicted grain loss on the cleaner and straw walker as a function of ground speed, crop yield, width of cut, and a set of crop properties. The model provides an interactive means to change crop properties and view the result in a graphical fashion.

7.1 Conclusions

7.1.1 Effect of Crop Properties on Combine Performance

Cleaner performance appeared to be sensitive to changes in grain angle of repose, grain density, chaff coefficient of friction, chaff compressibility modulus, chaff density, grain:M.O.G. ratio, and chaff mean length. The straw walker appeared to be influenced by grain angle of repose, straw coefficient of friction, grain density, straw compressibility modulus, and straw density. Crop properties appeared to influence the performance of the cleaner more than the straw walker. In general, a given property change caused a greater change in cleaner performance than straw walker performance.

Cleaner performance can be predicted with a multi-variable equation consisting of the following properties: grain angle of repose, chaff coefficient of friction, and grain density. Straw walker performance can be predicted using the following variables in a multi-variable equation: straw coefficient of friction, grain angle of repose, grain density, and straw density.

7.1.2 Combine Simulation

Parameters which describe an exponential performance curve were predicted as a function of crop properties. A performance curve for a machine is characterized by estimated regression coefficients. Prediction equations were constructed to predict the intercept and the slope of a performance curve as a function of crop properties. A unique performance curve is predicted for a set of crop properties which characterize a crop condition. Inputs to the model were crop yield, width of cut, ground speed, grain density, chaff mean length, chaff coefficient of friction, grain angle of repose, straw density, straw compressibility modulus, and grain moisture.

Simulated cleaner data explained 62.0 percent of the variation in cleaner performance while simulated straw walker data explained 70.0 percent of the variation in straw walker performance. The simulated cleaner performance was most affected by grain density and least affected by grain density. Simulated straw walker performance was most affected by straw density and least affected by grain density.

Crop properties were varied as a percentage of a specified mean value. The most realistic simulated cleaner performance occurred when grain and chaff properties were varied approximately 5.0 percent. Straw walker simulation performance was most realistic when grain and straw properties were varied by 10.0 percent.

7.2 Recommendations For Further Research

This study establishes the groundwork for bulk measurements of crop properties and their effects upon the cleaner and the straw walker. A similar approach should be taken to examine the effects of crop properties upon the threshing process. Also, the identification and measurement of aerodynamic properties should explain additional variation in cleaner and walker performance. Additional properties should be identified and measured to explain more of the variation in straw walker performance as only 30.0 percent of the variation of the in straw walker performance was attributed to crop properties.

Last, the range of moisture at a test site was limited because prototype testing was conducted when conditions were most favorable. A wider range in moisture conditions at a test site would result in more machine and property variation.

APPENDICES

APPENDIX A

Crop Bulk Properties and Machine Performance Measurements Data Set

TABLE 21

List of variable names used to describe crop data and a brief description of each variable.

Series	Deere and Company identification numbers for each machine test. The first two digits denote the year.
Cl5mfr	Chaff feedrate (t/h) at 0.5 percent grain loss.
Sllmfr	Total M.O.G. feedrate (t/h) at 1.0 percent grain loss.
Gmog	Grain to M.O.G. ratio.
Cmog	Chaff to M.O.G. ratio.
Gmost	Grain moisture (percent).
Gden	Grain density (kg/m^3).
Gaor	Grain angle of repose (degrees).
Cmost	Chaff moisture(percent) dry basis.
Cden	Chaff density (kb/m^3).
Ccomod	Chaff compressibility modulus (kN).
Cfrict	Chaff coefficient of friction.
Cmlntg	Chaff mean lenght (mm).
Smost	Straw moisture (percent) dry basis.
Sden	Straw density (kg/m^3).
Scomod	Straw compressibility modulus (kN).
Sfrict	Straw coefficient of friction.
Cla	Cleaner loss curve "a" coefficient (see note).
Clb	Cleaner loss curve "b" coefficient (see note).
Walka	Straw walker loss curve "a" coefficient (see note).
Walkb	Straw walker loss curve "b" coefficient (see note).

Note: Cleaner and straw walker performance had the following general equation form:

$$\text{Cl5mfr or Sllmfr} = \text{"a"} * \exp^{(\text{"b"} * \text{feedrate})}$$

Crop Location=Idaho 1980 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
1	80410	1.70	5.70	0.000	0.000	9.80	878.0	21.8	13.30	45.0	0.000	0.325	10.8	0.00	15.5	0.000	0.300	0.027	1.724	0.008	0.829
2	80411	1.75	5.95	0.000	0.000	8.80	877.0	20.6	7.10	45.0	0.000	0.360	9.400	0.00	18.8	0.000	0.340	0.021	1.831	0.011	0.758
3	80412	0.00	4.60	0.000	0.000	9.60	880.0	20.6	9.70	53.0	0.000	0.350	10	0.00	24.0	0.000	0.380	0.065	0.568	0.004	1.203
4	80415	2.27	0.00	0.000	0.000	11.50	854.0	22.3	10.80	41.5	0.000	0.290	12.4	0.00	14.0	0.000	0.335	0.008	1.724	0.006	0.729
5	80416	2.28	4.88	0.000	0.000	11.00	867.0	21.6	8.10	43.5	0.000	0.400	11	0.00	14.7	0.000	0.360	0.255	0.292	0.000	1.560
6	80417	1.10	6.56	0.000	0.000	16.90	839.0	24.5	16.70	54.0	0.000	0.390	12	0.00	15.5	0.000	0.390	0.005	4.039	0.013	0.662
7	80418	1.92	5.64	0.000	0.000	15.40	861.0	22	8.80	43.5	0.000	0.370	12	0.00	17.2	0.000	0.375	0.001	3.101	0.002	1.135
8	80420	1.40	7.93	0.000	0.000	15.40	853.0	23.1	22.70	51.5	0.000	0.430	12.8	0.00	16.9	0.000	0.390	0.003	3.526	0.020	0.554
9	80421	0.81	3.03	0.000	0.000	22.40	768.0	29.9	15.60	51.5	0.000	0.360	10.8	0.00	14.4	0.000	0.342	0.121	2.103	0.055	0.941
10	80432	1.46	7.35	0.000	0.000	12.00	810.0	21.3	17.70	45.0	0.000	0.388	11.8	0.00	13.8	0.000	0.336	0.010	2.684	0.022	0.519

Crop Location=Idaho 1980 Barley

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
11	80413	1.19	3.45	0.000	0.000	8.30	700.0	25.2	5.80	40.0	0.000	0.320	9.600	0.00	0.0	0.000	0.325	0.000	0.000	0.000	0.000
12	80414	1.60	5.40	0.000	0.000	9.20	702.0	25.1	14.20	40.0	0.000	0.370	10.6	0.00	14.3	0.000	0.320	0.000	0.000	0.000	0.000
13	80419	2.28	0.00	0.000	0.000	13.50	684.0	22.7	9.40	46.0	0.000	0.410	15.4	0.00	19.5	0.000	0.415	0.000	0.000	0.000	0.000
14	80422	0.95	3.52	0.000	0.000	18.60	688.0	23.8	9.60	42.0	0.000	0.377	8.000	0.00	12.9	0.000	0.342	0.000	0.000	0.000	0.000
15	80423	1.25	4.73	0.000	0.000	16.70	713.0	23.9	15.30	45.5	0.000	0.376	10.4	0.00	14.4	0.000	0.340	0.000	0.000	0.000	0.000
16	80424	0.70	4.12	0.000	0.000	14.00	715.0	23.2	8.50	43.5	0.000	0.354	10.4	0.00	13.9	0.000	0.354	0.000	0.000	0.000	0.000
17	80425	0.80	3.77	0.000	0.000	12.80	668.0	24.2	8.20	35.5	0.000	0.360	10.8	0.00	13.9	0.000	0.360	0.000	0.000	0.000	0.000
18	80426	0.88	4.74	0.000	0.000	14.00	690.0	25.8	19.70	54.0	0.000	0.420	9.200	0.00	13.6	0.000	0.370	0.000	0.000	0.000	0.000
19	80427	1.30	5.12	0.000	0.000	12.40	711.0	24.3	8.50	40.5	0.000	0.363	13.2	0.00	13.2	0.000	0.328	0.000	0.000	0.000	0.000
20	80428	0.93	3.04	0.000	0.000	11.50	700.0	23.8	11.50	39.0	0.000	0.339	11	0.00	17.3	0.000	0.406	0.000	0.000	0.000	0.000
21	80429	0.85	5.28	0.000	0.000	12.90	609.0	25.4	12.90	40.0	0.000	0.402	10.8	0.00	13.8	0.000	0.338	0.000	0.000	0.000	0.000
22	80430	1.24	4.04	0.000	0.000	10.60	701.0	23.2	7.10	40.0	0.000	0.354	10.6	0.00	14.9	0.000	0.346	0.000	0.000	0.000	0.000
23	80431	1.10	4.18	0.000	0.000	10.30	725.0	23.2	6.80	42.0	0.000	0.338	8.600	0.00	16.8	0.000	0.354	0.000	0.000	0.000	0.000

Crop Location—California 1982 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
24	82506	4.20	11.60	2.150	0.570	9.75	862.0	19.9	7.45	48.8	7.696	0.268	6.445	0.00	17.2	2.123	0.268	0.000	1.697	0.000	0.668
25	82509	4.00	11.90	1.400	0.510	9.78	914.0	19.3	5.21	71.5	12.78	0.269	5.595	0.00	22.3	2.010	0.293	0.001	1.545	0.000	0.759
26	82510	4.00	12.00	0.980	0.420	9.36	898.0	19.9	7.07	54.0	7.025	0.266	4.456	0.00	21.8	2.150	0.258	0.001	1.529	0.004	0.452
27	82511	0.00	0.00	3.350	0.480	9.28	892.0	19.9	8.82	47.5	8.153	0.274	7.695	0.00	18.9	2.760	0.261	0.006	2.125	0.112	0.135
28	82512	3.80	9.30	1.250	0.460	9.32	848.0	19.9	6.82	68.5	7.851	0.279	5.008	0.00	22.3	2.220	0.268	0.003	1.314	0.018	0.435
29	82525	0.00	0.00	1.180	0.430	9.60	872.0	19.9	1.55	50.3	7.461	0.281	5.442	0.00	18.0	1.980	0.290	0.000	0.000	0.000	0.000
30	82904	0.00	4.80	1.250	0.300	9.22	946.0	20.4	5.88	46.5	6.498	0.256	6.531	0.00	17.9	2.990	0.245	0.000	0.000	0.200	0.332
31	82915	0.00	0.00	0.000	0.000	8.94	872.0	24.3	17.74	55.5	3.957	0.269	6.518	0.00	23.6	2.060	0.258	0.000	0.000	0.000	0.000
32	82918	0.00	0.00	0.330	0.340	9.21	898.0	19.9	6.00	45.5	6.241	0.276	8.903	0.00	17.4	2.200	0.259	0.023	0.734	0.000	0.000
33	82931	0.00	7.80	0.650	0.380	8.32	844.0	23.8	5.80	46.5	10.29	0.281	9.614	0.00	16.6	2.020	0.295	0.060	0.534	0.230	0.187
34	0	0.00	0.00	0.000	0.000	10.04	896.0	20.4	3.00	55.0	5.675	0.290	4.694	0.00	14.4	1.830	0.299	0.000	0.000	0.000	0.000

Crop Location=North Dakota 1982 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
35	82721	0.00	0.00	0.750	0.420	11.14	784.0	19.9	9.39	31.0	5.637	0.332	7.636	0.00	16.7	2.970	0.383	0.000	0.000	0.000	0.000
36	82722	0.00	0.00	0.700	0.360	10.16	766.0	20.4	8.67	36.0	5.921	0.365	8.012	0.00	15.4	3.550	0.318	0.000	0.000	0.000	0.000
37	82723	0.00	0.00	0.720	0.260	11.90	788.0	19.3	15.96	51.0	8.423	0.393	6.178	0.00	16.8	2.153	0.375	0.000	0.000	0.000	0.000
38	82724	3.00	15.10	0.800	0.330	14.22	802.0	22.7	10.59	44.0	7.977	0.350	6.652	0.00	14.6	2.066	0.314	0.053	0.751	0.023	0.249
39	82728	3.10	13.80	1.030	0.410	12.38	808.0	19.9	9.71	42.0	6.670	0.297	6.288	0.00	13.4	2.754	0.299	0.010	1.262	0.004	0.393
40	82729	3.30	14.40	1.000	0.440	12.86	820.0	22.7	9.76	40.5	8.271	0.299	6.059	0.00	13.4	2.640	0.271	0.004	1.463	0.007	0.348
41	82730	0.00	13.00	0.850	0.430	11.82	830.0	23.2	3.50	33.8	5.699	0.293	8.125	0.00	12.8	2.793	0.303	0.000	0.000	0.007	0.377

Crop Location=Coal Valley 1982 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
42	1	0.00	9.20	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	13.4	1.867	0.291	0.000	0.000	0.016	0.456
43	2	0.00	7.70	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	15.8	1.720	0.289	0.000	0.000	0.008	0.630
44	3	0.00	7.20	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	20.2	1.850	0.289	0.000	0.000	0.017	0.568
45	4	0.00	7.20	0.000	0.000	17.82	779.5	24.2	0.00	0.0	0.000	0.000	0.000	0.00	15.8	1.720	0.289	0.000	0.000	0.008	0.684
46	5	0.00	7.30	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	15.5	1.520	0.347	0.000	0.000	0.005	0.720
47	6	0.00	7.30	0.000	0.000	18.34	794.0	24.8	0.00	0.0	0.000	0.000	0.000	0.00	18.1	1.660	0.302	0.000	0.000	0.004	0.768
48	7	0.00	6.90	0.000	0.000	18.26	791.0	24.5	0.00	0.0	0.000	0.000	0.000	0.00	15.6	1.470	0.310	0.000	0.000	0.000	1.119
49	8	0.00	7.60	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	17.9	1.690	0.290	0.000	0.000	0.005	0.704
50	9	0.00	6.30	0.000	0.000	18.89	782.8	26.6	0.00	0.0	0.000	0.000	0.000	0.00	20.2	1.850	0.289	0.000	0.000	0.010	0.734

Crop Location—Coal Valley 1982 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
51	10	0.00	5.40	0.000	0.000	12.46	823.5	21.9	0.00	0.0	0.000	0.000	0.000	0.00	18.8	1.566	0.335	0.000	0.000	0.079	0.474

Crop Location—Coal Valley 1983 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
52	1	1.80	0.00	0.830	0.290	14.11	786.0	22.7	10.43	37.4	3.990	0.300	7.543	0.00	0.0	0.000	0.000	0.047	1.279	0.000	0.000
53	2	2.60	0.00	0.370	0.190	13.61	808.0	22.7	10.94	44.4	4.310	0.293	6.917	0.00	0.0	0.000	0.000	0.072	0.747	0.000	0.000
54	3	1.70	0.00	0.700	0.160	17.85	772.0	25.9	15.90	41.3	4.830	0.310	9.679	0.00	0.0	0.000	0.000	0.054	1.278	0.000	0.000
55	4	0.00	0.00	0.430	0.170	18.08	778.0	28.3	14.29	48.9	4.660	0.331	7.825	0.00	0.0	0.000	0.000	0.000	0.000	0.000	0.000

Crop Location=North Dakota 1983 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
56	83535	0.90	6.40	1.550	0.320	10.70	650.0	25.4	7.60	46.8	3.370	0.370	5.899	0.00	13.7	1.730	0.347	0.089	2.004	0.001	1.064
57	83536	2.20	9.60	1.150	0.290	10.40	820.0	19.9	9.10	39.4	3.840	0.336	4.761	0.00	15.6	2.070	0.278	0.004	2.231	0.001	0.681
58	83537	0.00	8.50	0.870	0.200	10.60	830.0	22.2	11.30	41.3	3.860	0.354	6.012	0.00	0.0	0.000	0.000	0.109	0.183	0.003	0.683

Crop Location=North Dakota 1983 Barley

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
59	83417	0.90	6.40	1.520	0.270	17.10	612.0	24.9	12.20	45.9	3.630	0.409	3.812	0.00	14.0	1.810	0.432	0.086	1.942	0.001	1.106
60	83418	1.50	7.10	1.580	0.320	11.90	693.0	24.3	8.90	42.5	3.800	0.390	5.523	0.00	16.1	1.830	0.396	0.101	1.088	0.001	0.970
61	83419	1.20	7.70	1.810	0.290	13.80	621.0	25.2	11.40	48.9	3.600	0.358	4.199	0.00	12.9	1.850	0.386	0.030	2.410	0.019	0.516
62	83421	1.40	0.00	1.700	0.390	12.50	630.0	24.5	10.70	39.4	3.480	0.359	3.880	0.00	13.8	1.680	0.353	0.004	3.404	0.000	0.000
63	83532	1.20	6.30	1.290	0.430	8.70	695.0	25.4	9.40	34.0	3.640	0.377	7.829	0.00	20.0	2.440	0.340	0.036	2.175	0.001	1.107
64	83533	1.00	6.70	1.540	0.300	12.00	628.0	24.9	10.10	41.2	3.600	0.345	5.121	0.00	15.5	1.810	0.321	0.021	3.012	0.002	0.959
65	83534	1.20	7.10	1.590	0.430	11.20	631.0	25.4	8.30	40.6	3.320	0.320	5.522	0.00	16.6	1.800	0.310	0.027	2.465	0.002	0.864

Crop Location-Coal Valley 1984 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
66	6	0.00	0.00	1.980	0.000	0.00	0.0	0.00	8.50	34.1	3.515	0.282	5.847	81.02	0.0	0.000	0.000	0.000	0.000	0.000	0.000
67	7	0.00	0.00	2.120	0.000	0.00	0.0	0.00	8.24	40.3	3.401	0.279	6.694	104.50	0.0	0.000	0.000	0.000	0.000	0.000	0.000
68	9	0.00	0.00	2.010	0.000	0.00	0.0	0.00	8.44	35.9	3.369	0.286	6.648	82.25	0.0	0.000	0.000	0.000	0.000	0.000	0.000
69	10	0.00	0.00	2.230	0.000	0.00	0.0	0.00	8.50	39.5	3.603	0.272	6.064	113.20	0.0	0.000	0.000	0.000	0.000	0.000	0.000
70	11	0.00	0.00	2.220	0.000	0.00	0.0	0.00	16.29	48.3	3.852	0.423	5.588	92.10	0.0	0.000	0.000	0.000	0.000	0.000	0.000
71	12	0.00	0.00	2.310	0.000	0.00	0.0	0.00	10.43	36.7	4.045	0.274	6.258	64.60	0.0	0.000	0.000	0.000	0.000	0.000	0.000
72	13	0.00	0.00	2.210	0.000	0.00	0.0	0.00	14.20	37.8	3.362	0.335	7.462	84.93	0.0	0.000	0.000	0.000	0.000	0.000	0.000
73	14	0.00	0.00	2.550	0.000	0.00	0.0	0.00	16.48	32.9	3.250	0.416	6.822	71.38	0.0	0.000	0.000	0.000	0.000	0.000	0.000
74	15	0.00	0.00	2.440	0.000	0.00	0.0	0.00	18.12	38.9	3.523	0.385	6.040	33.25	0.0	0.000	0.000	0.000	0.000	0.000	0.000
75	16	0.00	0.00	2.300	0.000	0.00	0.0	0.00	14.37	38.4	3.471	0.317	6.767	35.98	0.0	0.000	0.000	0.000	0.000	0.000	0.000
76	17	0.00	0.00	2.190	0.000	0.00	0.0	0.00	13.18	39.3	3.434	0.311	6.783	101.10	0.0	0.000	0.000	0.000	0.000	0.000	0.000
77	18	0.00	0.00	2.110	0.000	0.00	0.0	0.00	7.44	38.0	3.292	0.293	6.493	78.83	0.0	0.000	0.000	0.000	0.000	0.000	0.000
78	19	0.00	0.00	2.150	0.000	0.00	0.0	0.00	13.56	35.8	2.966	0.276	6.977	45.28	0.0	0.000	0.000	0.000	0.000	0.000	0.000
79	20	0.00	0.00	2.170	0.000	0.00	0.0	0.00	13.45	45.0	3.470	0.339	6.456	129.90	0.0	0.000	0.000	0.000	0.000	0.000	0.000
80	21	0.00	0.00	2.240	0.000	0.00	0.0	0.00	15.67	41.7	3.293	0.331	6.570	65.59	0.0	0.000	0.000	0.000	0.000	0.000	0.000
81	22	0.00	0.00	2.350	0.000	0.00	0.0	0.00	13.86	38.9	3.442	0.318	6.944	81.92	0.0	0.000	0.000	0.000	0.000	0.000	0.000
82	23	0.00	0.00	2.180	0.000	0.00	0.0	0.00	16.21	37.6	3.181	0.328	7.312	73.76	0.0	0.000	0.000	0.000	0.000	0.000	0.000
83	24	0.00	0.00	2.070	0.000	0.00	0.0	0.00	7.75	33.9	3.094	0.274	7.221	79.10	0.0	0.000	0.000	0.000	0.000	0.000	0.000
84	25	0.00	0.00	2.060	0.000	0.00	0.0	0.00	15.63	44.4	3.282	0.375	6.633	99.59	0.0	0.000	0.000	0.000	0.000	0.000	0.000
85	26	0.00	0.00	2.070	0.000	0.00	0.0	0.00	8.64	41.8	3.144	0.297	5.197	156.70	0.0	0.000	0.000	0.000	0.000	0.000	0.000
86	27	0.00	0.00	2.300	0.000	0.00	0.0	0.00	8.65	36.3	3.618	0.272	6.268	84.77	0.0	0.000	0.000	0.000	0.000	0.000	0.000

87	28	0.00	0.00	2.060	0.000	0.00	0.0	0.00	16.79	32.4	3.938	0.354	6.568	44.72	0.0	0.000	0.000	0.000	0.000	0.000	0.000
88	29	0.00	0.00	2.130	0.000	0.00	0.0	0.00	8.41	40.8	3.863	0.260	5.945	80.60	0.0	0.000	0.000	0.000	0.000	0.000	0.000
89	30	0.00	0.00	2.190	0.000	0.00	0.0	0.00	9.71	32.8	3.491	0.268	7.554	55.68	0.0	0.000	0.000	0.000	0.000	0.000	0.000
90	31	0.00	0.00	2.250	0.000	0.00	0.0	0.00	13.59	42.6	4.198	0.294	5.770	103.90	0.0	0.000	0.000	0.000	0.000	0.000	0.000
91	32	0.00	0.00	2.320	0.000	0.00	0.0	0.00	18.42	42.4	3.596	0.344	5.780	97.41	0.0	0.000	0.000	0.000	0.000	0.000	0.000
92	33	0.00	0.00	2.280	0.000	0.00	0.0	0.00	14.25	36.9	3.318	0.279	11.44	55.79	0.0	0.000	0.000	0.000	0.000	0.000	0.000
93	34	0.00	0.00	2.260	0.000	0.00	0.0	0.00	9.50	35.5	5.206	0.267	6.414	88.19	0.0	0.000	0.000	0.000	0.000	0.000	0.000
94	35	0.00	0.00	2.030	0.000	0.00	0.0	0.00	13.38	39.4	3.216	0.300	8.589	78.59	0.0	0.000	0.000	0.000	0.000	0.000	0.000
95	36	0.00	0.00	2.060	0.000	0.00	0.0	0.00	9.94	40.6	3.440	0.392	7.470	121.40	0.0	0.000	0.000	0.000	0.000	0.000	0.000
96	37	0.00	0.00	2.040	0.000	0.00	0.0	0.00	10.41	39.3	3.219	0.265	6.946	97.50	0.0	0.000	0.000	0.000	0.000	0.000	0.000
97	38	0.00	0.00	1.950	0.000	0.00	0.0	0.00	18.03	34.3	2.770	0.394	8.505	74.85	0.0	0.000	0.000	0.000	0.000	0.000	0.000
98	39	0.00	0.00	1.890	0.000	0.00	0.0	0.00	14.82	36.0	3.071	0.306	6.913	83.43	0.0	0.000	0.000	0.000	0.000	0.000	0.000
99	40	0.00	0.00	1.940	0.000	0.00	0.0	0.00	9.31	40.1	4.172	0.257	5.968	56.78	0.0	0.000	0.000	0.000	0.000	0.000	0.000
100	41	0.00	0.00	2.130	0.000	0.00	0.0	0.00	9.91	32.4	3.692	0.276	8.502	70.06	0.0	0.000	0.000	0.000	0.000	0.000	0.000
101	42	0.00	0.00	2.170	0.000	0.00	0.0	0.00	14.90	37.1	2.847	0.333	6.718	118.40	0.0	0.000	0.000	0.000	0.000	0.000	0.000
102	43	0.00	0.00	2.050	0.000	0.00	0.0	0.00	11.33	36.6	3.080	0.305	7.350	72.51	0.0	0.000	0.000	0.000	0.000	0.000	0.000
103	44	0.00	0.00	2.240	0.000	0.00	0.0	0.00	16.03	47.9	3.514	0.424	5.534	116.90	0.0	0.000	0.000	0.000	0.000	0.000	0.000
104	5	0.00	0.00	0.000	0.000	0.00	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	23.5	1.350	0.533	0.000	0.000	0.000	0.000
105	6	0.00	0.00	0.000	0.000	0.00	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	15.5	2.660	0.318	0.000	0.000	0.000	0.000
106	7	0.00	0.00	0.000	0.000	0.00	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	17.4	1.700	0.432	0.000	0.000	0.000	0.000
107	8	0.00	10.70	0.000	0.000	15.50	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	16.2	2.130	0.391	0.000	0.000	0.005	0.500
108	9	0.00	0.00	0.000	0.000	12.43	832.0	22.7	0.00	0.0	0.000	0.000	0.000	0.00	14.9	2.370	0.352	0.000	0.000	0.000	0.000
109	10	0.00	0.00	0.000	0.000	0.00	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	16.8	1.680	0.365	0.000	0.000	0.000	0.000
110	11	0.00	0.00	0.000	0.000	0.00	0.0	0.00	0.00	0.0	0.000	0.000	0.000	0.00	16.4	2.000	0.310	0.000	0.000	0.000	0.000
111	12	0.00	0.00	0.000	0.000	18.52	793.0	22.9	0.00	0.0	0.000	0.000	0.000	0.00	20.9	1.570	0.456	0.000	0.000	0.000	0.000
112	13	0.00	11.20	0.000	0.000	12.00	831.0	19.6	0.00	0.0	0.000	0.000	0.000	0.00	13.3	1.770	0.317	0.000	0.000	0.035	0.300
113	14	0.00	0.00	0.000	0.000	25.87	708.0	27.4	0.00	0.0	0.000	0.000	0.000	0.00	16.0	2.000	0.352	0.000	0.000	0.000	0.000
114	15	0.00	0.00	0.000	0.000	22.26	766.0	25.8	0.00	0.0	0.000	0.000	0.000	0.00	13.0	1.830	0.350	0.000	0.000	0.000	0.000

Crop Location=Coal Valley 1984 Wheat

OBS	SERIES	CL5MFR	SL1MFR	GMOG	CMOG	GMOST	GDEN	GAOR	CMOST	CDEN	CCOMOD	CFRICT	CMLNTG	SMOST	SDEN	SCOMOD	SFRICT	CLA	CLB	WALKA	WALKB
115	16	0.00	0.00	0.000	0.000	19.55	765.0	23.8	0.00	0.0	0.000	0.000	0.000	0.00	0.0	2.260	0.308	0.000	0.000	0.000	0.000
116	17	0.00	0.00	0.000	0.000	18.20	751.0	19.9	0.00	0.0	0.000	0.000	0.000	0.00	13.9	2.330	0.346	0.000	0.000	0.000	0.000
117	18	0.00	0.00	0.000	0.000	20.02	749.0	23	0.00	0.0	0.000	0.000	0.000	0.00	15.3	2.310	0.429	0.000	0.000	0.000	0.000
118	19	0.00	0.00	0.000	0.000	16.23	770.0	20.4	0.00	0.0	0.000	0.000	0.000	0.00	10.2	1.410	0.385	0.000	0.000	0.000	0.000
119	20	0.00	0.00	0.000	0.000	15.04	765.0	19.7	0.00	0.0	0.000	0.000	0.000	0.00	15.6	2.340	0.364	0.000	0.000	0.000	0.000
120	21	0.00	0.00	0.000	0.000	13.51	762.0	19.9	0.00	0.0	0.000	0.000	0.000	0.00	19.7	2.340	0.385	0.000	0.000	0.000	0.000
121	22	0.00	0.00	0.000	0.000	37.91	683.0	26	0.00	0.0	0.000	0.000	0.000	0.00	30.4	1.750	0.443	0.000	0.000	0.000	0.000
122	23	0.00	9.50	0.000	0.000	14.12	783.0	19.3	0.00	0.0	0.000	0.000	0.000	0.00	14.7	2.360	0.378	0.000	0.000	0.001	0.685
123	24	0.00	0.00	0.000	0.000	23.46	735.0	26	0.00	0.0	0.000	0.000	0.000	0.00	23.3	1.863	0.457	0.000	0.000	0.000	0.000
124	25	0.00	0.00	0.000	0.000	15.02	743.0	19.9	0.00	0.0	0.000	0.000	0.000	0.00	14.3	2.045	0.334	0.000	0.000	0.000	0.000
125	26	0.00	0.00	0.000	0.000	23.66	745.0	25.3	0.00	0.0	0.000	0.000	0.000	0.00	19.3	2.110	0.300	0.000	0.000	0.000	0.000
126	27	0.00	0.00	0.000	0.000	13.52	760.0	19.3	0.00	0.0	0.000	0.000	0.000	0.00	15.2	2.270	0.295	0.000	0.000	0.000	0.000
127	28	0.00	8.90	0.000	0.000	23.27	709.0	26.2	0.00	0.0	0.000	0.000	0.000	0.00	12.6	1.720	0.334	0.000	0.000	0.028	0.401
128	29	0.00	8.50	0.000	0.000	23.22	752.0	26	0.00	0.0	0.000	0.000	0.000	0.00	21.2	1.440	0.358	0.000	0.000	0.087	0.288
129	30	0.00	0.00	0.000	0.000	16.43	755.0	19.2	0.00	0.0	0.000	0.000	0.000	0.00	13.9	2.180	0.334	0.000	0.000	0.000	0.000
130	31	0.00	0.00	0.000	0.000	12.00	750.0	18.8	0.00	0.0	0.000	0.000	0.000	0.00	17.7	1.697	0.281	0.000	0.000	0.000	0.000
131	32	0.00	0.00	0.000	0.000	17.10	713.0	20.6	0.00	0.0	0.000	0.000	0.000	0.00	11.9	0.000	0.334	0.000	0.000	0.000	0.000
132	33	0.00	0.00	0.000	0.000	20.07	750.0	20.1	0.00	0.0	0.000	0.000	0.000	0.00	13.7	2.020	0.366	0.000	0.000	0.000	0.000
133	34	0.00	0.00	0.000	0.000	14.03	717.0	16.8	0.00	0.0	0.000	0.000	0.000	0.00	13.0	2.491	0.339	0.000	0.000	0.000	0.000
134	35	0.00	0.00	0.000	0.000	13.22	743.0	17.7	0.00	0.0	0.000	0.000	0.000	0.00	14.4	2.260	0.305	0.000	0.000	0.000	0.000
135	36	0.00	0.00	0.000	0.000	12.58	750.0	15.4	0.00	0.0	0.000	0.000	0.000	0.00	14.5	2.890	0.314	0.000	0.000	0.000	0.000

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136 37 0.00 0.00 0.000 0.000 19.80 712.0 22.6 0.00 0.0 0.000 0.000 0.000 0.00 13.3 2.278 0.351 0.000 0.000 0.000 0.000
137 38 0.00 0.00 0.000 0.000 17.77 743.0 19.9 0.00 0.0 0.000 0.000 0.000 0.00 12.1 1.880 0.378 0.000 0.000 0.000 0.000
138 39 0.00 0.00 0.000 0.000 15.97 745.0 19.3 0.00 0.0 0.000 0.000 0.000 0.00 13.8 2.330 0.347 0.000 0.000 0.000 0.000
139 40 0.00 9.00 0.000 0.000 12.90 746.0 16.6 0.00 0.0 0.000 0.000 0.000 0.00 14.5 2.580 0.310 0.000 0.000 0.059 0.316
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APPENDIX B

Scatter Plots of Combine Performance Versus Crop Properties

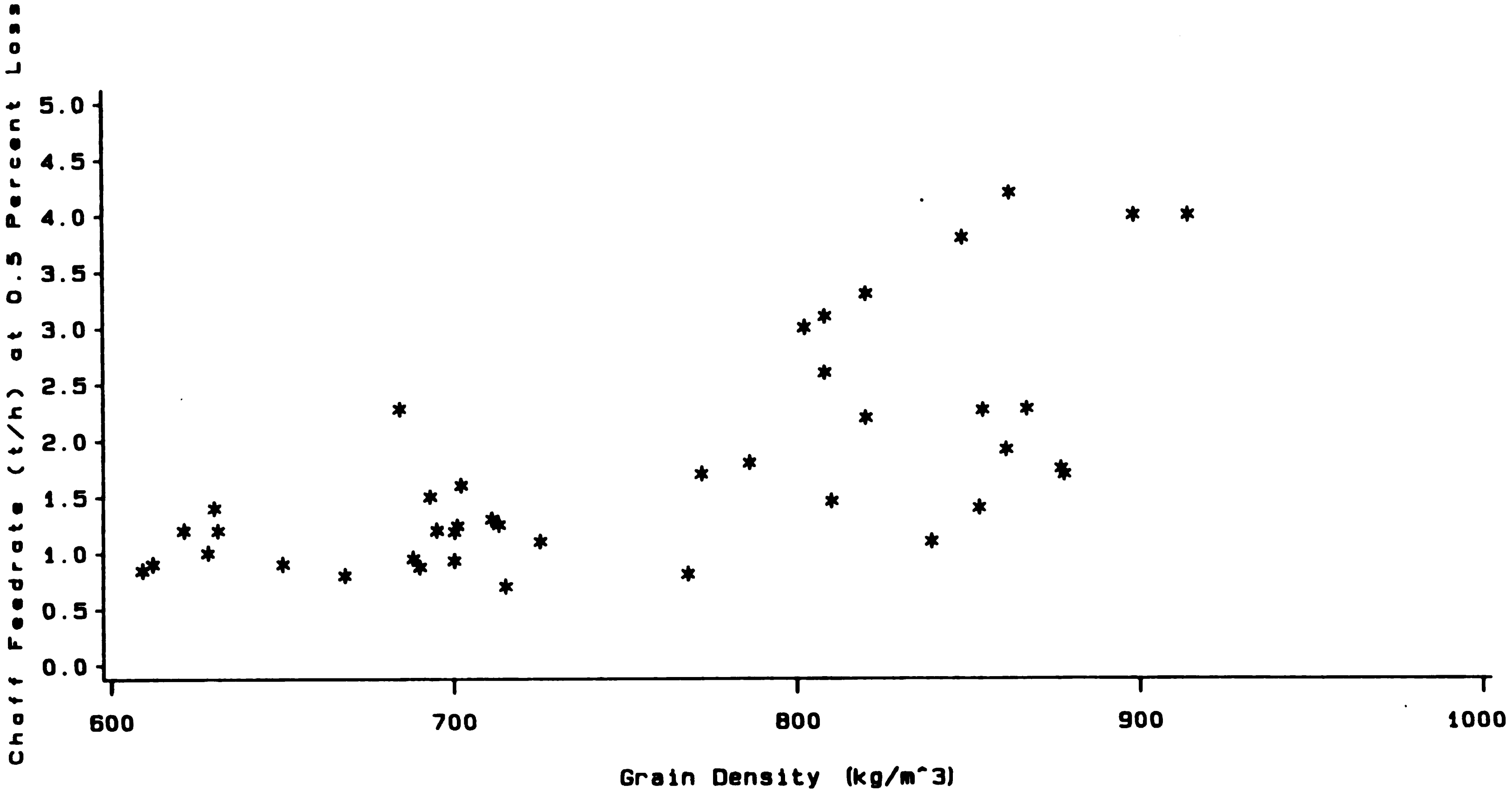


FIGURE 21

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSS VERSUS GRAIN DENSITY (kg/m^3)

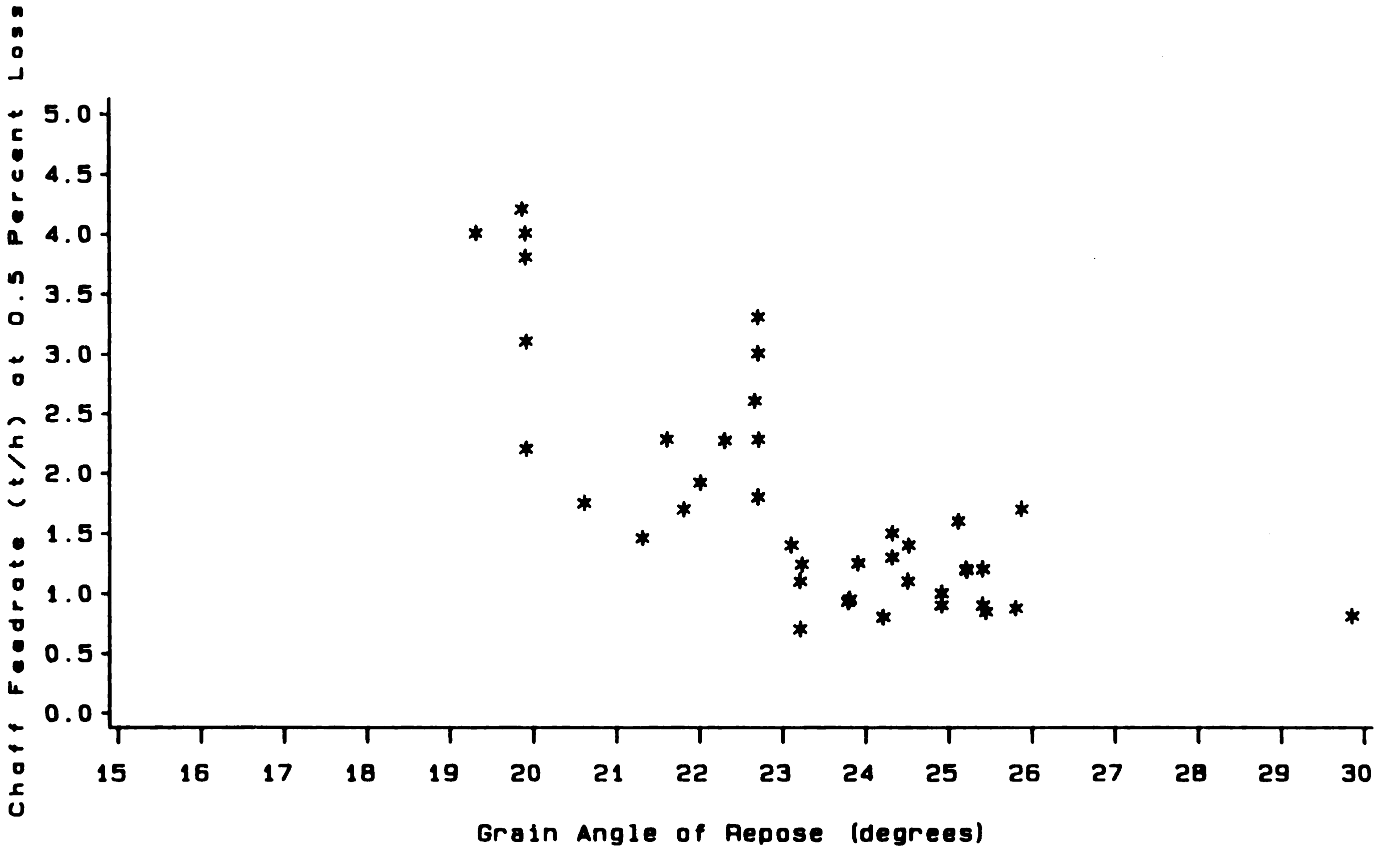


FIGURE 22

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSS VERSUS GRAIN ANGLE OF REPOSE (DEGREES)

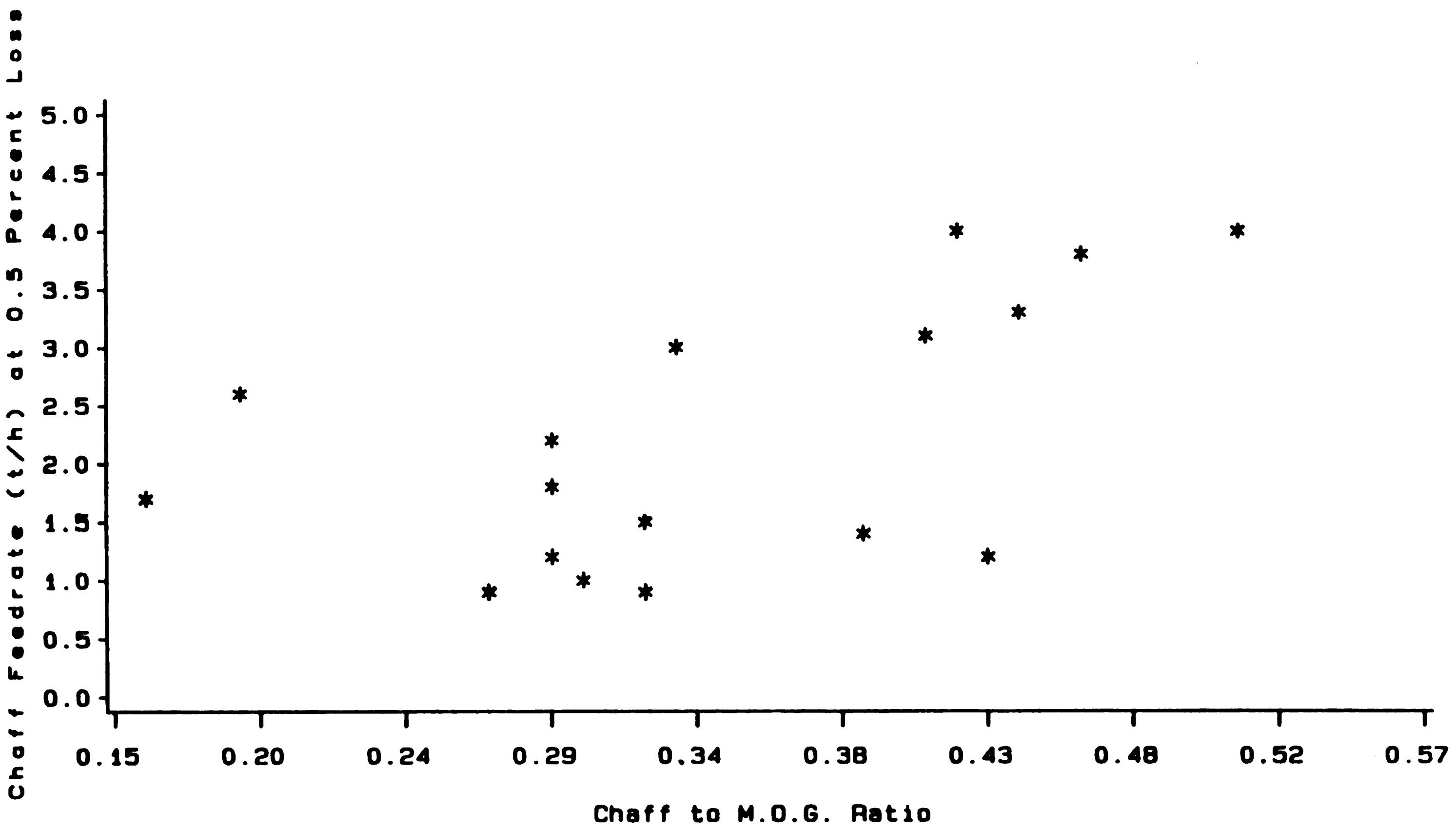


FIGURE 23

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT
GRAIN LOSS VERSUS CHAFF TO M.O.G. RATIO

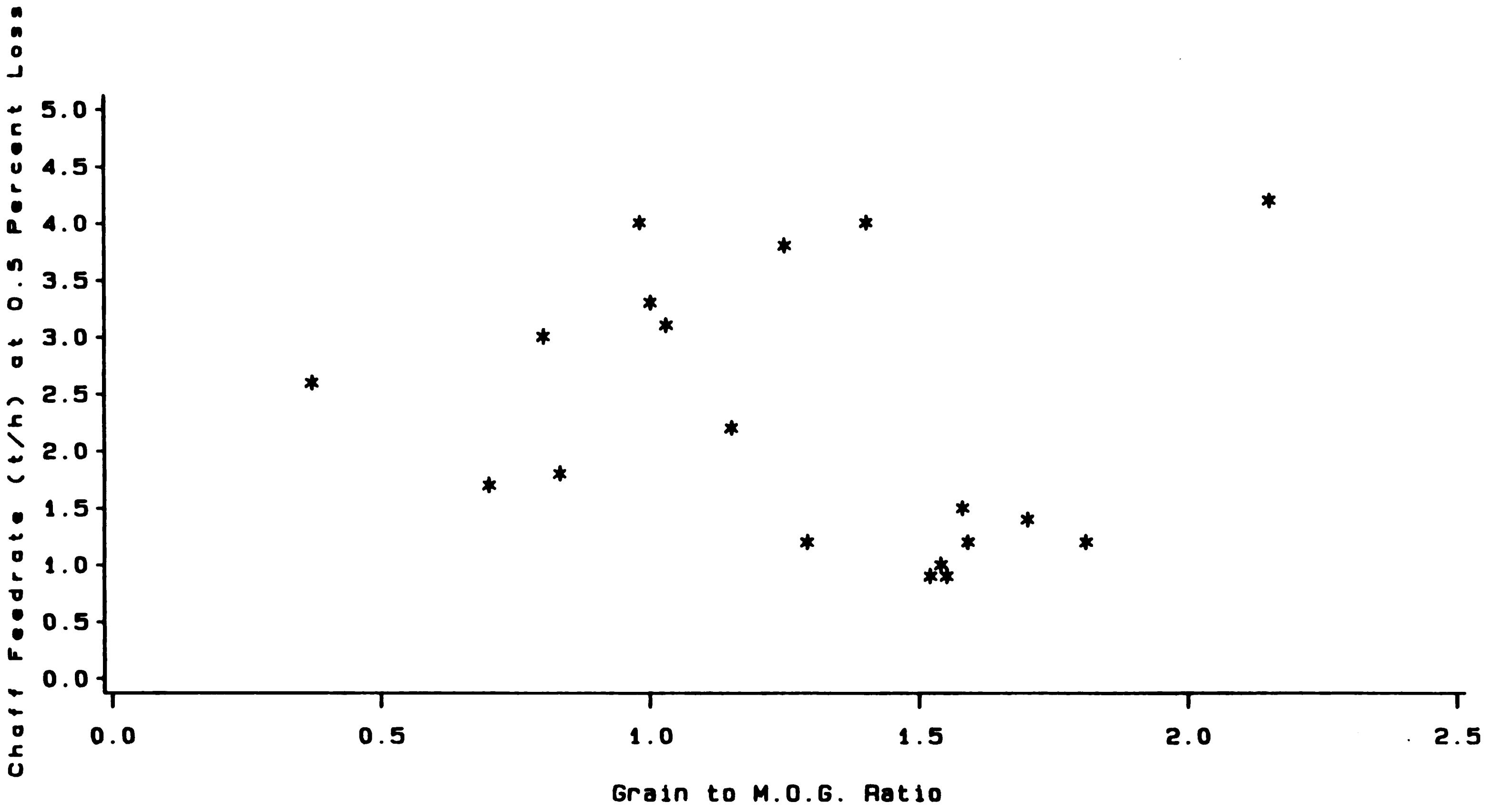


FIGURE 24

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSS VERSUS GRAIN TO M.O.G. RATIO

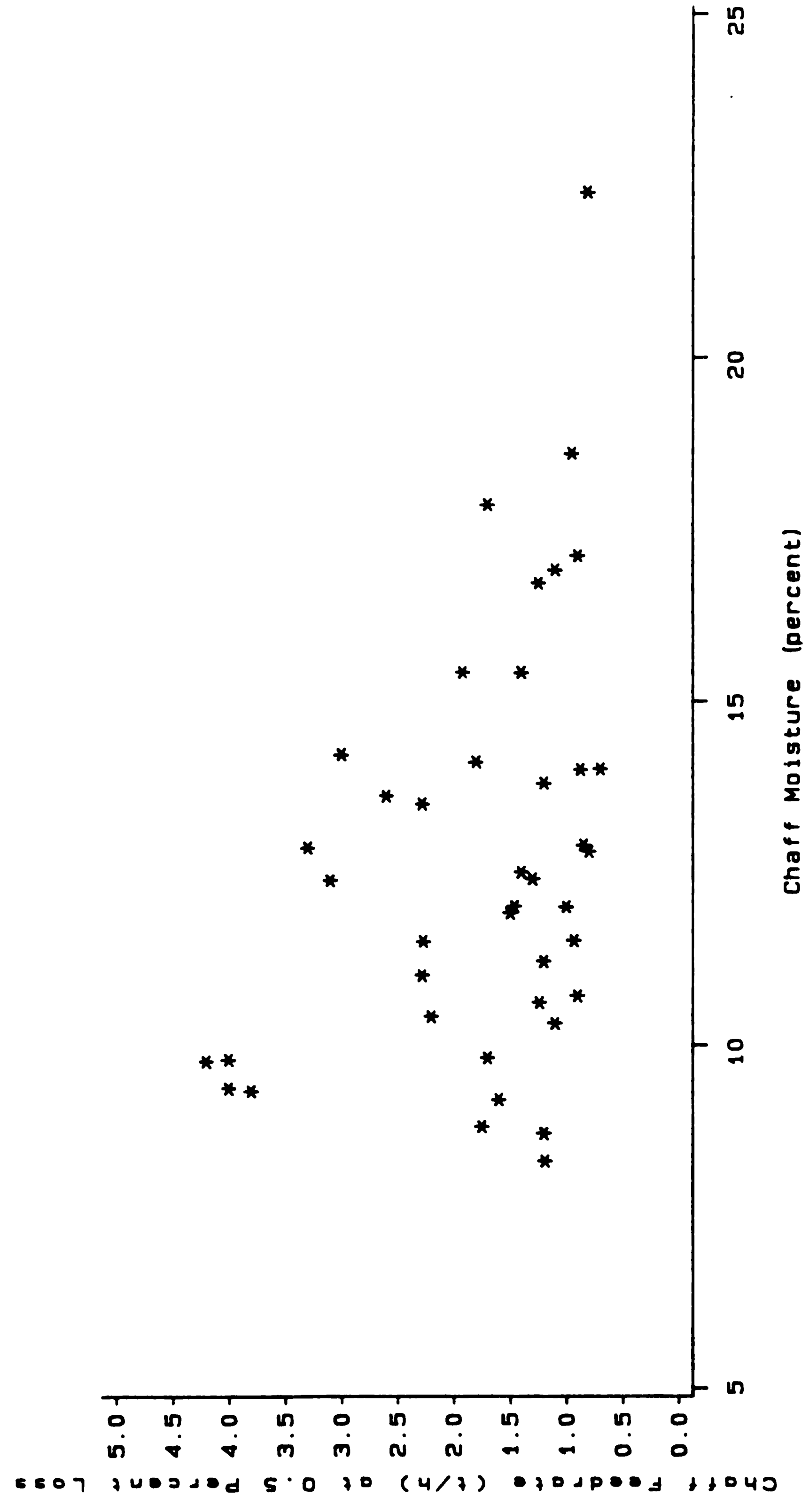


FIGURE 25

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSS VERSUS CHAFF MOISTURE (PERCENT DRY BASIS)

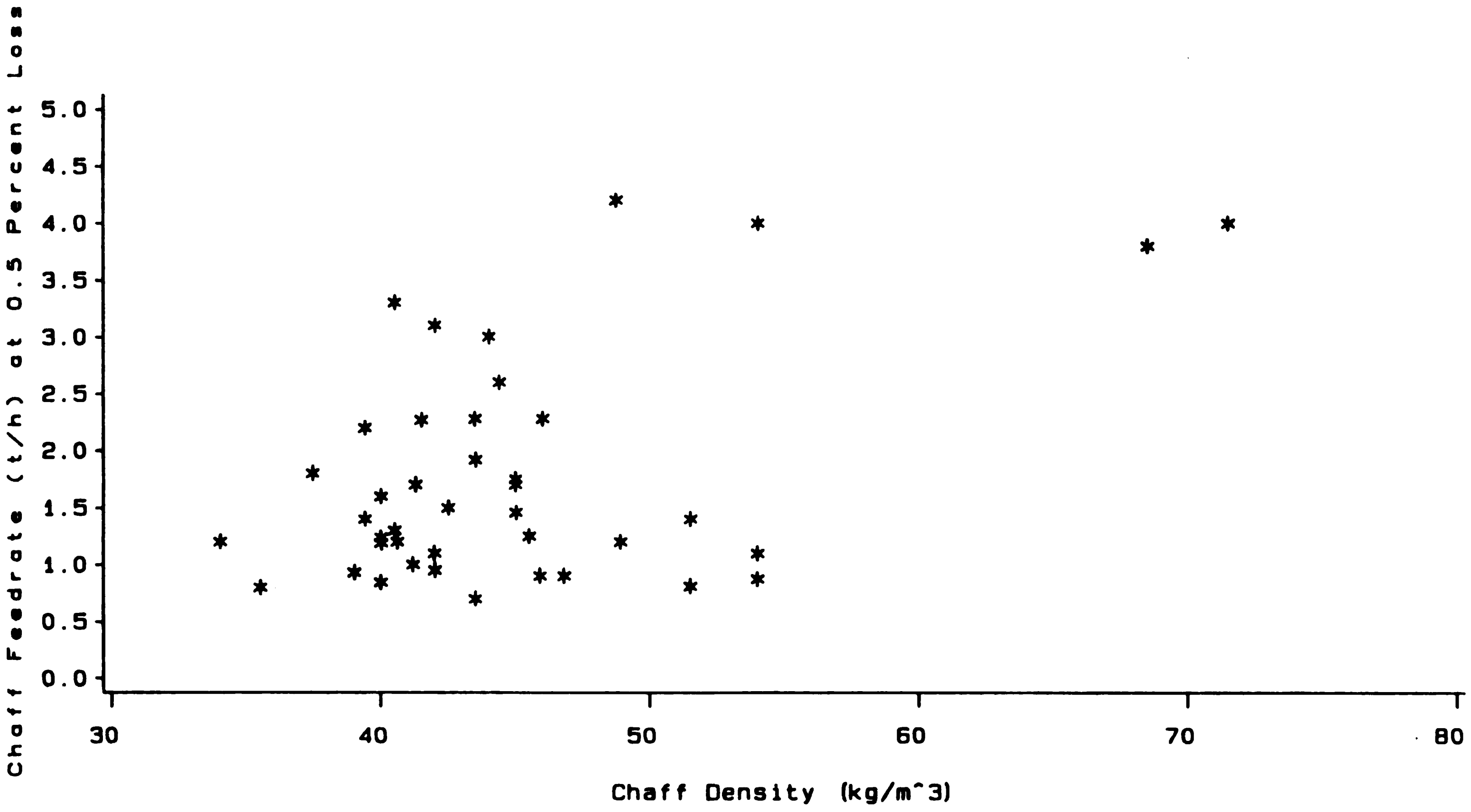


FIGURE 26

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSSVERSUS CHAFF DENSITY (kg/m^3)

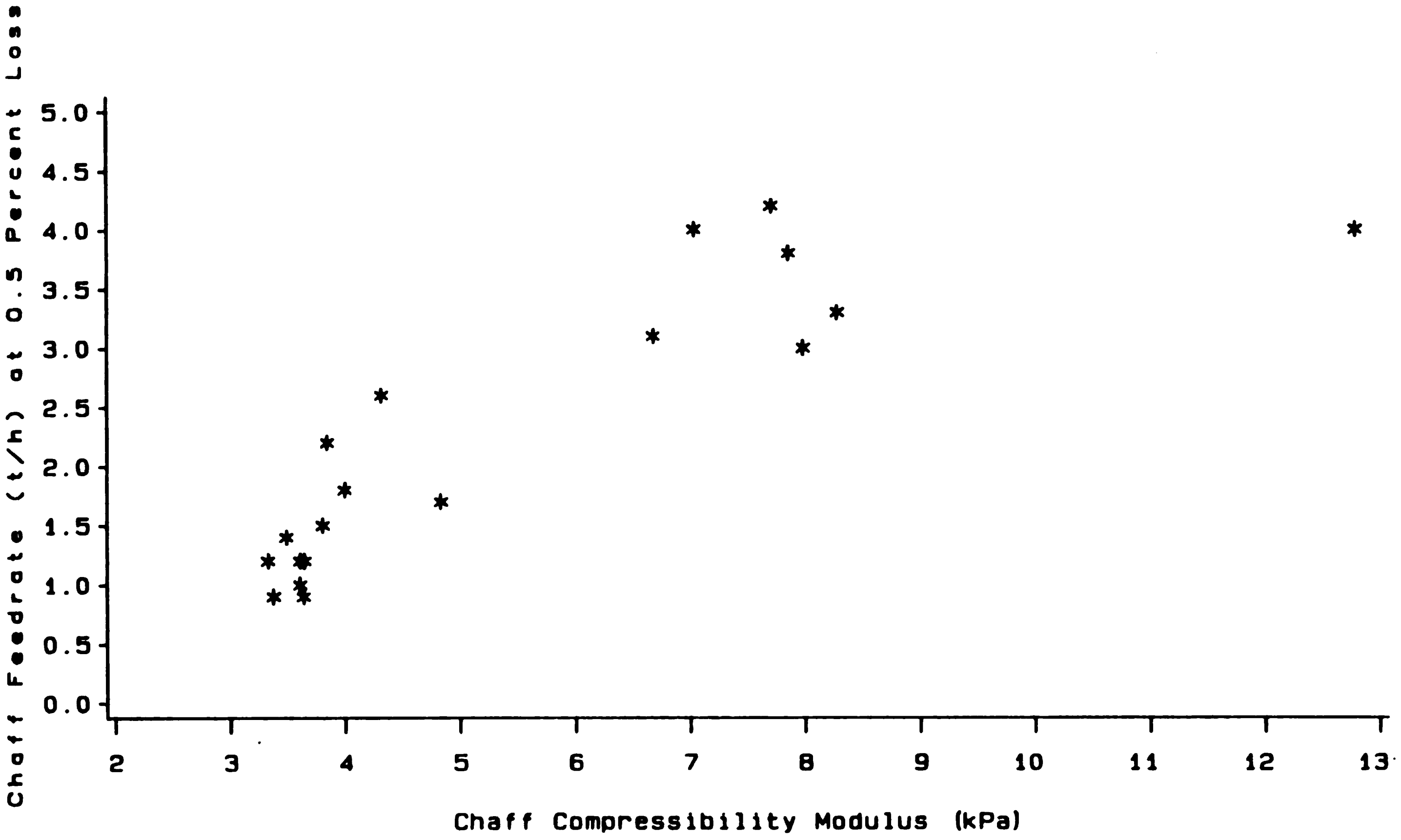


FIGURE 27

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT GRAIN LOSS VERSUS CHAFF COMPRESSIBILITY MODULUS (kPa)

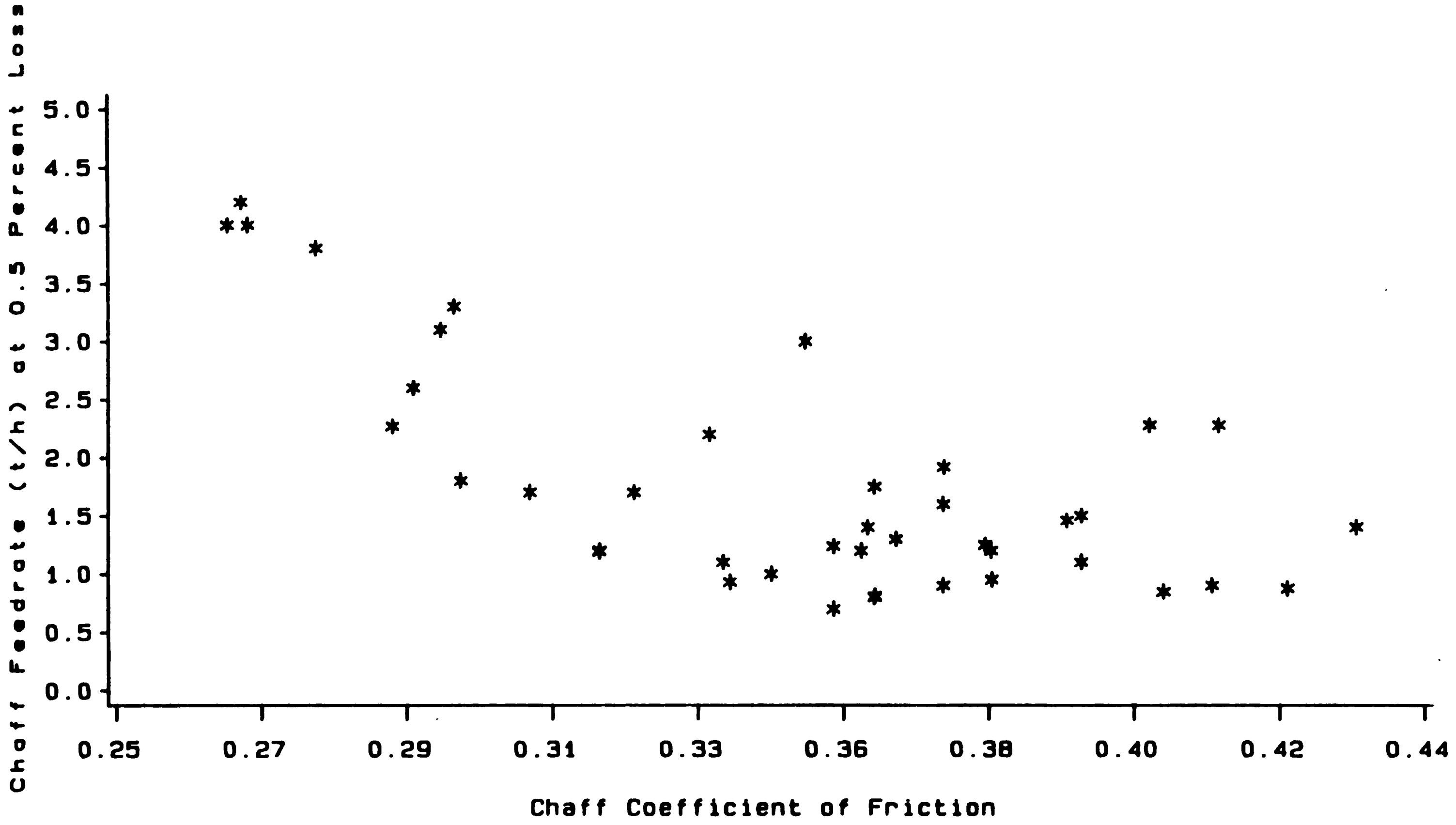


FIGURE 28

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT
GRAIN LOSS VERSUS CHAFF COEFFICIENT OF FRICTION

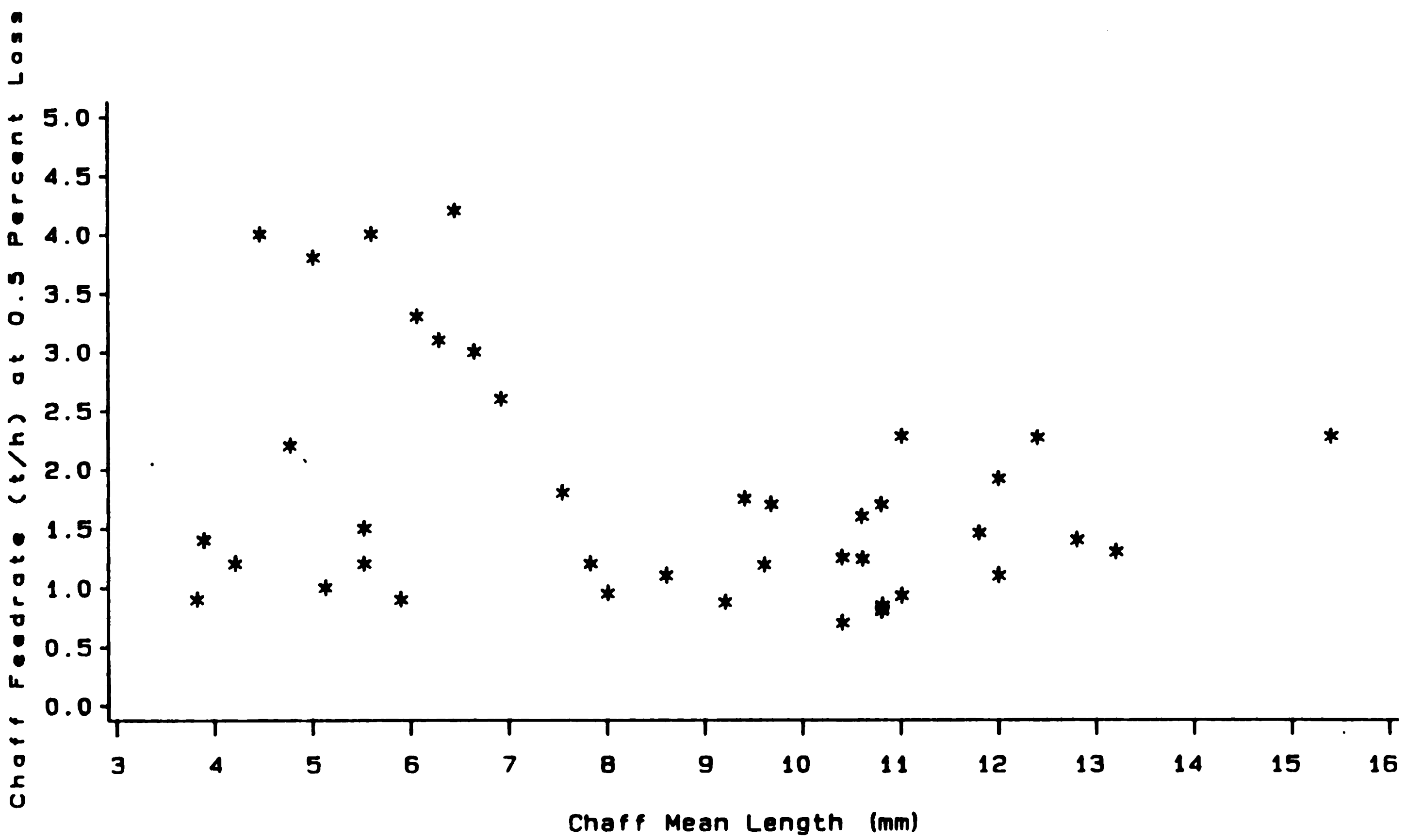


FIGURE 29

SCATTER PLOT OF CHAFF FEEDRATE (t/h) AT 0.5 PERCENT
GRAIN LOSS VERSUS CHAFF MEAN LENGTH (mm)

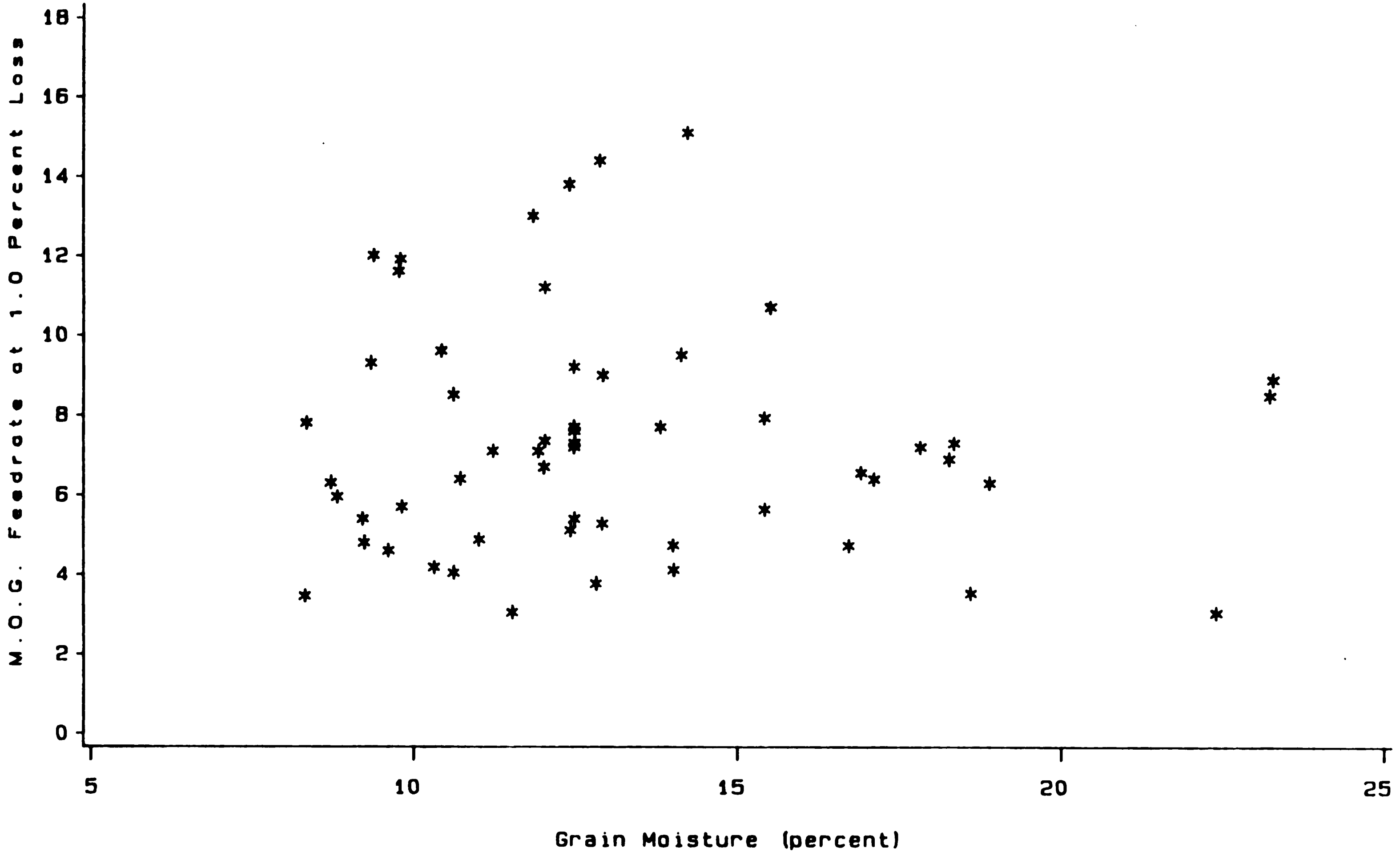


FIGURE 30

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT
GRAIN LOSS VERSUS GRAIN MOISTURE (PERCENT DRY BASIS)

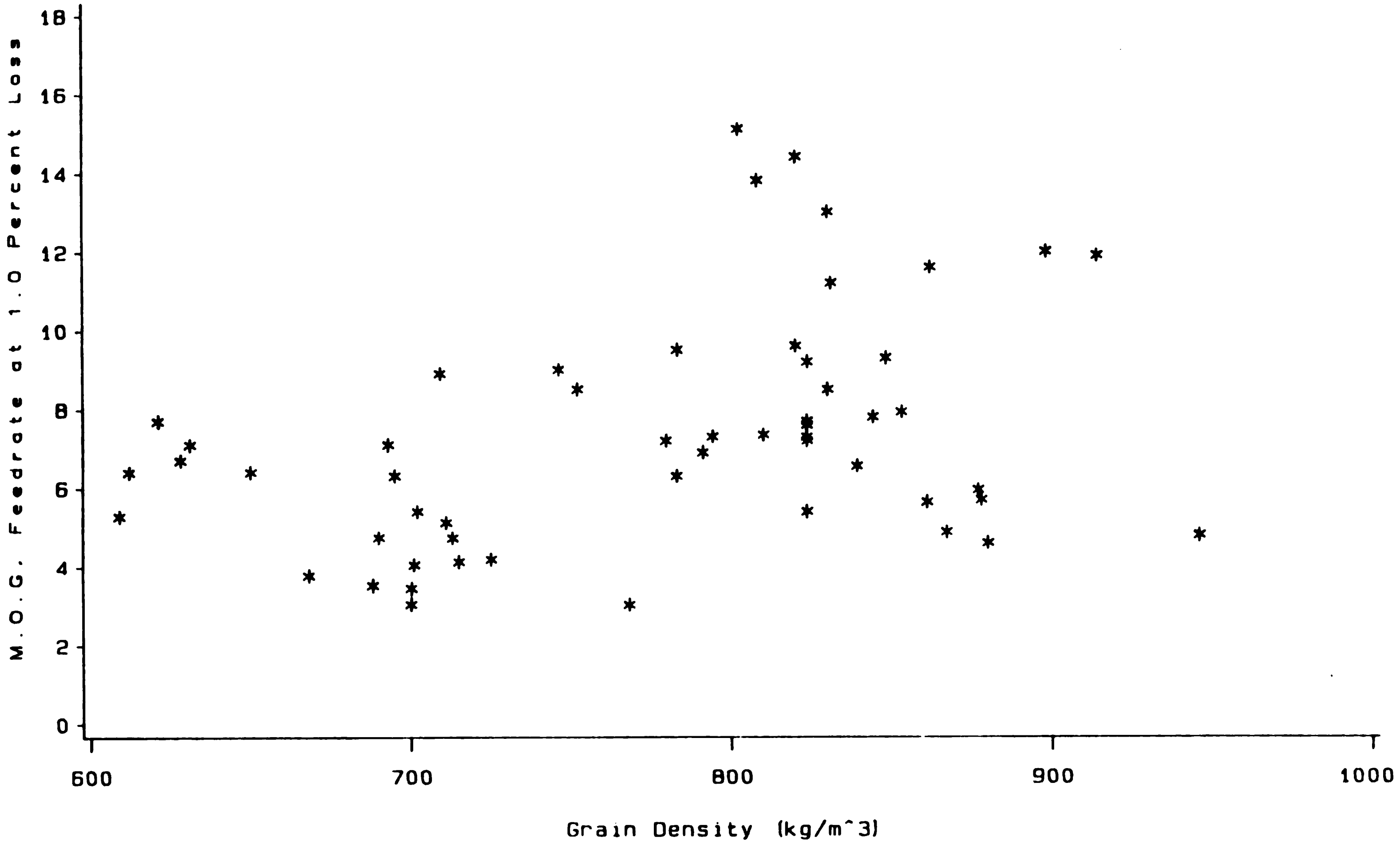


FIGURE 31

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT GRAIN LOSS VERSUS GRAIN DENSITY (kg/m^3)

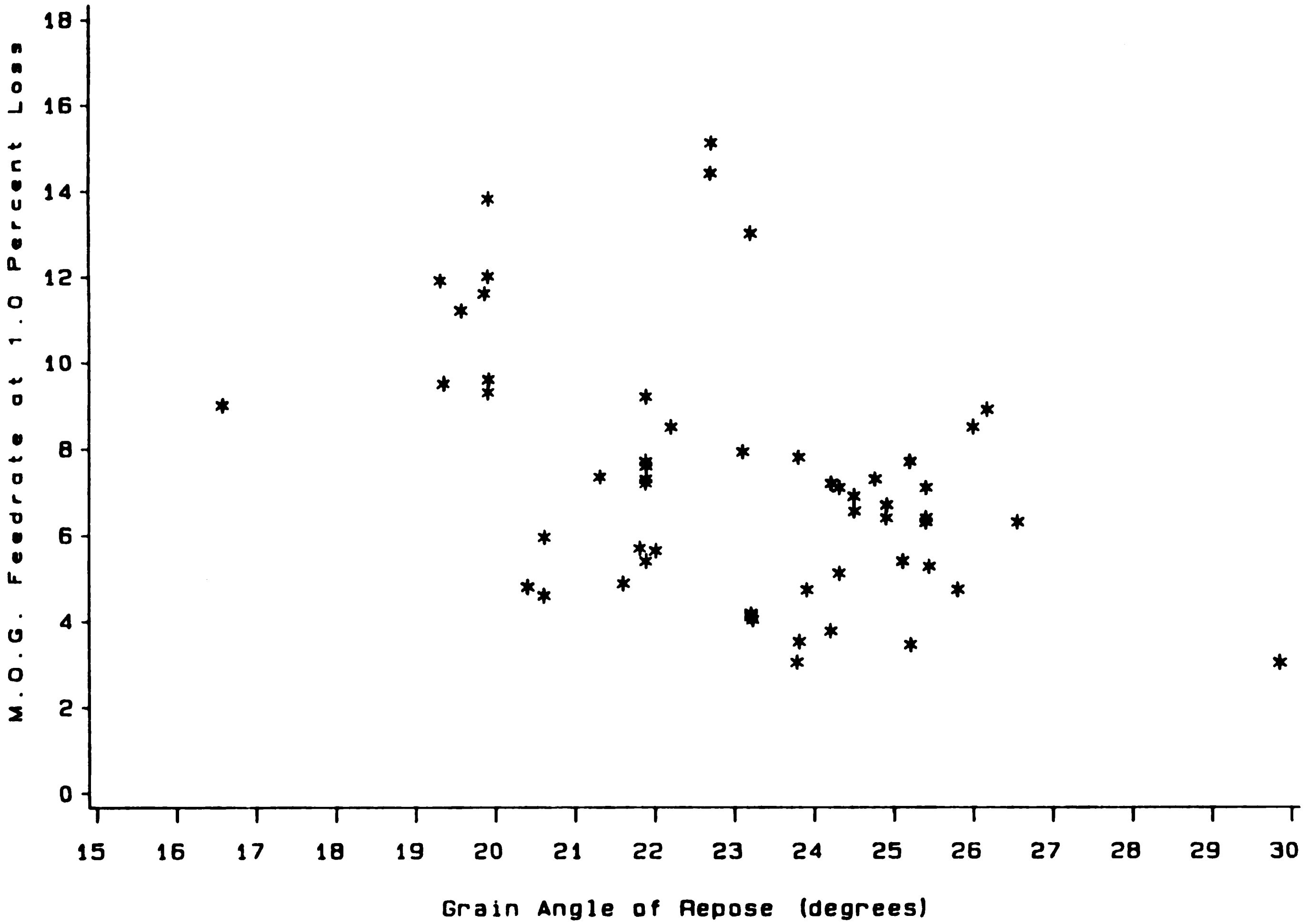


FIGURE 32

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT
GRAIN LOSS VERSUS GRAIN ANGLE OF REPOSE (DEGREES)

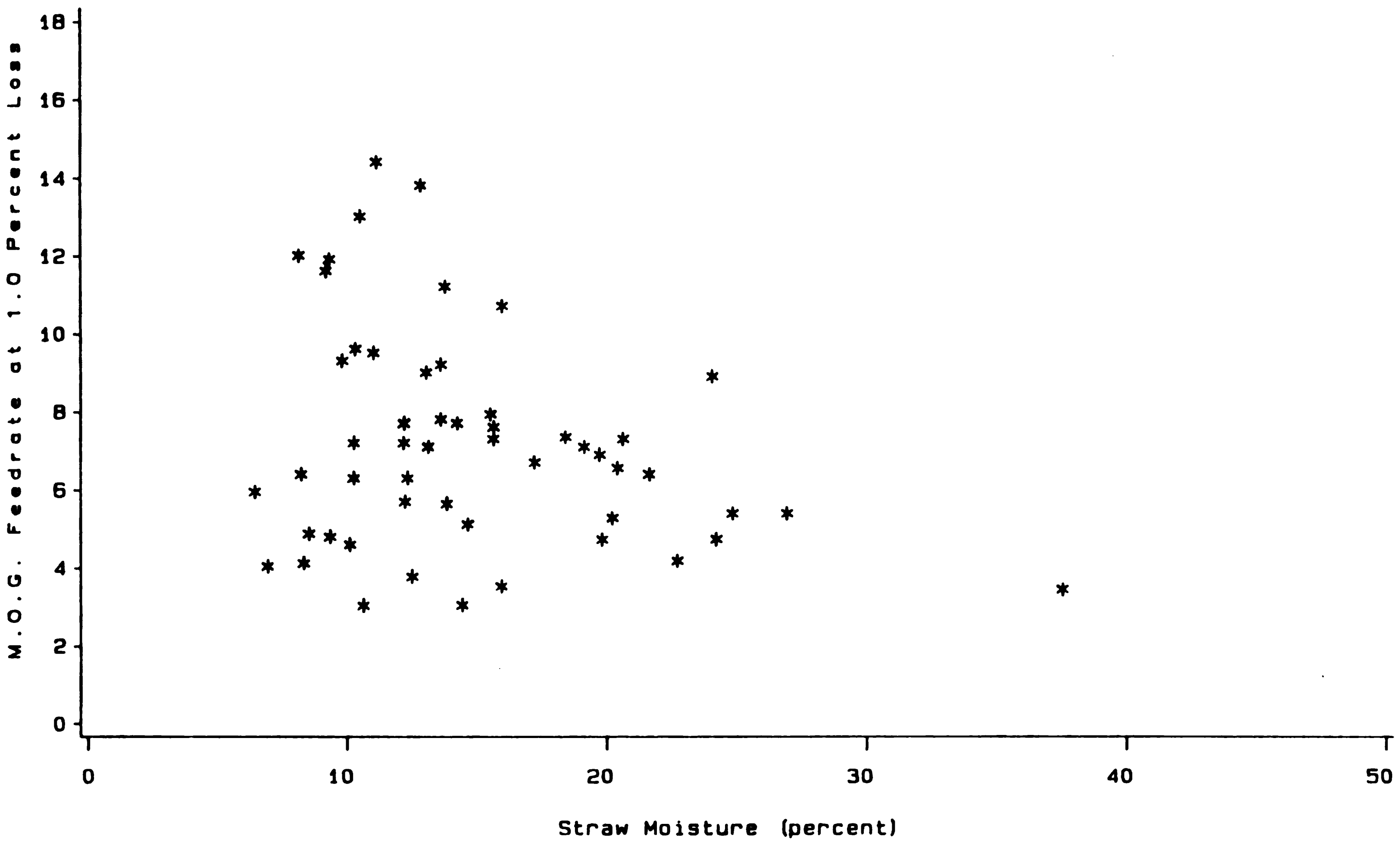


FIGURE 33

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT
GRAIN LOSS VERSUS STRAW MOISTURE (PERCENT DRY BASIS)

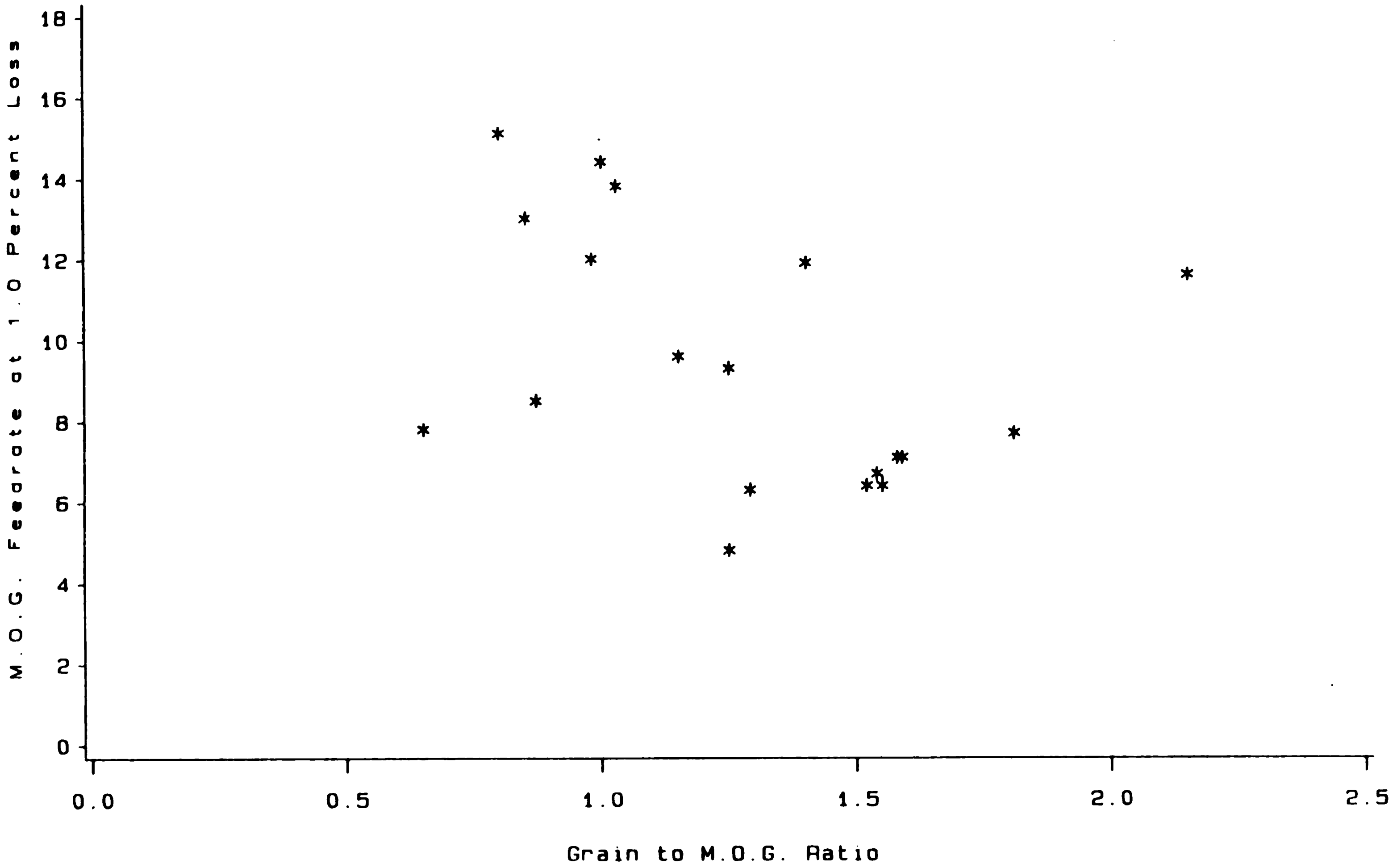


FIGURE 34

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT GRAIN LOSS VERSUS GRAIN TO M.O.G. RATIO

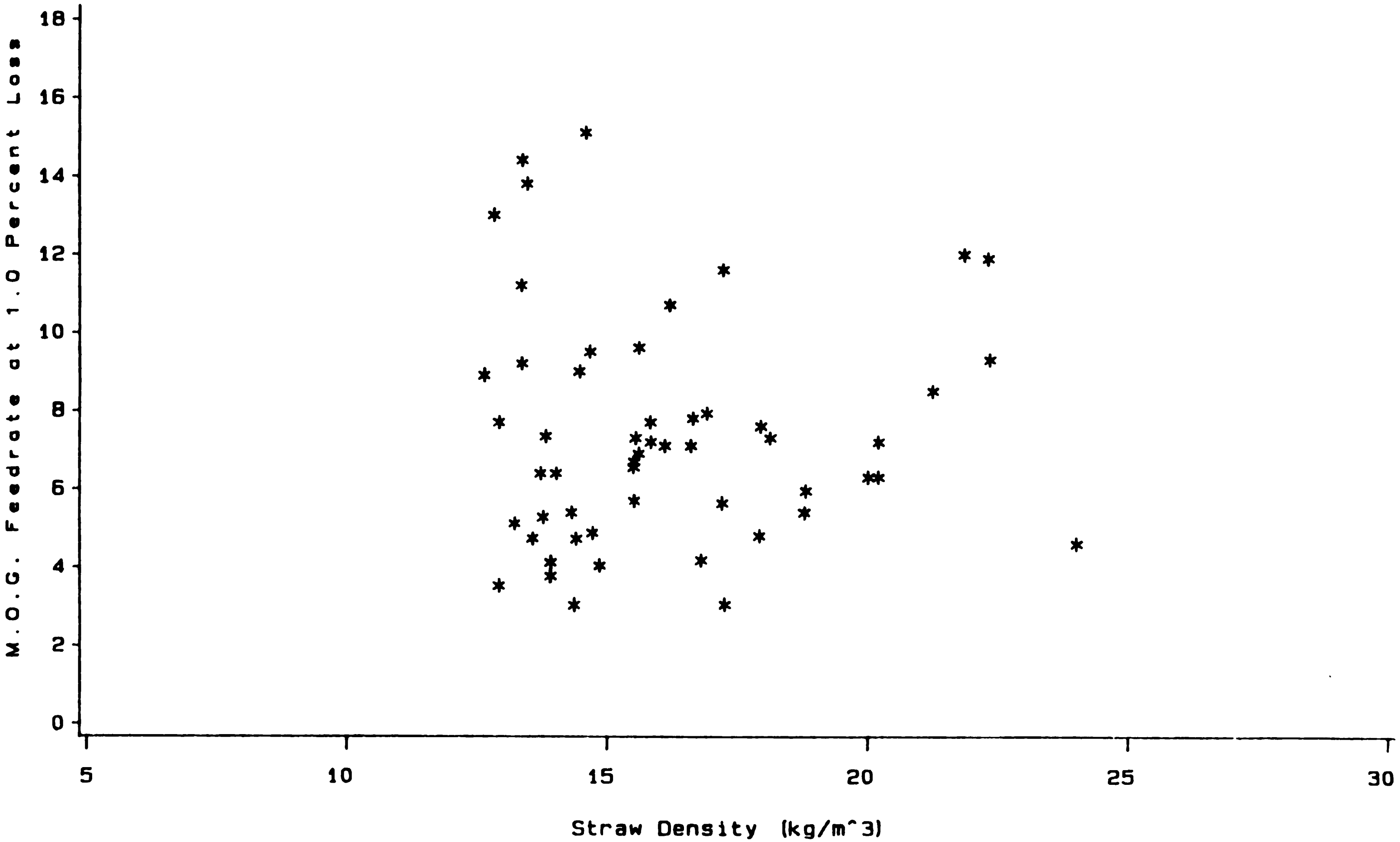


FIGURE 35

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT GRAIN LOSS VERSUS STRAW DENSITY (kg/m^3)

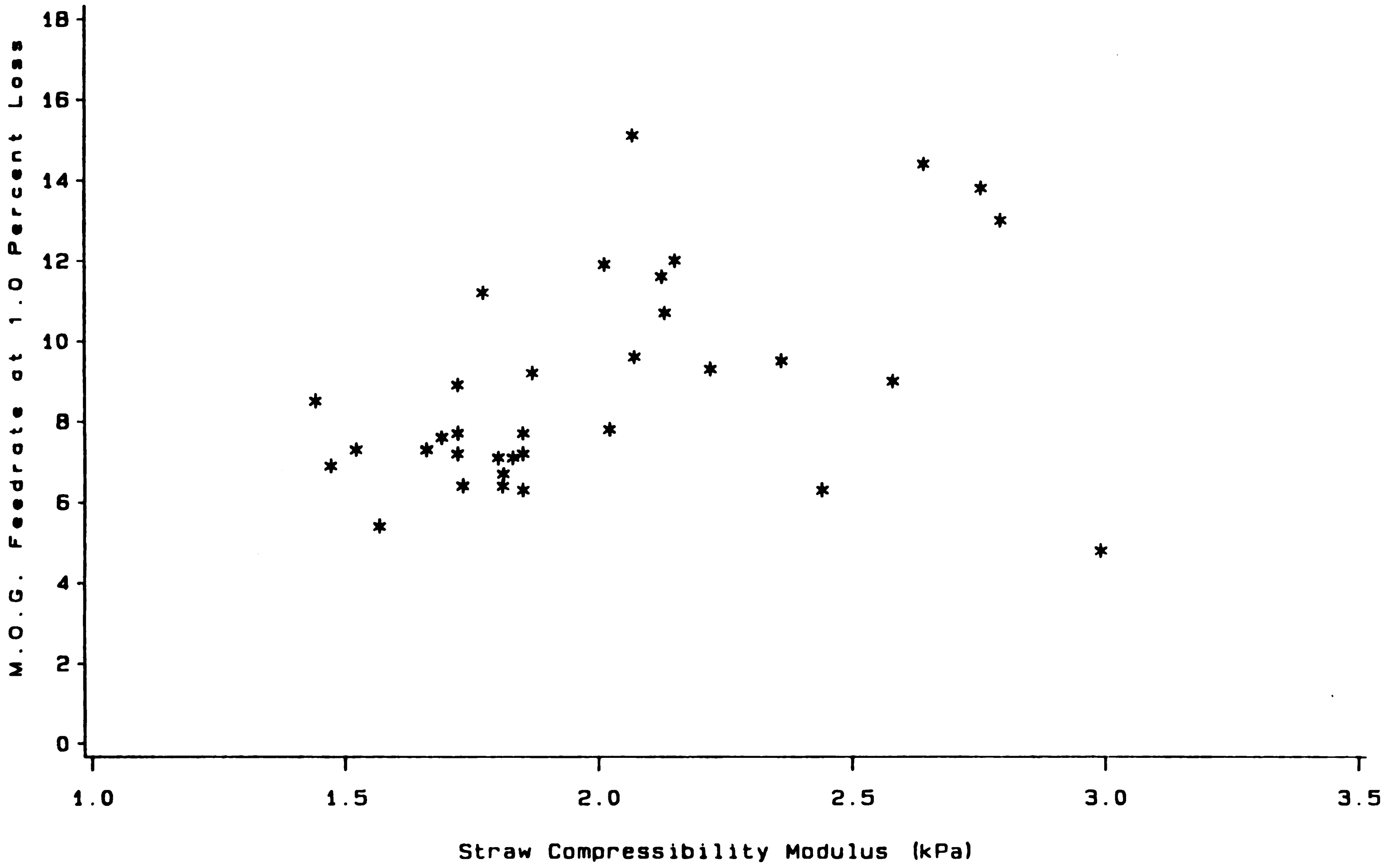


FIGURE 36

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT GRAIN LOSS VERSUS STRAW COMPRESSIBILITY MODULUS (kPa)

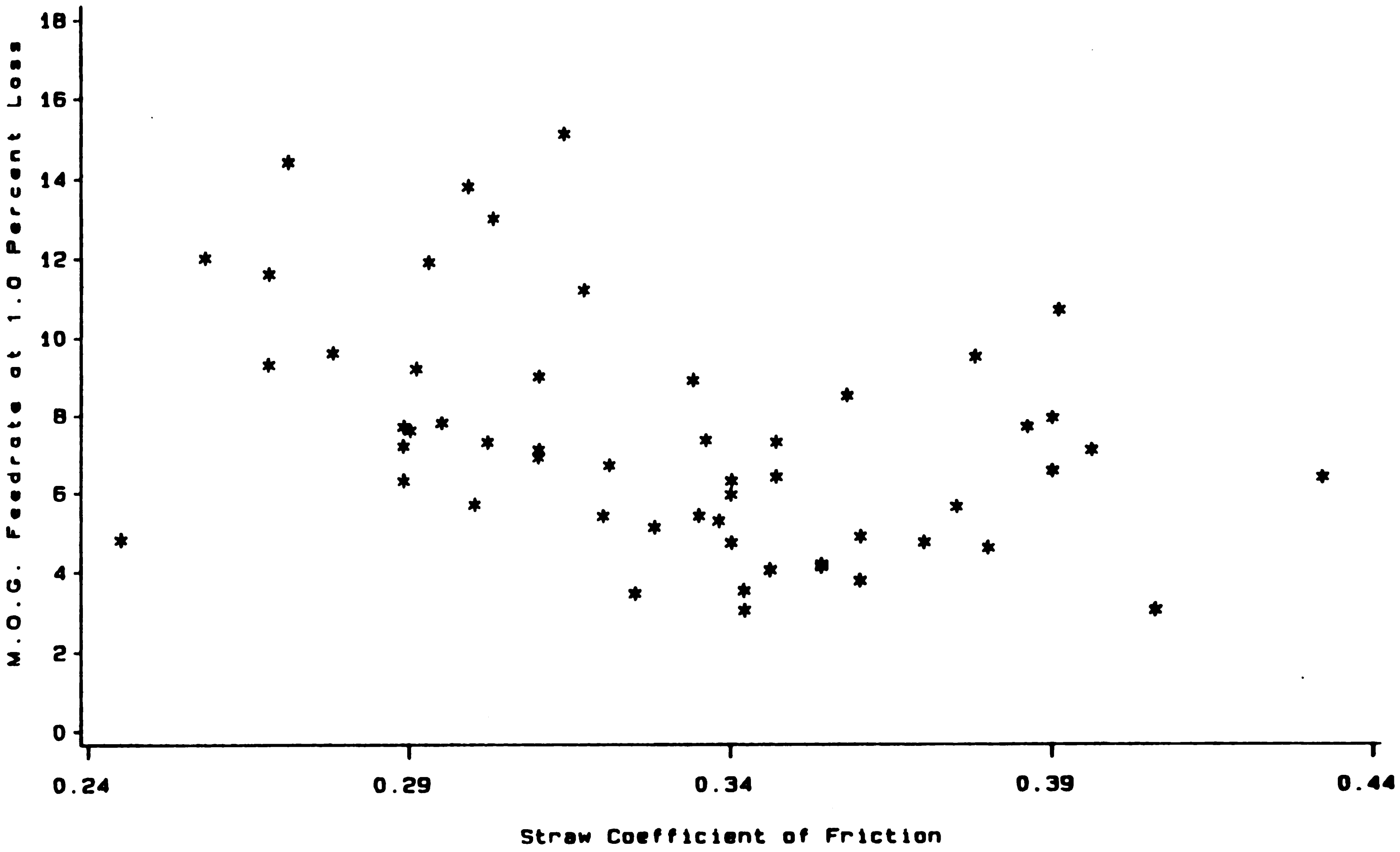


FIGURE 37

SCATTER PLOT OF M.O.G. FEEDRATE (t/h) AT 1.0 PERCENT GRAIN LOSS VERSUS STRAW COEFFICIENT OF FRICTION

APPENDIX C

Scatter Plots of Crop Properties Versus Crop Moisture

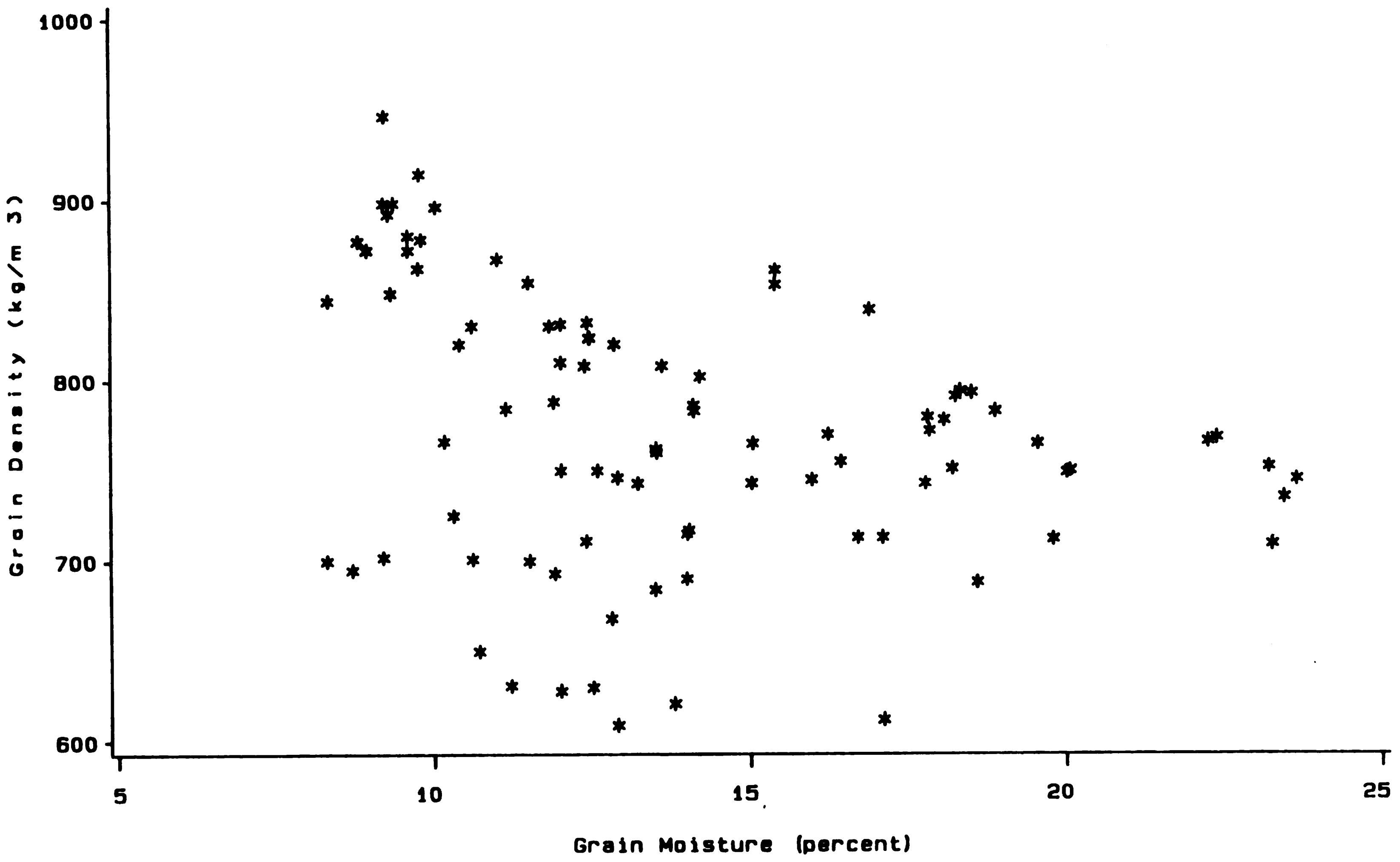


FIGURE 38

SCATTER PLOT OF GRAIN DENSITY (kg/m^3) VERSUS GRAIN MOISTURE (PERCENT)

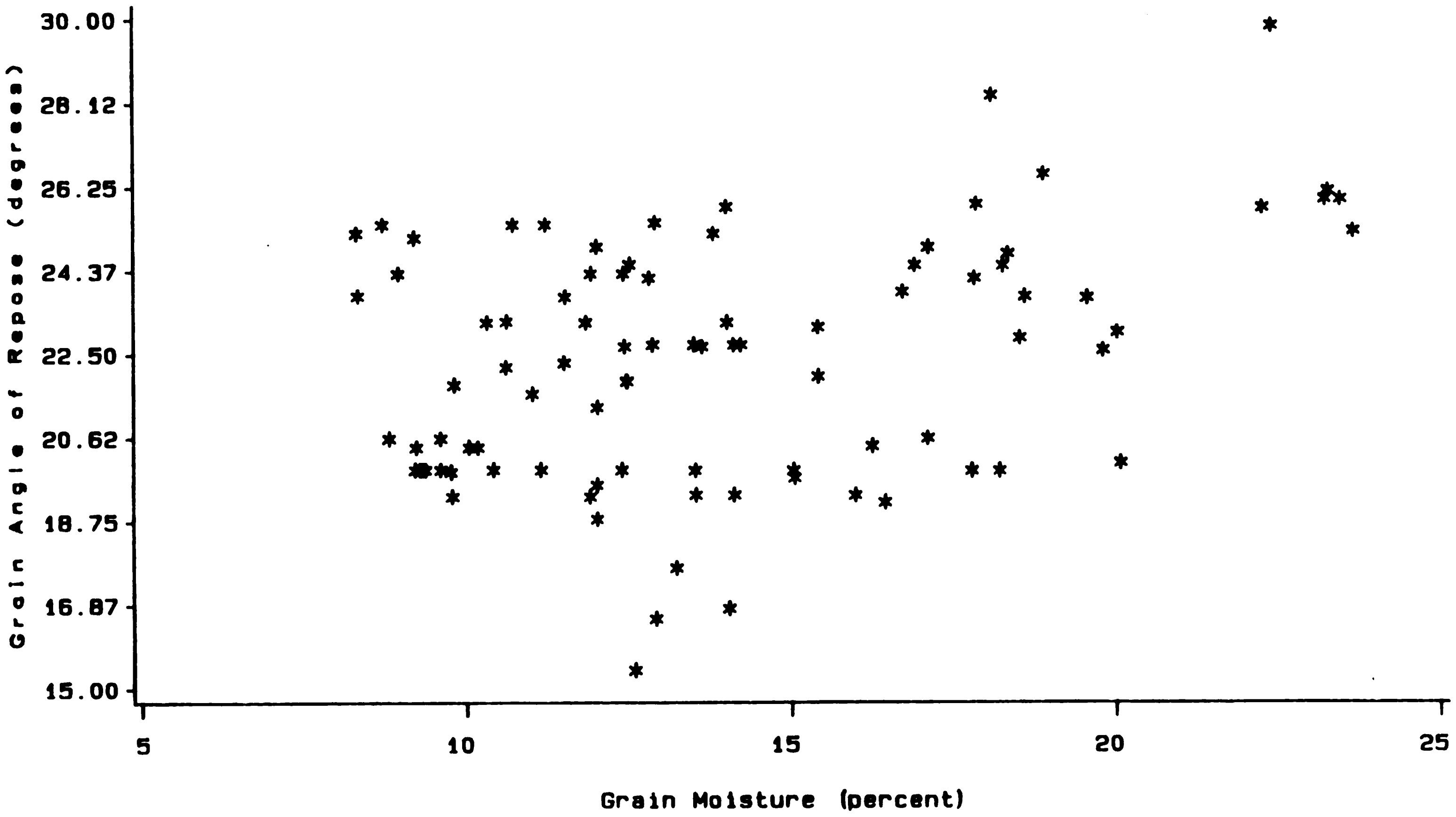


FIGURE 39

SCATTER PLOT OF GRAIN ANGLE OF REPOSE (DEGREES)
VERSUS GRAIN MOISTURE (PERCENT)

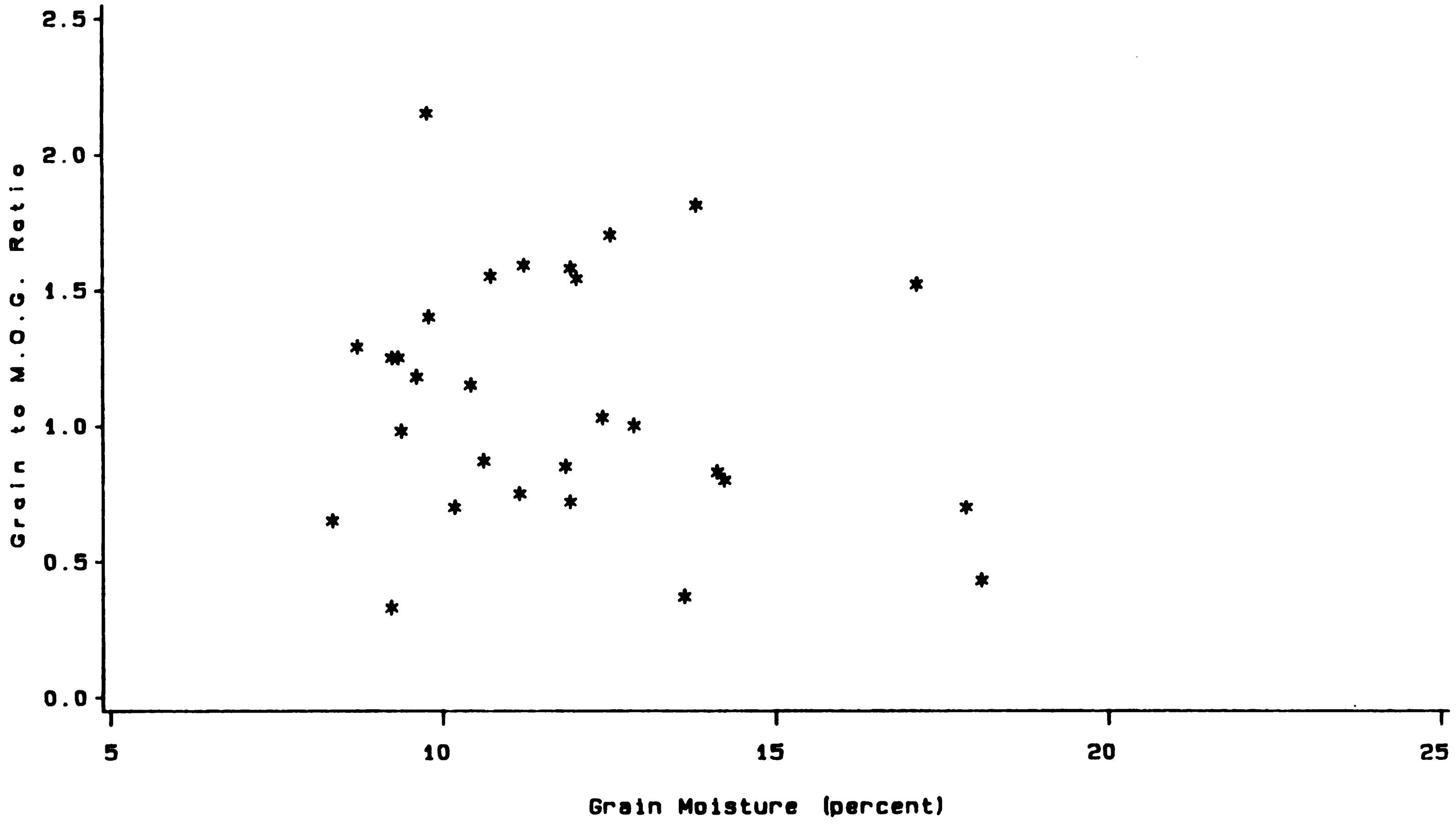


FIGURE 40

SCATTER PLOT OF GRAIN TO M.O.G. RATIO
VERSUS GRAIN MOISTURE (PERCENT)

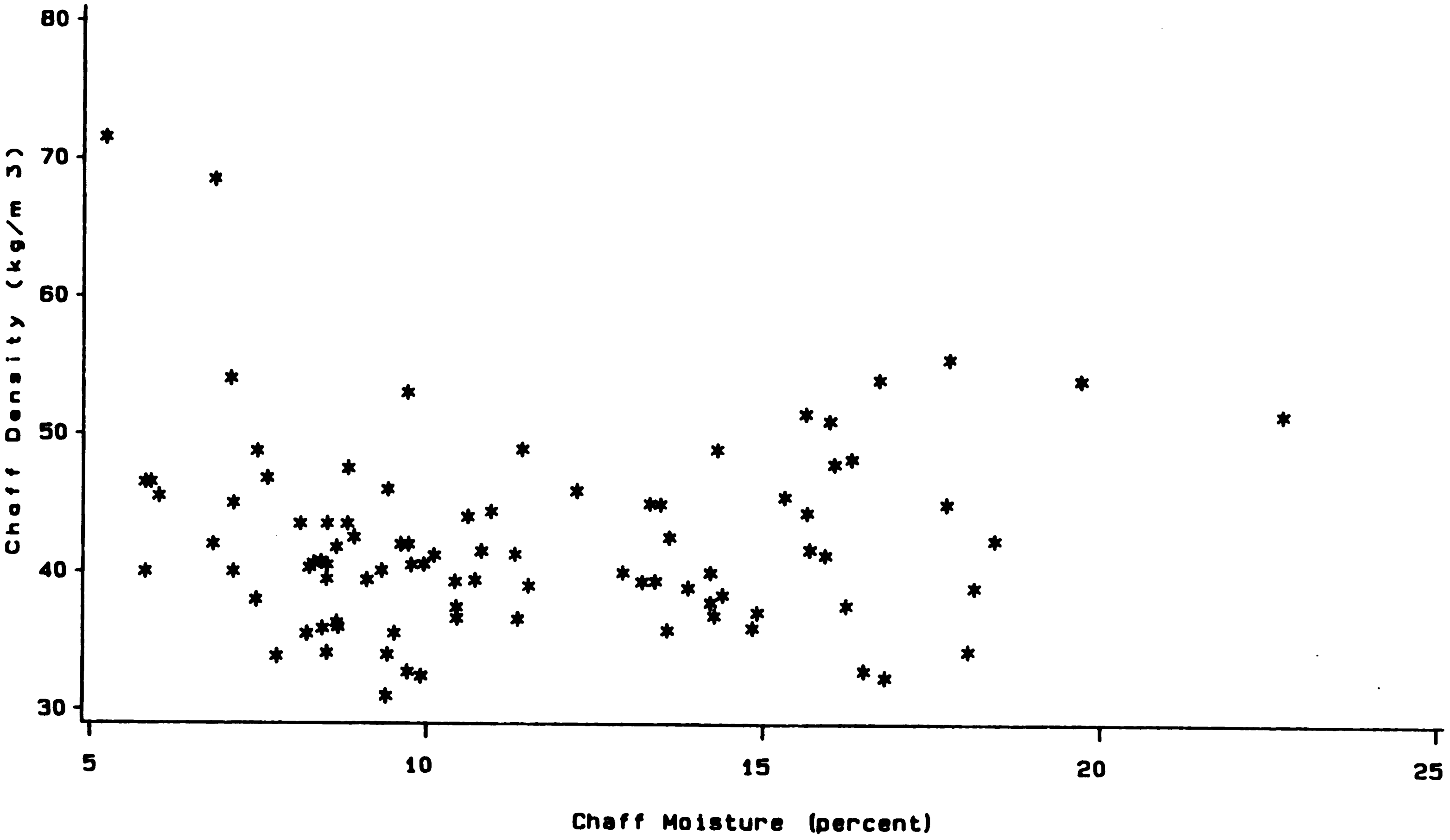


FIGURE 41

SCATTER PLOT OF CHAFF DENSITY (kg/m^3) VERSUS
CHAFF MOISTURE (PERCENT DRY BASIS)

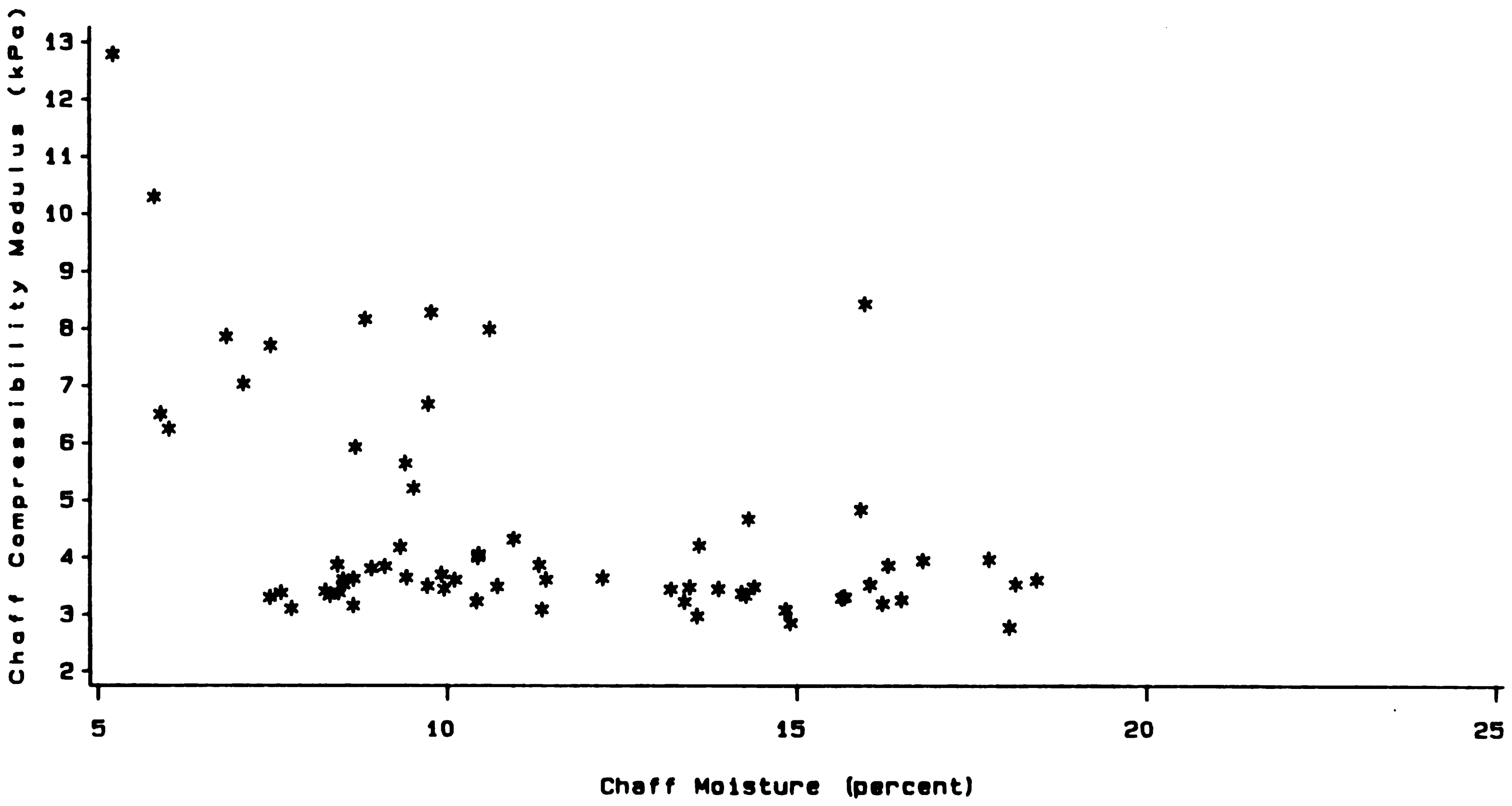


FIGURE 42

SCATTER PLOT OF CHAFF COMPRESSIBILITY MODULUS (kPa)
VERSUS CHAFF MOISTURE (PERCENT DRY BASIS)

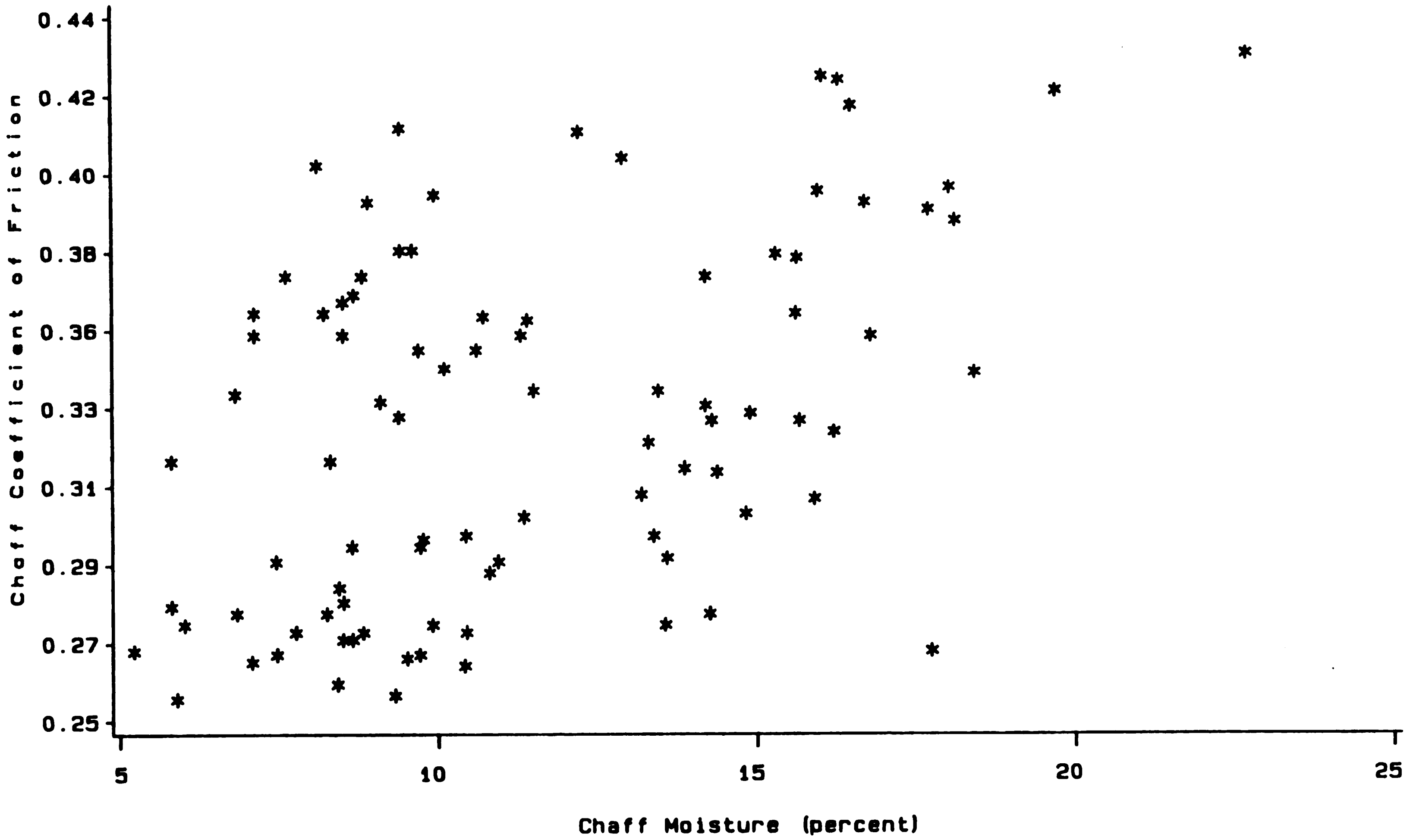


FIGURE 43

SCATTER PLOT OF CHAFF COEFFICIENT OF FRICTION
VERSUS CHAFF MOISTURE (PERCENT DRY BASIS)

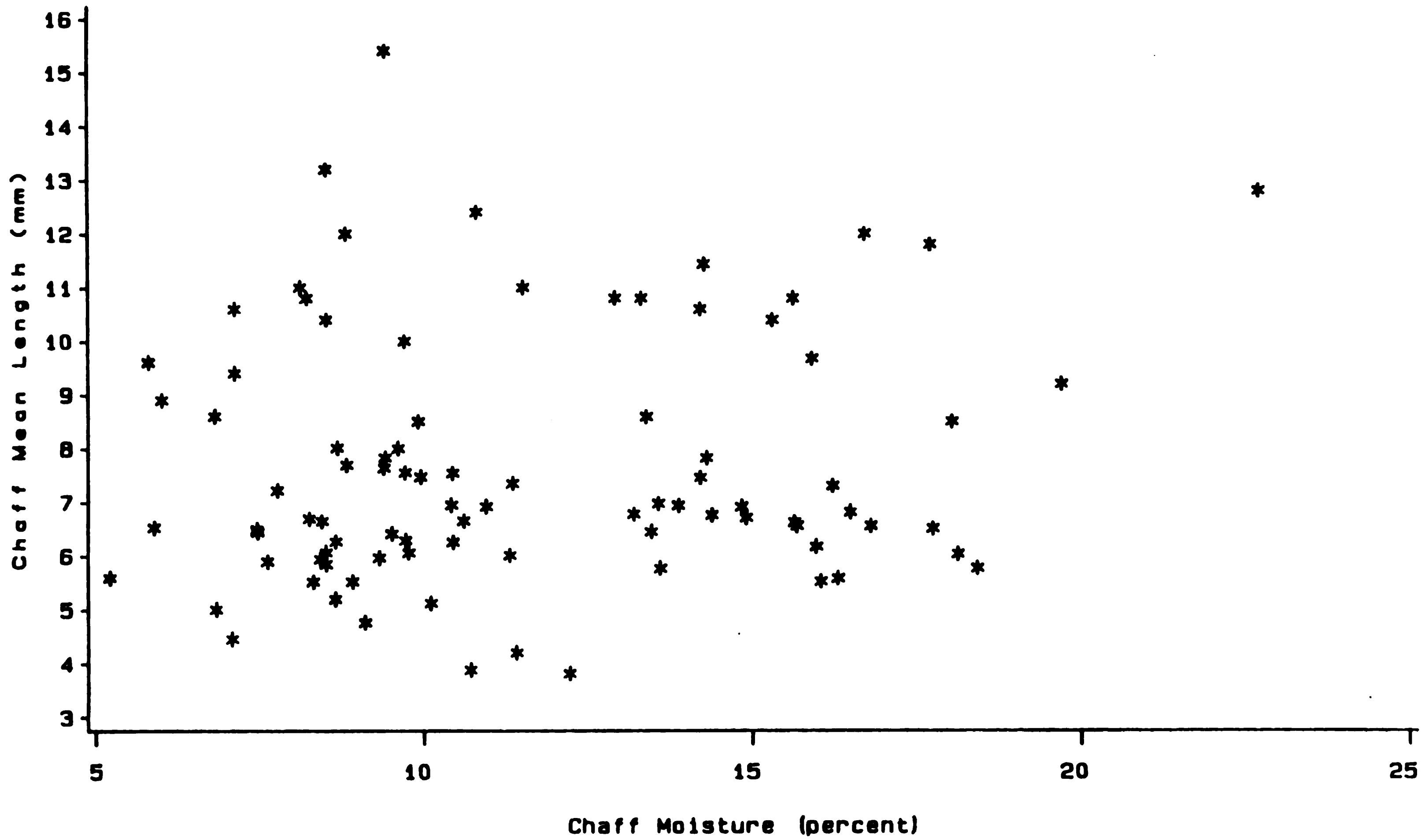


FIGURE 44

SCATTER PLOT OF CHAFF MEAN LENGTH (mm)
VERSUS CHAFF MOISTURE (PERCENT DRY BASIS)

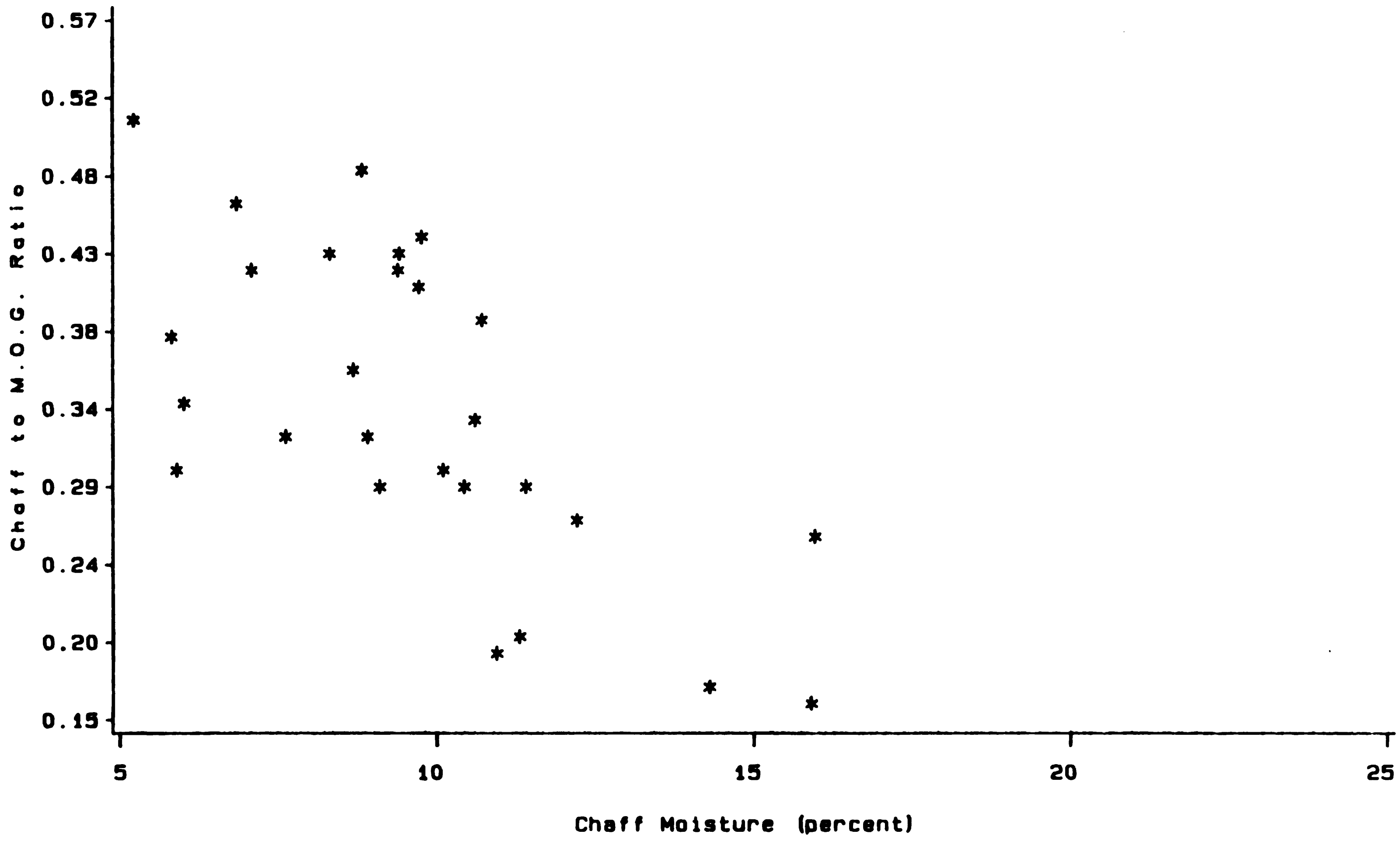


FIGURE 45

SCATTER PLOT OF CHAFF TO M.O.G. RATIO
VERSUS CHAFF MOISTURE (PERCENT DRY BASIS)

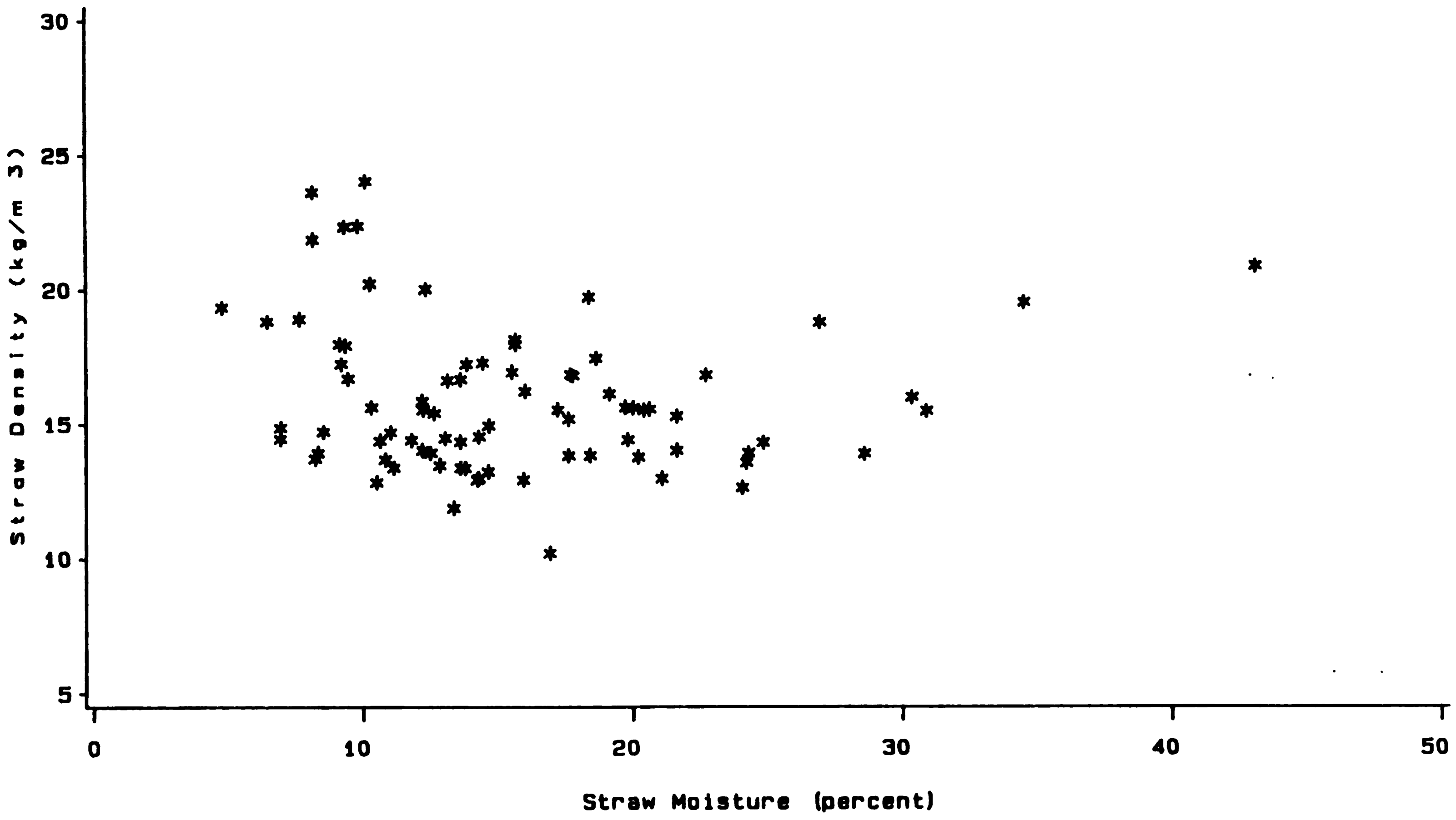


FIGURE 46

STRAW DENSITY (kg/m^3) VERSUS STRAW MOISTURE
(PERCENT DRY BASIS)

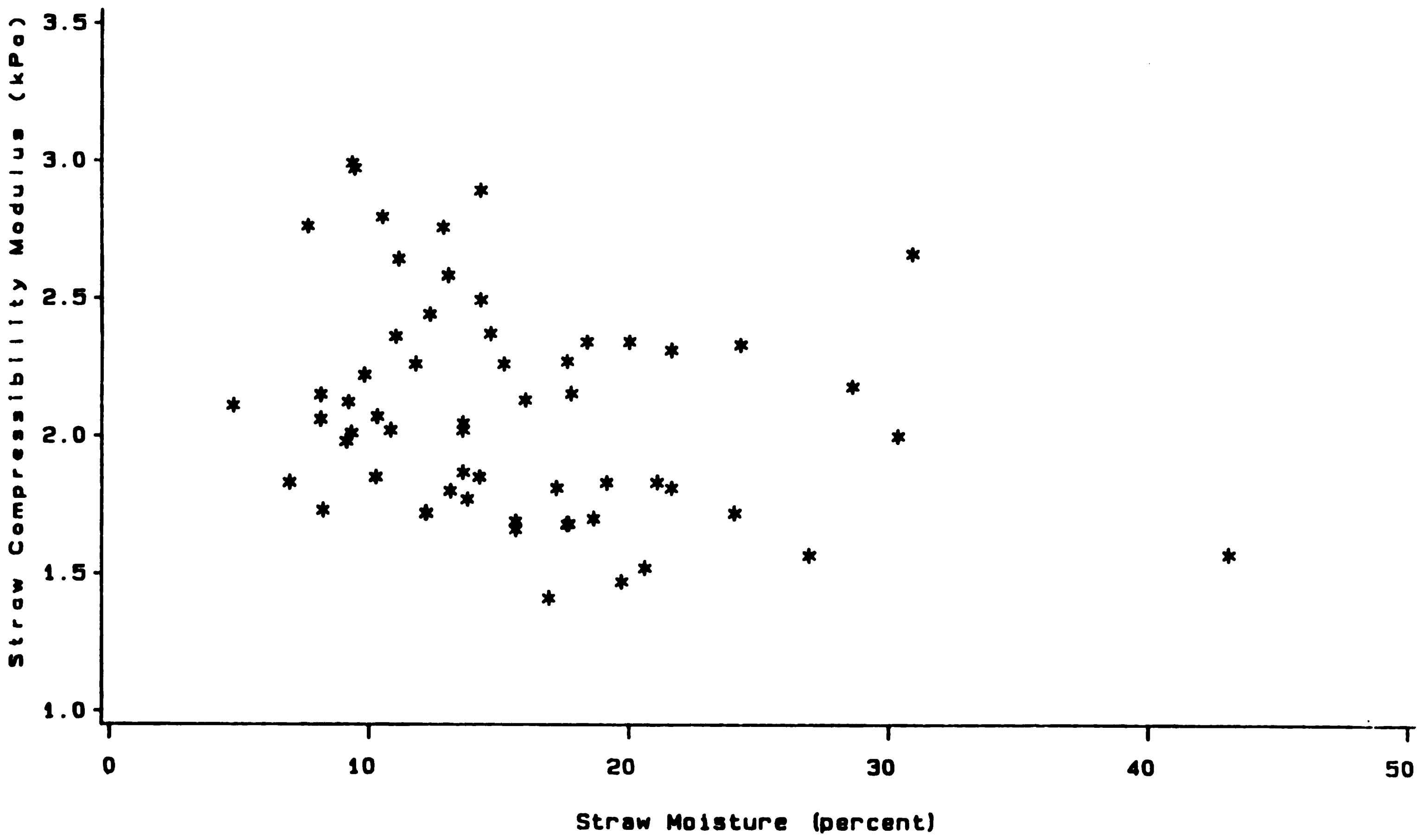


FIGURE 47

STRAW COMPRESSIBILITY MODULUS (kPa)
VERSUS STRAW MOISTURE (PERCENT DRY BASIS)

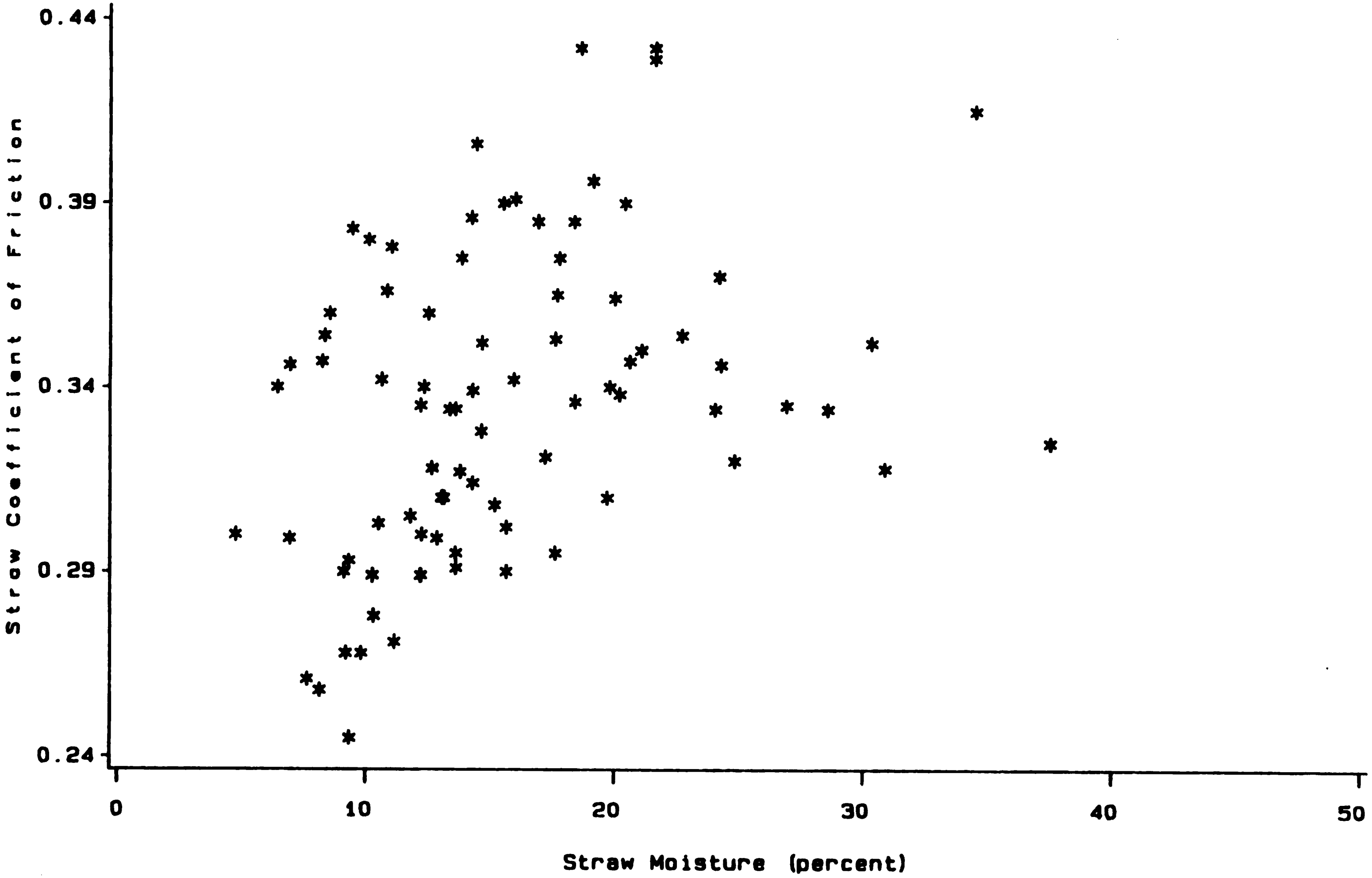


FIGURE 48

STRAW COEFFICIENT OF FRICTION VERSUS
STRAW MOISTURE (PERCENT DRY BASIS)

APPENDIX D

Combine Simulation Model Source Code

```
1 '*********************************************************************
2 '*                         COMBINE SIMULATION                         *
3 '*    Wilbur Mahoney, Michigan State University Ag. Engineering      *
4 '*                                                                   *
5 '*********************************************************************
6 '
7 '  VARIABLES:
8 '  Crop - array, contains crop property data
9 '  Coeff - array, column one is "a" term of property versus moisture
10'          equations, column two is "b" term
11'  X,Y - arrays, interpolation tables for normal distribution
12'  Cfeed,Mfeed - array, chaff feedrate and total M.O.G. feedrate
13'  Closs,Wloss,Tloss - array, cleaner loss, walker loss,
     and total loss
14'  Info - array, contains the property and loss data
     generated by each run
15'  Variation$ - character, turns random number generator on and off
16'  R$ - character, determines if a new "a" calculated for
     property equations
17'
20 'crops 1=gmost 2=ganro 3 gdeno 4=cmost 5=cfrict 6=cmlntg
    7=smost 8=smod 9=sdenwb
22 'coeff for props vs. moisture
    column 1 = intercept    column 2 = slope
23 'cmost=f(gmost)3 smost=f(gmost)5 ganro=f(gmost)1 gdeno=f(gmost)2
24 'cfrict=f(cmost)4 smod=f(smost)7 sdenwb=f(smost)6
25 'coeff contains coeff for cla,clb,sla,slb from row 8-23
26 'row      8     9       10      11      12
27 'cla-ganro   cmlntg   cfrict   gdeno  const
28 'row     13     14      15      16
29 ' clb  gdeno   cfrict   ganro   const
30 'row     17      18       19
31 'sla    smost    smod     const
32 'row     20       21       22       23
33 'slb    gdeno    sdenwb    smost   const
34 'pred contains rvs from original coefficients
35 '
170 KEY OFF
175 RANDOMIZE
180 OPTION BASE 1
181 SCREEN 2
185'
190 DIM X(100),Y(100),XX(100),YY(100),CROP(4,15),
    COEFF(30,2),PRED(20),TLOSS(30,10)
200 DIM A(21),B(21),RATE(20),LOSS(20),CFEED(30,10),MFEED(30,10),
    CLOSS(30,10),WLOSS(30,10),INFO(30,25),MOIST(4,30)
230 COUNT=1:O$="OFF":TOG=1:R$="OFF":GRAPH=1:LOOPS=0:Z$="off"
231'
232' load crop data for California, and both N. Dakota sites
233'
240 DATA 9,20.7,885,9,.27,6.44,9,2.21,19,1.39,.14,.43,.04
250 DATA
    12.06,21.16,800,9.65,.333,6.99,18.177,2.7,14.71,.836,.086,.379,.0379
260 DATA 11.9,24.2,681,9.9,.36,5.26,14.84,1.89,15.35,1.46,.015,.324,.032
261'
262'load data for interpolation used by random number distribution
    generator
```

```
263'
270 DATA 0,0.05,0.1,0.15,0.2,0.25,0.3,0.35,0.4,0.45,0.5
280 DATA 0.55,0.6,0.65,0.7,0.75,0.8,0.85,0.9,0.95,1.00
290 DATA -4.0,-1.645,-1.282,-1.036,-0.842,-0.674,-0.524
300 DATA -0.385,-0.253,-0.126,0.0,0.126,0.253,0.385
310 DATA 0.524,0.674,0.842,1.036,1.282,1.645,4.0
311'
312' load data for property prediction equations
313'
320 DATA
    5.784,.454,964.985,-.0883,.764,1.102,.122,.379,1.479,.896,8.129,.219
    6,3.175,-.147,7.639,.155
330 DATA
    3.761,.852,9.488,1.837,1.513,1.1,.024,.026,-7.3,1.55,-3.03,1.26,-4.0
    3,1.72,1.38E25,3.3E24,4.35,100,1.79e-15,100,-2.24,100,-.674,100,.614
    ,100,460268,100
331'
340 FOR I=1 TO 3:'read crop data
350 FOR J=1 TO 13
360 READ CROP(I,J)
370 NEXT J
380 NEXT I
381'
390 FOR I=1 TO 21:READ XX(I):NEXT I:'read data for rand generator
400 FOR I=1 TO 21:READ YY(I):NEXT I:'read data for rand generator
403'
405 'read data for property prediction equations
406'
410 FOR I=1 TO 21:FOR J=1 TO 2:READ COEFF(I,J):NEXT J:NEXT I
411'
412' define function keys
413'
420 KEY 1,+CHR$(13)
430 KEY 2,+CHR$(13)
440 KEY 3,+CHR$(13)
450 KEY 5,+CHR$(13)
460 KEY 4,+CHR$(13)
470 KEY 6,+CHR$(13)
480 KEY 7,+CHR$(13)
490 KEY(1) ON:KEY(2) ON:KEY(3) ON:KEY(4) ON:KEY(5) ON
500 KEY(6) ON:KEY(10) ON:KEY(7) ON:KEY(8) OFF:KEY(9) OFF:KEY(10) ON
502'
505 VARIATION$="OFF" 'turn off random function generator
510 BEEP
518 CLS
520 G$="off"
530 GOSUB 3840   'display main menu
540 ON KEY(1)GOSUB 5320    'select crop and moisture conditions
550 ON KEY(2) GOSUB 615    'run simulation
560 ON KEY(3) GOSUB 2150   'plot loss curves
570 ON KEY(5) GOSUB 1660   'stochastic parameters
580 ON KEY(4) GOSUB 3180   'scatter plots
590 ON KEY(6) GOSUB 4060   'print stats for each simulation
595 ON KEY(7) GOSUB 9000   'exit program
600 GOTO 520
610 END
615 FOR PASS = 1 TO CROPS  'start curve for selected crop
```

```
620 Z$="ON"
630 GMOST=MOIST(PASS,MOISTURES+1)
631 GOSUB 4890              'adjust property equations for another curve
650 FOR MOISTPASS=1 TO MOISTURES 'start another curve at a new moist
    level
660 CROP(NUM(PASS),1)=MOIST(PASS,MOISTPASS)
680 LIMIT=3.5
690 CLS:
700 COUNT=1:R$="OFF"
720 LOOPS=LOOPS+1
730 CURVE(LOOPS)=LOOPS
740 LOCATE 20,20:PRINT"wait.....execution has begun......it may take a
    while"
741' initialize summation variables for property averages
743 GMOSTAVG=0:CMOSTAVG=0:SMOSTAVG=0:GANRAVG=0:
    GDENAVG=0:CFRICTAVG=0:CMLNTGAVG=0
744 SMODAVG=0:SDENAVG=0:MFEEDAVG=0:
    CFEEDAVG=0:CMOGAVG=0:GMOGAVG=0
745'
746' step thru each curve by 0.5 mph increments
750 FOR SPEED =.1 TO LIMIT STEP .5  ' limit is the number of points per
    on a curve
760 SPEED(COUNT,LOOPS)=SPEED
765 GOSUB 4700              ' get predicted property values
787 CMOG=CROP(NUM(PASS),12)
789 GMOG=CROP(NUM(PASS),10)
794 R$="ON"
795 MFEED(COUNT,LOOPS)=SPEED*YIELD(PASS)*19*1/GMOG*.00329  'calc mog
    feedrate
830 CFEED(COUNT,LOOPS)=CMOG*MFEED(COUNT,LOOPS) 'calc chaff feedrate
860 '
870' NCOUNT=9
880' FOR N=1 TO 15
890' Y5=COEFF(NCOUNT,1):S5=COEFF(NCOUNT,2)
900' IF N<9 THEN S5=COEFF(NCOUNT,2)
910' IF N>=9 THEN S5=COEFF(NCOUNT,2)
930' PRED(N)=Y5
940' NCOUNT=NCOUNT+1
950' NEXT N
957'
958' calculate "a" and "b" terms for cleaner loss and walker loss
959'
960 CLA=CROP(NUM(PASS),2)^3.76*CROP(NUM(PASS),6)^3.31*
        CROP(NUM(PASS),5)^8.03*3.34E-06
970 CLB=CROP(NUM(PASS),3)^-5.03*CROP(NUM(PASS),5)^-3.41*9.18E+12
980 SLA=CROP(NUM(PASS),3)^4.438*1.796E-15
990 SLB=CROP(NUM(PASS),3)^-2.24*CROP(NUM(PASS),8)^-.674*
        CROP(NUM(PASS),9)^.614*460268!
991'
995' calculate losses
996'
1000 CLOSS(COUNT,LOOPS)=CLA*EXP(CFEED(COUNT,LOOPS)*CLB)
1001 IF CLOSS(COUNT,LOOPS)>=100 THEN CLOSS(COUNT,LOOPS)=100
1005 WLOSS(COUNT,LOOPS)=SLA*EXP(MFEED(COUNT,LOOPS)*SLB)
1006 IF WLOSS(COUNT,LOOPS)>=100 THEN WLOSS(COUNT,LOOPS)=100
1020 TLOSS(COUNT,LOOPS)=WLOSS(COUNT,LOOPS)+CLOSS(COUNT,LOOPS)
1021 IF TLOSS(COUNT,LOOPS)>=100 THEN TLOSS(COUNT,LOOPS)=100
```

```
1026 IF CLOSS(COUNT,LOOPS)<0! THEN CLOSS(COUNT,LOOPS)=1E-33
1027 IF WLOSS(COUNT,LOOPS)<0! THEN WLOSS(COUNT,LOOPS)=1E-33
1028 IF TLOSS(COUNT,LOOPS)<0! THEN TLOSS(COUNT,LOOPS)=1E-33
1150 GCOUNT=COUNT
1160 IF COUNT >1 THEN GOSUB 3100
1190 GMOSTAVG=CROP(NUM(PASS),1)+GMOSTAVG:
              MFEEDAVG=MFEED(COUNT,LOOPS)+MFEEDAVG
1191 GANRAVG=CROP(NUM(PASS),2)+GANRAVG:
             CFEEDAVG=CFEED(COUNT,LOOPS)+CFEEDAVG
1192 GDENAVG=CROP(NUM(PASS),3)+GDENAVG
1193 CMOSTAVG=CROP(NUM(PASS),4)+CMOSTAVG
1194 CFRICTAVG=CROP(NUM(PASS),5)+CFRICTAVG
1195 CMLNTGAVG=CROP(NUM(PASS),6)+CMLNTGAVG
1196 SMOSTAVG=CROP(NUM(PASS),7)+SMOSTAVG
1197 SMODAVG=CROP(NUM(PASS),8)+SMODAVG
1198 SDENAVG=CROP(NUM(PASS),9)+SDENAVG
1199 GMOGAVG=GMOG+GMOGAVG:CMOGAVG=CMOG+CMOGAVG:COUNT=COUNT+1
1200 NEXT SPEED
1202 COUNT=COUNT-1
1210 GCOUNT=COUNT  'pass count to plot
1220 INFO(LOOPS,10)=GMOGAVG/COUNT:INFO(LOOPS,11)=CMOGAVG/COUNT
1221 INFO(LOOPS,1)=GMOSTAVG/COUNT:INFO(LOOPS,2)=GANRAVG/COUNT
1222 INFO(LOOPS,3)=GDENAVG/COUNT
1223 INFO(LOOPS,4)=CMOSTAVG/COUNT
1224 INFO(LOOPS,5)=CFRICTAVG/COUNT
1225 INFO(LOOPS,6)=CMLNTGAVG/COUNT
1226 INFO(LOOPS,7)=SMOSTAVG/COUNT
1227 INFO(LOOPS,8)=SMODAVG/COUNT
1228 INFO(LOOPS,9)=SDENAVG/COUNT
1229 MFEEDAVG=MFEEDAVG/COUNT
1230 CFEEDAVG=CFEEDAVG/COUNT
1270 INFO(LOOPS,12)=(-.69-B0C)/B1C
1280 INFO(LOOPS,13)=-B0W/B1W
1290 INFO(LOOPS,14)=(.69-B0T)/B1T
1300 INFO(LOOPS,15)=R2C:INFO(LOOPS,16)=R2W:INFO(LOOPS,17)=R2T
1310 INFO(LOOPS,18)=B0C:INFO(LOOPS,19)=B0W:INFO(LOOPS,20)=B0T
1320 INFO(LOOPS,21)=B1C:INFO(LOOPS,22)=B1W:INFO(LOOPS,23)=B1T
1330 INFO(LOOPS,24)=NUM(PASS)
1340 NEXT MOISTPASS,PASS
1350 CLS
1360 RETURN
1361'
1370 'subroutine normal distribution
1371'
1380 FOR J = 1 TO 100
1390 X1=RND(1)
1400 FOR I = 1 TO 21
1410 IF X1 < XX(I) THEN 1430
1420 NEXT I
1430 Y2=(X1-XX(I-1))*(YY(I)-YY(I-1))/(XX(I)-XX(I-1))+YY(I-1)
1440 Y3=Y5 + S5*Y2
1450 NEXT J
1460 RETURN
1465'
1470 'subroutine least squares
1475'
1480 B2=0:B3=0:B4=0:B6=0:B7=0:R3=0:B0=0:B1=0
```

```
1490 FOR I=1 TO COUNT
1500 B3=B3+RATE(I):B4=B4+LOSS(I)
1510 B6=B6+RATE(I)^2:B2=B2+RATE(I)*LOSS(I)
1520 R3=R3+LOSS(I)^2
1530 NEXT I
1540 S1=B6-COUNT*(B3/COUNT)^2
1550 S2=R3-COUNT*(B4/COUNT)^2
1560 B7=B3^2
1570 B8=B2-B3*B4/COUNT
1580 W9=B6-B7/COUNT
1590 B1=B8/W9
1600 B0=B4/COUNT-B1*(B3/COUNT)
1610 R4=B2-B3*B4/COUNT
1620 R5=(B6-B7/COUNT)*(R3-B4^2/COUNT):R5NEW=(.0001/R4)^2:IF R5<=R5NEW
     THEN R2=.000001:GOTO 1640
1625 R2=R4/R5^.5
1630 S3=S2-B1^2*S1
1640 'S4=SQR((S3/(COUNT-2)))
1650 RETURN
1660 'parameter change subroutine
1661 CLS
1662 IF Z$<>"ON" THEN LOCATE 10,20:PRINT"You have not selected any crop
     information":LOCATE 11,20:FOR I=1 TO 2000:NEXT I:CLS:RETURN
1690 R$="OFF":VARIATION$="ON"  'turn on random generator
1700 GOSUB 7500'go to get crop variation
1740 IF TEMP=13 THEN C$="1 % WALKER LOSS"
1830 CLS
1840 RETURN
1845'
1850 'plotting routine
1860 '
1870 XRANGE=300/(XMAX-XMIN)
1880 YRANGE=120/(YMAX-YMIN)
1890 PSET (330,130)
1900 DRAW "u120 r300 d120 1300"
1910 FOR I=1 TO GCOUNT
1920 X(I)=330+ABS((XRANGE*(XMIN-RATE(I))))
1930 Y(I)=130-ABS((YRANGE*(YMIN-LOSS(I))))
1940 NEXT I
1950 FOR I=GRAPH TO GCOUNT
1960 IF X(I)>638 GOTO 2030
1970 IF Y(I)<20 GOTO 2030
1980 IF Y(I)<0 GOTO 2030
1990 IF X(I)<0 GOTO 2030
2000 PSET (X(I),Y(I))
2010 IF G$="off" THEN GOSUB 3930  'get symbol to plot
2020 IF G$="on" THEN GOSUB 4000
2030 NEXT I
2040 Y=10:X=330
2041 XLABEL=40
2045 FOR LABEL=XMIN TO XMAX STEP (XMAX-XMIN)/5
2046 LOCATE 18,XLABEL:PRINT USING"###.##";LABEL
2047 XLABEL=XLABEL+7
2048 NEXT LABEL
2049 YLABEL=2
2050 FOR LABEL =YMAX TO YMIN STEP - (YMAX-YMIN)/5
2060 LOCATE YLABEL,34:PRINT USING"###.##";LABEL
```

```
2070 YLABEL=YLABEL+3
2080 NEXT LABEL
2090 PSET(330,130)
2100 FOR I=1 TO 5:X=(300/5)+X:PSET(X,130):DRAW"U8":NEXT I
2110 PSET(330,10)
2120 FOR I=1 TO 5
2130 Y=(120/5)+Y:PSET(330,Y):DRAW"R15":NEXT I
2140 RETURN
2150 'subroutine to toggle between curves
2160 GCOUNT=0:GRAPH=1:NEWLOOPS=LOOPS:G$="off"
2170 CLS
2180 LOCATE 10,20:PRINT"The first five or less curves are plotted
2190 LOCATE 11,20:PRINT"by default.  To select specific curves
2200 LOCATE 12,20:PRINT"strike the space bar.  To select the
2210 LOCATE 13,20:PRINT"default condition strike any key
2220 K$=INKEY$
2230 IF LEN(K$)=0 GOTO 2220
2240 IF K$=" " THEN GOSUB 5030
2250 CLS
2260 IF TOG>3 THEN TOG=1
2270 IF TOG=1 THEN L$="CLEANING LOSS CURVE"
2280 IF TOG=2 THEN L$="WALKER LOSS CURVE"
2290 IF TOG=3 THEN L$="TOTAL LOSS CURVE"
2300 GCOUNT=COUNT
2310 IF NEWLOOPS>5 THEN NEWLOOPS=5
2320 IF TOG><1 THEN GOTO 2440
2330 FOR OO=1 TO NEWLOOPS
2340 NN=CURVE(OO)
2350 FOR J=1 TO COUNT:RATE(J)=CFEED(J,NN):LOSS(J)=(CLOSS(J,NN)):NEXT J
2360 XMIN=0:XMAX=5:YMIN=0:YMAX=5
2370 GOSUB 1850
2380 NEXT OO
2390 GOSUB 2930
2400 C$="CHAFF FEEDRATE (T/H)"
2410 GOSUB 5200       'label x-axis
2420 C$="CLEANER LOSS %"
2430 GOSUB 5230       'label y-axis
2440 IF TOG><2 THEN GOTO 2560
2450 FOR OO=1 TO NEWLOOPS
2460 NN=CURVE(OO)
2470 FOR J=1 TO COUNT:RATE(J)=MFEED(J,NN):LOSS(J)=(WLOSS(J,NN)):NEXT J
2480 XMAX=15:YMAX=5:XMIN=0:YMIN=0
2490 GOSUB 1850
2500 NEXT OO
2510 GOSUB 2930
2520 C$="MOG FEEDRATE (T/H)"
2530 GOSUB 5200        'label x-axis
2540 C$="WALKER LOSS %"
2550 GOSUB 5230        'label y-axis
2560 IF TOG <3 THEN GOTO 2680
2570 FOR OO=1 TO NEWLOOPS
2580 NN=CURVE(OO)
2590 FOR J=1 TO COUNT:LOSS(J)=CLOSS(J,NN)+WLOSS(J,NN):NEXT J
2595 FOR J=1 TO COUNT:RATE(J)=SPEED(J,NN):NEXT J
2600 XMAX=5:YMAX=5:XMIN=0:YMIN=0
2610 GOSUB 1850
2620 NEXT OO
```

```
2630 GOSUB 2930
2640 C$="ground speed (m/h)"
2650 GOSUB 5200          'label x-axis
2660 C$="TOTAL LOSS %"
2670 GOSUB 5230          'label y-axis
2680 LOCATE 1,50:PRINT L$
2690 TOG=TOG+1
2700 LOCATE 22,1:PRINT"strike the space bar to exit plot"
2710 LOCATE 23,1:PRINT"strike any other key to continue"
2720 K$=INKEY$
2730 IF LEN(K$)=0 GOTO 2720
2740 IF K$<>" " GOTO 2250
2750 CLS
2760 RETURN
2765 '
2770 'graph all curves on same screen
2771'
2780 IF G$="ON" THEN GOTO 2850
2790 PSET(20,10):GOSUB 2890
2800 PSET(230,10):GOSUB 2890
2810 PSET(440,10):GOSUB 2890
2820 LOCATE 1,10:PRINT"CLEANER LOSS CURVE"
2830 LOCATE 1,35:PRINT"WALKER LOSS CURVE"
2840 LOCATE 1,60:PRINT"TOTAL LOSS CURVE"
2850 PSET(X,Y)
2860 DRAW"E2 G4 E2 F2 H4"
2870 G$="ON"
2880 RETURN
2890 DRAW"D100 R190 U100 L190"
2900 DRAW"D20 R190 D20 L190 D20 R190 D20 L190 U80"
2910 DRAW"R38 D100 R38 U100 R38 D100 R38 U100"
2920 RETURN
2930 ' print info about each curve at plot edge
2940 PSET(180,3)
2950 YPOS=0
2960 LOCATE 1,1
2970 FOR NN=1 TO LOOPS
2980 GOSUB 3930 'get symbol and plot
2990 GOSUB 4980    'GET CROP LABEL
3000 PRINT H$
3010 PRINT "GRAIN  MOISTURE = ";INFO(NN,1)
3020 IF TOG=1 THEN PRINT"CAPACITY = ";INFO(NN,12);"(T/H)"
3030 IF TOG=2 THEN PRINT "CAPACITY = ";INFO(NN,13);"(T/H)"
3040 IF TOG=3 THEN PRINT"SPEED = ";INFO(LOOPS,14);"(M/H)"
3050 YPOS=YPOS+32
3060 PSET(180,YPOS+3)
3070 PRINT
3080 NEXT NN
3090 RETURN
3095'
3100 ' subroutine calculates statistics for each loss curve
3101 ' "a", "b" and r-square
3102'
3110 FOR J=1 TO COUNT:
     RATE(J)=CFEED(J,LOOPS):LOSS(J)=LOG(CLOSS(J,LOOPS)):
     NEXT J
3120 GOSUB 1470:B0C=B0:B1C=B1:R2C=R2
```

```
3130 FOR J=1 TO COUNT:
     RATE(J)=MFEED(J,LOOPS):LOSS(J)=LOG(WLOSS(J,LOOPS)):
     NEXT J
3140 GOSUB 1470:B0W=B0:B1W=B1:R2W=R2
3150 FOR J=1 TO COUNT:
     LOSS(J)=LOG(WLOSS(J,LOOPS)+CLOSS(J,LOOPS)):
     NEXT J
3155 FOR J=1 TO COUNT:
     RATE(J)=SPEED(J,LOOPS):
     NEXT J
3160 GOSUB 1470:B0T=B0:B1T=B1:R2T=R2
3170 RETURN
3175'
3180 'subroutine to plot properties and loss information
3185 '
3190 CLS:G$="on"
3200 LOCATE 1,1:PRINT"1 = grain moisture"
3210 PRINT"2 = grain angle of repose"
3220 PRINT"3 = grain density"
3230 PRINT"4 = chaff moisture"
3240 PRINT"5 = chaff friction"
3250 PRINT"6 = chaff mean length"
3260 PRINT"7 = straw moisture"
3270 PRINT"8 = straw modulus"
3280 PRINT"9 = straw density"
3290 PRINT"10 = grain to mog ratio"
3300 PRINT"11 = chaff to mog ratio"
3310 PRINT"12 = chaff feedrate at 1/2 % loss"
3320 PRINT"13 = mog feedrate at 1 % loss"
3330 PRINT"14 = mog feedrate at 2 % total loss"
3340 LOCATE 1,40:PRINT"select the x-axis variable"
3350 LOCATE 2,40:INPUT XVAR
3360 LOCATE 4,40:PRINT"select the y-axis variable"
3370 LOCATE 6,40:INPUT YVAR
3380 XMAX=-9999!:YMAX=-9999!
3390 XMIN=99999!:YMIN=99999!
3400 FOR I=1 TO LOOPS
3410 IF INFO(I,XVAR)>XMAX THEN XMAX=INFO(I,XVAR)
3420 IF INFO(I,XVAR)<XMIN THEN XMIN=INFO(I,XVAR)
3430 IF INFO(I,YVAR)>YMAX THEN YMAX=INFO(I,YVAR)
3440 IF INFO(I,YVAR)<YMIN THEN YMIN=INFO(I,YVAR)
3450 NEXT I
3460 XMIN=XMIN*.9:XMAX=XMAX*1.1
3470 YMIN=YMIN*.9:YMAX=YMAX*1.1
3480 GCOUNT=0
3490 CHECK(1)=INFO(1,24)
3500 NN=1
3510 GOSUB 4980 ' go get crop label
3520 YPOS=0
3530 LOCATE 1,1
3550 FOR O=1 TO LOOPS:RATE(O)=INFO(O,XVAR):LOSS(O)=INFO(O,YVAR)
3560 GCOUNT=GCOUNT+1
3570 GRAPH=GCOUNT  'setup to plot one point and return
3580 IF O=1 THEN CLS
3590 GOSUB 1850
3610 FLAG=0
3620 NN=0:M=0
```

```
3630 CHECK(O)=INFO(O,24)
3631 IF O=1 THEN LOCATE 1,1:  PRINT H$:PSET(180,3):GOSUB 4000:GOTO 3710
3640 FOR JJ=1 TO M-1
3650 IF CHECK(JJ)=INFO(O,24) THEN FLAG=1
3660 NEXT JJ
3670 IF FLAG= 1 GOTO 3710
3671 YPOS=YPOS+25
3672 PSET(180,YPOS+3)
3673 LOCATE O+1,1
3681 PRINT
3690 GOSUB 4980  'get crop label because it is not a duplicate
3700 PRINT H$    'print label
3703 GOSUB 4000  'pick up symbol
3710 NEXT O
3720 FOR I=1 TO 2
3730 IF I=1 THEN TEMP=XVAR
3740 IF I=2 THEN TEMP=YVAR
3750 GOSUB 5620  'pick up property labels
3760 IF I=1 THEN GOSUB 5200 'label x-axis
3770 IF I=2 THEN GOSUB 5230 'label y-axis
3780 NEXT I
3790 LOCATE 23,1:PRINT "strike any key to continue"
3800 K$=INKEY$
3810 IF LEN(K$)=0 GOTO 3800
3820 CLS
3830 RETURN
3835'
3840 'subroutine to display main menu
3845'
3850 LOCATE 10,20:PRINT"F1. select crop location"
3860 LOCATE 11,20:PRINT"F2. run simulation"
3870 LOCATE 12,20:PRINT"F3. plot loss curves"
3880 LOCATE 13,20:PRINT"F4. plot scatter plots of properties"
3890 LOCATE 14,20:PRINT"F5. set parameters for stochastic process"
3900 LOCATE 15,20:PRINT"F6. display historical data from simulation run"
3901 LOCATE 16,20:PRINT"F7. exit program
3920 RETURN
3925'
3930 'subroutine to determine which symbol to plot
3935'
3940 IF NN=1 THEN DRAW"U3 d3 h3 f3 L3 R3 g3 e3 d3 u3 f3 h3 r3 l3 e3"
3950 IF NN=2 THEN DRAW"u3 l3 d6 r6 u6 l3"
3960 IF NN=3 THEN DRAW"e3 g6 e3 h3 f6"
3970 IF NN=4 THEN DRAW"e3 l6 f6 l6 e3"
3980 IF NN=5 THEN DRAW"U3 D6 L3 U6 R6 D6 L3 R3 U3 L6"
3990 RETURN
3995'
4000 IF INFO(O,24)=1 THEN DRAW"U3 d3 h3 f3 L3 R3 g3 e3 d3 u3 f3 h3 r3 l3
     e3"
4010 IF INFO(O,24)=2 THEN DRAW"u3 l3 d6 r6 u6 l3"
4020 IF INFO(O,24)=3 THEN DRAW"e3 g6 e3 h3 f6"
4030 IF INFO(O,24)=4 THEN DRAW"e3 l6 f6 l6 e3"
4040 IF INFO(O,24)=5 THEN DRAW"U3 D6 L3 U6 R6 D6 L3 R3 U3 L6"
4050 RETURN
4055'
4056'subroutine to display historical information for each curve
4057'
```

```
4060 CYCLE=1:RAT=1:CLS:SCREEN 0
4070 WHILE RAT
4080 NN=CYCLE:GOSUB 4980
4090 LOCATE 1,20:PRINT H$;" AT";INFO(CYCLE,1);"PERCENT GRAIN MOISTURE"
4100 LOCATE 4,1:PRINT"                    CLEANING LOSS          WALKER LOSS
     TOTAL LOSS"
4110 LOCATE 7,1:PRINT"R SQUARE  "
4120 LOCATE 7,21:PRINT USING "#.##";INFO(CYCLE,15)
4130 LOCATE 7,41:PRINT USING "#.##";INFO(CYCLE,16)
4140 LOCATE 7,66:PRINT USING"#.##";INFO(CYCLE,17)
4150 LOCATE 9,1:PRINT "INTERCEPT 'a'"
4160 LOCATE 9,20:PRINT USING "##.##^^^^";INFO(CYCLE,18)
4170 LOCATE 9,40:PRINT USING"##.##^^^^";INFO(CYCLE,19)
4180 LOCATE 9,65:PRINT USING"##.##^^^^";INFO(CYCLE,20)
4190 LOCATE 11,1:PRINT"SLOPE 'b'"
4200 LOCATE 11,20:PRINT USING"##.##^^^^";INFO(CYCLE,21)
4210 LOCATE 11,40:PRINT USING"##.##^^^^";INFO(CYCLE,22)
4220 LOCATE 11,65:PRINT USING"##.##^^^^";INFO(CYCLE,23)
4230 LOCATE 13,1:PRINT "FEEDRATE (t/h)"
4240 LOCATE 14,1:PRINT"(see below)"
4250 LOCATE 13,20:PRINT USING"##.##";INFO(CYCLE,12)
4260 LOCATE 13,41:PRINT USING "##.##";INFO(CYCLE,13)
4270 LOCATE 13,65:PRINT USING"##.##";INFO(CYCLE,14)
4280 LOCATE 16,1:PRINT"GRAIN ANGLE OF REPOSE ="
4290 PRINT"GRAIN DENSITY ="
4300 PRINT "CHAFF MOISTURE ="
4310 PRINT"CHAFF FRICTION ="
4320 PRINT "CHAFF LENGTH ="
4330 LOCATE 16,40:PRINT "STRAW MOISTURE ="
4340 LOCATE 17,40:PRINT"STRAW MODULUS ="
4350 LOCATE 18,40:PRINT "STRAW DENSITY ="
4360 LOCATE 19,40:PRINT "AVG. GRAIN:MOG ="
4370 LOCATE 20,40:PRINT "AVG. CHAFF:MOG ="
4380 LOCATE 16,28:PRINT USING "###.###";INFO(CYCLE,2)
4390 LOCATE 17,28:PRINT USING "###.###";INFO(CYCLE,3)
4400 LOCATE 18,28:PRINT USING "###.###";INFO(CYCLE,4)
4410 LOCATE 19,28:PRINT USING "###.###";INFO(CYCLE,5)
4420 LOCATE 20,28:PRINT USING "###.###";INFO(CYCLE,6)
4430 LOCATE 16,65:PRINT USING "###.###";INFO(CYCLE,7)
4440 LOCATE 17,65:PRINT USING "###.###";INFO(CYCLE,8)
4450 LOCATE 18,65:PRINT USING "###.###";INFO(CYCLE,9)
4460 LOCATE 19,65:PRINT USING "###.###";INFO(CYCLE,10)
4470 LOCATE 20,65:PRINT USING "###.###";INFO(CYCLE,11)
4480 LOCATE 22,1:PRINT"cleaner - chaff feedrate at 1/2 %  cleaner loss
     walker - mog feedrate"
4490 LOCATE 23,1:PRINT"at 1 % walker loss  total - mog feedrate at 2 %
     total loss"
4500 CYCLE=CYCLE+1
4510 IF CYCLE>LOOPS THEN RAT=0
4520 IF CYCLE>LOOPS THEN CYCLE=1
4530 K$=INKEY$
4540 IF LEN(K$)=0 THEN 4530
4550 IF K$="P" THEN GOSUB 4600
4560 '
4570 WEND
4580 SCREEN 2
4590 RETURN
```

```
4591'
4600 'subroutine to dump screen contents to printer
4610 '
4620 WIDTH "LPT1:",80
4630 FOR ROW = 1 TO 24
4640 FOR COL = 1 TO 80
4650 CHAR=SCREEN(ROW,COL)
4660 IF CHAR=0 THEN CHAR=32
4670 LPRINT CHR$(CHAR);
4680 NEXT COL,ROW
4690 RETURN
4700 '
4701 ' subroutine to calculate properties as functions of moisture
4702 '
4701 IF R$="OFF" THEN Y5=CROP(NUM(PASS),1):S5=CROP(NUM(PASS),1)*GMOSTVAR
4702 IF R$="OFF" THEN MOISTEMP=Y5:DEVTEMP=S5
4703 IF R$="ON" THEN Y5=MOISTEMP:S5=DEVTEMP
4705 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),1)=Y3
4710 CROP(NUM(PASS),4)=CROP(NUM(PASS),1)^COEFF(3,2)*COEFF(3,1)
4711 Y5=CROP(NUM(PASS),4):S5=CROP(NUM(PASS),4)*CMOSTVAR
4712 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),4)=Y3
4720 CROP(NUM(PASS),7)=CROP(NUM(PASS),1)^COEFF(5,2)*COEFF(5,1)
4721 Y5=CROP(NUM(PASS),7):S5=CROP(NUM(PASS),7)*SMOSTVAR
4722 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),7)=Y3
4730 CROP(NUM(PASS),2)=CROP(NUM(PASS),1)^COEFF(1,2)*COEFF(1,1)
4731 Y5=CROP(NUM(PASS),2):S5=CROP(NUM(PASS),2)*GANGVAR
4732 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),2)=Y3
4740 CROP(NUM(PASS),3)=CROP(NUM(PASS),1)^COEFF(2,2)*COEFF(2,1)
4741 Y5=CROP(NUM(PASS),3):S5=CROP(NUM(PASS),3)*GDENVAR
4742 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),3)=Y3
4750 CROP(NUM(PASS),5)=CROP(NUM(PASS),4)^COEFF(4,2)*COEFF(4,1)
4751 Y5=CROP(NUM(PASS),5):S5=CROP(NUM(PASS),5)*CFRICTVAR
4752 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),5)=Y3
4760 CROP(NUM(PASS),8)=CROP(NUM(PASS),7)^COEFF(7,2)*COEFF(7,1)
4761 Y5=CROP(NUM(PASS),8):S5=CROP(NUM(PASS),8)*SMODVAR
4762 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),8)=Y3
4770 CROP(NUM(PASS),9)=CROP(NUM(PASS),7)^COEFF(6,2)*COEFF(6,1)
4771 Y5=CROP(NUM(PASS),9):S5=CROP(NUM(PASS),9)*SDENVAR
4772 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),9)=Y3
4776 CROP(NUM(PASS),6)=CROP(NUM(PASS),4)^COEFF(8,2)*COEFF(8,1)
4777 Y5=CROP(NUM(PASS),6):S5=CROP(NUM(PASS),6)*CMLNTGVAR
4778 IF VARIATION$="ON" THEN GOSUB 1370:CROP(NUM(PASS),6)=Y3
4780 RETURN
4800'
4801' adjust each property curve for moisture reference
4802'
4890 COEFF(1,1)=CROP(NUM(PASS),2)/GMOST^COEFF(1,2)
4900 COEFF(2,1)=CROP(NUM(PASS),3)/GMOST^COEFF(2,2)
4910 COEFF(3,1)=CROP(NUM(PASS),4)/GMOST^COEFF(3,2)
4920 COEFF(4,1)=CROP(NUM(PASS),5)/CROP(NUM(PASS),4)^COEFF(4,2)
4930 COEFF(5,1)=CROP(NUM(PASS),7)/GMOST^COEFF(5,2)
4940 COEFF(6,1)=CROP(NUM(PASS),9)/CROP(NUM(PASS),7)^COEFF(6,2)
4950 COEFF(7,1)=CROP(NUM(PASS),8)/CROP(NUM(PASS),7)^COEFF(7,2)
4951 COEFF(8,1)=CROP(NUM(PASS),6)/CROP(NUM(PASS),4)^COEFF(8,2)
4970 RETURN
4975'
4976' subroutine to assign labels used to plot loss curves
```

```
4977'
4980 IF NUM(NN)=1 THEN H$="CALIFORNIA WHEAT"
4990 IF NUM(NN)=2 THEN H$="NORTH DAKOTA WHEAT"
5000 IF NUM(NN)=3 THEN H$="NORTH DAKOTA BARLEY"
5010 IF NUM(NN)=4 THEN H$="Special Blend"
5020 RETURN
5021'
5022' subroutine to select loss curves to plot
5023'
5030 CLS:LOCATE 5,20:PRINT LOOPS;" are available to choose from"
5040 LOCATE 10,20:PRINT"You may plot (1-5) curves on the same plot"
5050 LOCATE 11,21:INPUT"Enter the number of curves you wish to
     plot";NEWLOOPS
5060 IF NEWLOOPS <= 5 GOTO 5110
5070 BEEP:CLS
5080 LOCATE 10,20:PRINT"you choose more than 5 curves
5090 LOCATE 11,20:PRINT"try again (1-5)
5100 GOTO 5030
5110 CLS
5120 FOR NN=1 TO LOOPS
5130 GOSUB 4980  ' go get crop identification label
5140 PRINT "Curve (";NN;")  ";H$," at";INFO(NN,1)
5150 NEXT NN
5160 FOR I=1 TO NEWLOOPS
5170 LOCATE 10,40:INPUT"Enter curve number",CURVE(I)
5180 NEXT I
5190 RETURN
5191'
5200 'label x-axis subroutine
5205 '
5210 LOCATE 20,42+(37-LEN(C$))/2:PRINT C$
5220 RETURN
5225'
5230 'label y-axis subroutine
5235 '
5240 A$="":L=LEN(C$):L1=(18-L)/2
5250 FOR X=1 TO L1:A$=A$+"":NEXT X
5260 A$=A$+C$
5270 FOR X=LEN(A$) TO 18:A$=A$+"":NEXT X
5280 FOR X=3 TO 20
5290 LOCATE X,33:PRINT MID$(A$,X-2,1)
5300 NEXT X
5310 RETURN
5315 '
5320 'crop and grain moisture selection routine
5325 '
5321 Z$="ON":CLS
5340 LOCATE 10,15:PRINT"You may select a maximum of 4 crops per
     simulation"
5350 LOCATE 11,15:PRINT"and a maximum of 5 moisture levels per crop."
5360 LOCATE 18,25:PRINT "strike any key to continue"
5370 K$=INKEY$
5380 IF LEN(K$)=0 GOTO 5370
5381 cls
5400 LOCATE 7,20:INPUT"HOW MANY CROPS DO YOU WANT TO USE";CROPS
5410 FOR I=1 TO CROPS
5420 GOSUB 5560               'display crop codes for the user
```

```
5430 LOCATE 9,20:INPUT"ENTER THE CROP";NUM(I)
5440 IF NUM(I)>4 THEN BEEP:CLS:LOCATE 9,20:PRINT"there are 4 crops and
     no more":LOCATE 10,20:INPUT"ENTER THE CROP AGAIN";NUM(I)
5450 LOCATE 11,20:INPUT"ENTER THE CROP YIELD";YIELD(I)
5460 IF NUM(I)=4 THEN GOSUB 5780       'enter crop properties
5470 CLS:LOCATE 7,20:INPUT"HOW MANY MOISTURE LEVELS  "; MOISTURES
5480 FOR J=1 TO MOISTURES
5490 LOCATE 9+J,20:INPUT"ENTER THE GRAIN MOISTURE LEVEL
     DESIRED";MOIST(I,J)
5500 NEXT J
5510 LOCATE 11+J,20:INPUT"ENTER THE REFERENCE MOISTURE FOR CURVE
     ADJUSTMENT";MOIST(I,J)
5520 NEXT I
5530 BEEP
5540 CLS
5550 RETURN
5551'
5552' subroutine to display available crop data
5553'
5560 CLS
5570 LOCATE 2,30:PRINT "(1)=california wheat"
5580 LOCATE 3,30:PRINT "(2)=north dakota barley"
5590 LOCATE 4,30:PRINT "(3)=north dakota wheat"
5600 LOCATE 5,30:PRINT "(4)=you describe crop"
5610 RETURN
5611'
5612' property labels
5613'
5620 IF TEMP=1 THEN C$="GRAIN MOISTURE"
5630 IF TEMP=2 THEN C$="ANGLE OF REPOSE"
5640 IF TEMP=3 THEN C$="GRAIN DENSITY"
5650 IF TEMP=4 THEN C$="CHAFF MOISTURE"
5660 IF TEMP=5 THEN C$="CHAFF FRICTION"
5670 IF TEMP=6 THEN C$="CHAFF LENGTH"
5680 IF TEMP=7 THEN C$="STRAW MOISTURE"
5690 IF TEMP=8 THEN C$="STRAW MODULUS"
5700 IF TEMP=9 THEN C$="STRAW DENSITY"
5710 IF TEMP=10 THEN C$="GRAIN:MOG RATIO"
5720 IF TEMP=11 THEN C$="CHAFF:MOG RATIO"
5730 IF TEMP=12 THEN C$="1/2 % CLEANER LOSS"
5740 IF TEMP=13 THEN C$="1 % WALKER LOSS"
5750 IF TEMP=14 THEN C$="2 % TOTAL LOSS"
5770 RETURN
5771'
5772' subroutine to enter crop properties
5773'
5780 CLS:LOCATE 2,20:PRINT"CROP PROPERTIES ROUTINE"
5790 FOR TEMP=1 TO 11
5800 GOSUB 5620
5810 LOCATE TEMP+5,15:PRINT C$
5820 NEXT TEMP
5830 LOCATE 6,40:INPUT "* ",CROP(NUM(I),1)
5840 LOCATE 7,40:INPUT "*  ",CROP(NUM(I),2)
5850 LOCATE 8,40:INPUT "*  ",CROP(NUM(I),3)
5860 LOCATE 9,40:INPUT "*  ",CROP(NUM(I),4)
5870 LOCATE 10,40:INPUT "*  ",CROP(NUM(I),5)
5880 LOCATE 11,40:INPUT "*  ",CROP(NUM(I),6)
```

```
5890 LOCATE 12,40:INPUT "*  ",CROP(NUM(I),7)
5900 LOCATE 13,40:INPUT"*  ",CROP(NUM(I),8)
5910 LOCATE 14,40:INPUT"*  ",CROP(NUM(I),9)
5920 LOCATE 15,40:INPUT"*  ",CROP(NUM(I),10)
5930 LOCATE 16,40:INPUT"*  ",CROP(NUM(I),12)
5940 RETURN
5941'
5942' subroutine to input variation for each crop property
5943'
7500 CLS:LOCATE 2,20:PRINT"CROP VARIATION ROUTINE"
7510 FOR TEMP=1 TO 9
7520 GOSUB 5620
8000 LOCATE TEMP+5,15:PRINT C$
8010 NEXT TEMP
8020 LOCATE 6,40:INPUT "* ",GMOSTVAR
8030 LOCATE 7,40:INPUT "*  ",GANGVAR
8040 LOCATE 8,40:INPUT "*  ",GDENVAR
8050 LOCATE 9,40:INPUT "*  ",CMOSTVAR
8060 LOCATE 10,40:INPUT "*  ",CFRICTVAR
8070 LOCATE 11,40:INPUT "*  ",CMLNTGVAR
8080 LOCATE 12,40:INPUT "*  ",SMOSTVAR
8090 LOCATE 13,40:INPUT"*  ",SMODVAR
8095 LOCATE 14,40:INPUT"*   ",SDENVAR
8400 RETURN
9000 CLOSE:END
9001 RETURN
```

APPENDIX E

Combine Simulation Interactive Session

SIMULATION INSTRUCTIONS AND SAMPLE PROGRAM OUTPUTS

The simulation program was written in Microsoft Basic and implemented on an IBM-compatible micro-computer which utilized an Intel 8086 central processing unit. The simulation of a single loss curve required approximately five minutes to complete when the program was executed as interpreted code. The execution time was reduced to approximately one minute per curve simulation by compiling and linking the source code into a single executable module.

The documentation of the program is contained within the source code. The major variables are explained in a block of comment lines at the beginning of the program.

Function keys (F1 - F7) are used to select program options from a menu display. The inputs to the program are a series of crop properties and the random variation of each property expressed as a percentage, grain to M.O.G. and chaff to M.O.G. ratios, ground speed (mph), header width (feet), and crop yield (bushels). The simulation provides options to display cleaner, straw walker, and total loss curves and a means to construct scatter plots of each property or machine parameter expressed as a function of another property or machine parameter.

The following text and figures describe the execution of the combine simulation program. Throughout the instruction, input from the user will be **highlighted**. Some inputs must be terminated by pressing the RETURN key which is denoted as <RET>. The instructions assume that you are already familiar with the MS-DOS operating system and are able to boot the computer and begin the execution of a program. A typical interactive session begins as follows:

1. **Random Number Seed (-32768 to 32767) Enter a number <RET>**

2. **Wait for the following screen display:**

```
F1. select crop location
F2. run simulation
F3. plot loss curves
F4. plot scatter plots of properties
F5. set parameters for stochastic process
F6. display historical data from simulation run
F7. exit program
```

3. **Press function key F1.** At this point it is necessary to select the number of machine performance curves to simulate and the crop properties values which describe a crop. This example will select one set of crop properties and three moisture conditions to simulate. The following message is displayed:

> You may select a maximum of 4 crops per simulation
> and a maximum of 5 moisture levels per crop. Strike
> any key to continue. **Press any key.**
>
> How many crops do you want to use? **Enter 1 <RET>**
>
> Select the crops you wish to use. **Enter 4 <RET>**

Note: You may choose crop properties which are representative of a California wheat crop, a North Dakota wheat crop, or a North Dakota barley crop. You may also elect to describe the crop by its properties. If you are unfamiliar with the range of crop property values reference Table 2 on page of Chapter IV.

```
          Crop Properties Routine

     Grain Moisture      12.00 <RET>
     Angle of Repose     20.00 <RET>
     Grain Density      775.00 <RET>
     Chaff Density       35.00 <RET>
     Chaff Friction       0.27 <RET>
     Chaff Length         6.50 <RET>
     Straw Moisture      12.00 <RET>
     Straw Modulus        2.20 <RET>
     Straw Density       19.00 <RET>
     Grain:MOG Ratio      1.39 <RET>
     Chaff:MOG Ratio      0.43 <RET>

How many moisture levels? Enter 3 <RET>

Enter the grain moisture level desired? 12 <RET>
Enter the grain moisture level desired? 13 <RET>
Enter the grain moisture level desired? 14 <RET>
Enter the reference moisture level? 12 <RET>
```

4. It is now necessary to select the amount of variation for each crop as a percentage. Press F5.

```
               Crop Variation Routine

     Grain Moisture    1.0
     Angle of Repose   1.0
     Grain Density     1.0
     Chaff Moisture    1.0
     Chaff Friction    1.0
     Chaff Length      1.0
     Straw Moisture    1.0
     Straw Modulus     1.0
     Straw Density     1.0
```

Note: The simulation of cleaner performance appears most realistic when chaff and grain properties vary by approximately 5.0 percent. Likewise, walker performance appears most realistic when the properties in the walker loss equation vary by 10.0 percent.

5. **Press F2** to simulate the performance of a combine harvester.

6. **Press F3** to produce loss curves for the cleaner, the walker, or the total loss curve. You will be prompted for the curves to display from a menu or select the first five performance curves. For this example **press <RET>**, default to display the performance curves for one crop at three moisture levels. You may toggle between each type of curve by pressing the space bar. The display begins with cleaner curves. **Press the space bar** to display the walker curves. Each time you press the spacebar another set of curves is displayed.

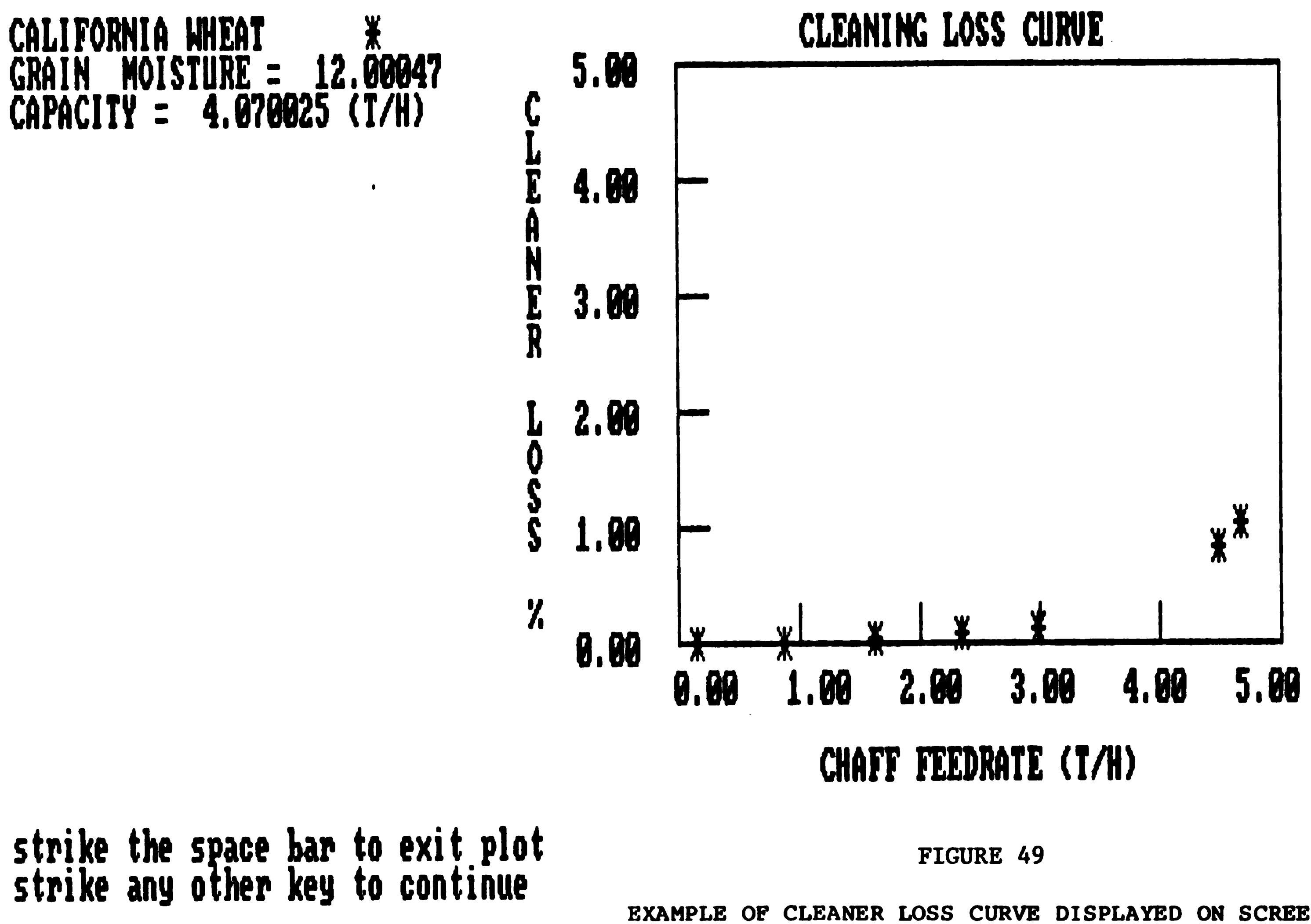
7. **Press F4** to create a scatter plot of one property versus another property or to plot the machine performance versus a property. For example, to plot grain density versus grain moisture, select the appropriate property from the display by entering the number of the property at the prompt(Figure 21).

Enter a property. 1 **<RET>**

Enter a property. 3 **<RET>**

8. **Press F6** to display a summary of the crop property mean values, the coefficients of the predicted loss curves, and the predicted feed rates. Figure 22 is an example of the statistics provided for each simulation run. For example, there are three such summaries created by this example set of program inputs. **Press the spacebar** to display the next summary.

9. **Press F8** to exit the program and return to DOS.

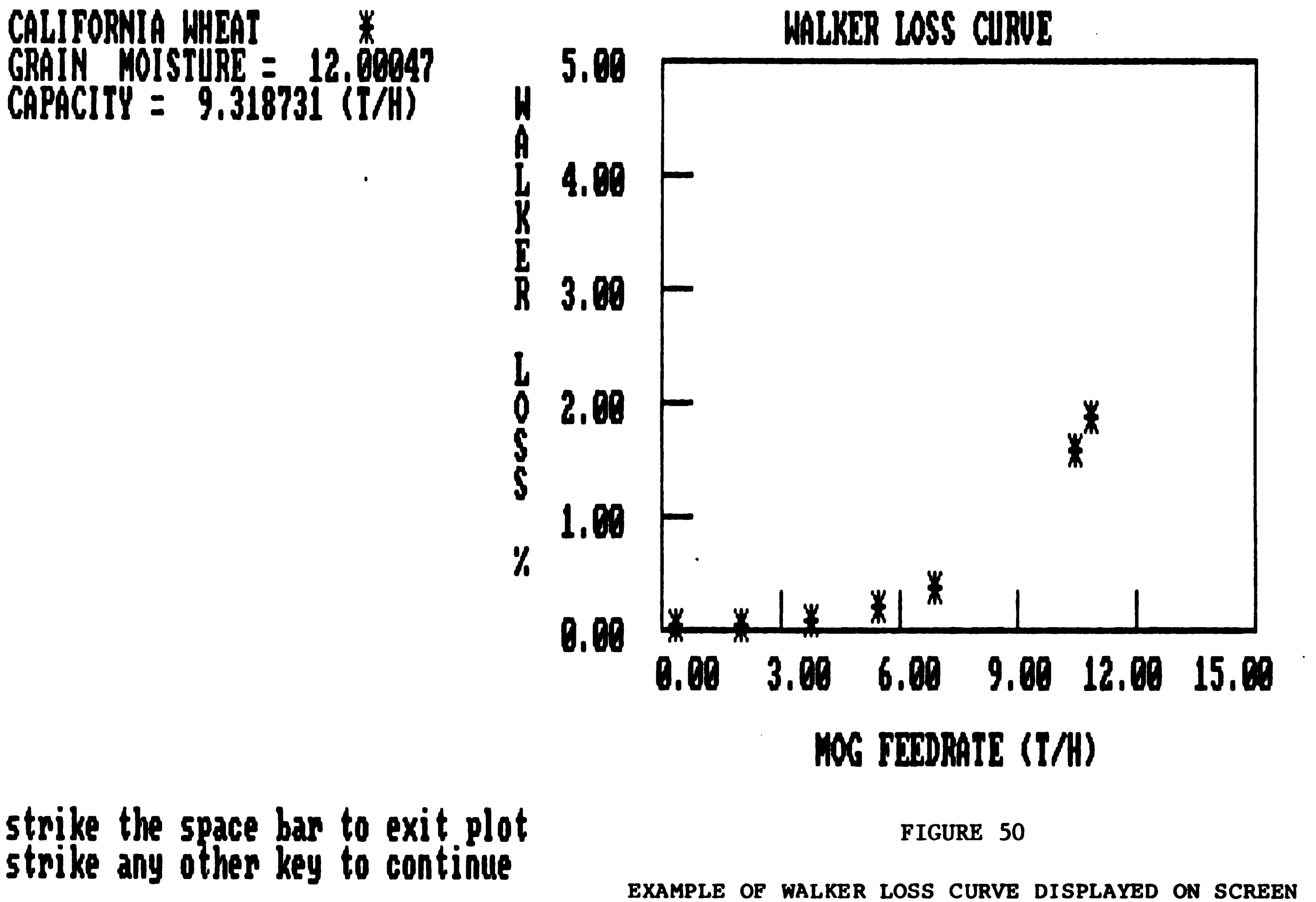


CALIFORNIA WHEAT *
GRAIN MOISTURE = 12.00047
CAPACITY = 4.070025 (T/H)

strike the space bar to exit plot
strike any other key to continue

FIGURE 49

EXAMPLE OF CLEANER LOSS CURVE DISPLAYED ON SCREEN
BY PRESSING THE F3 FUNCTION KEY

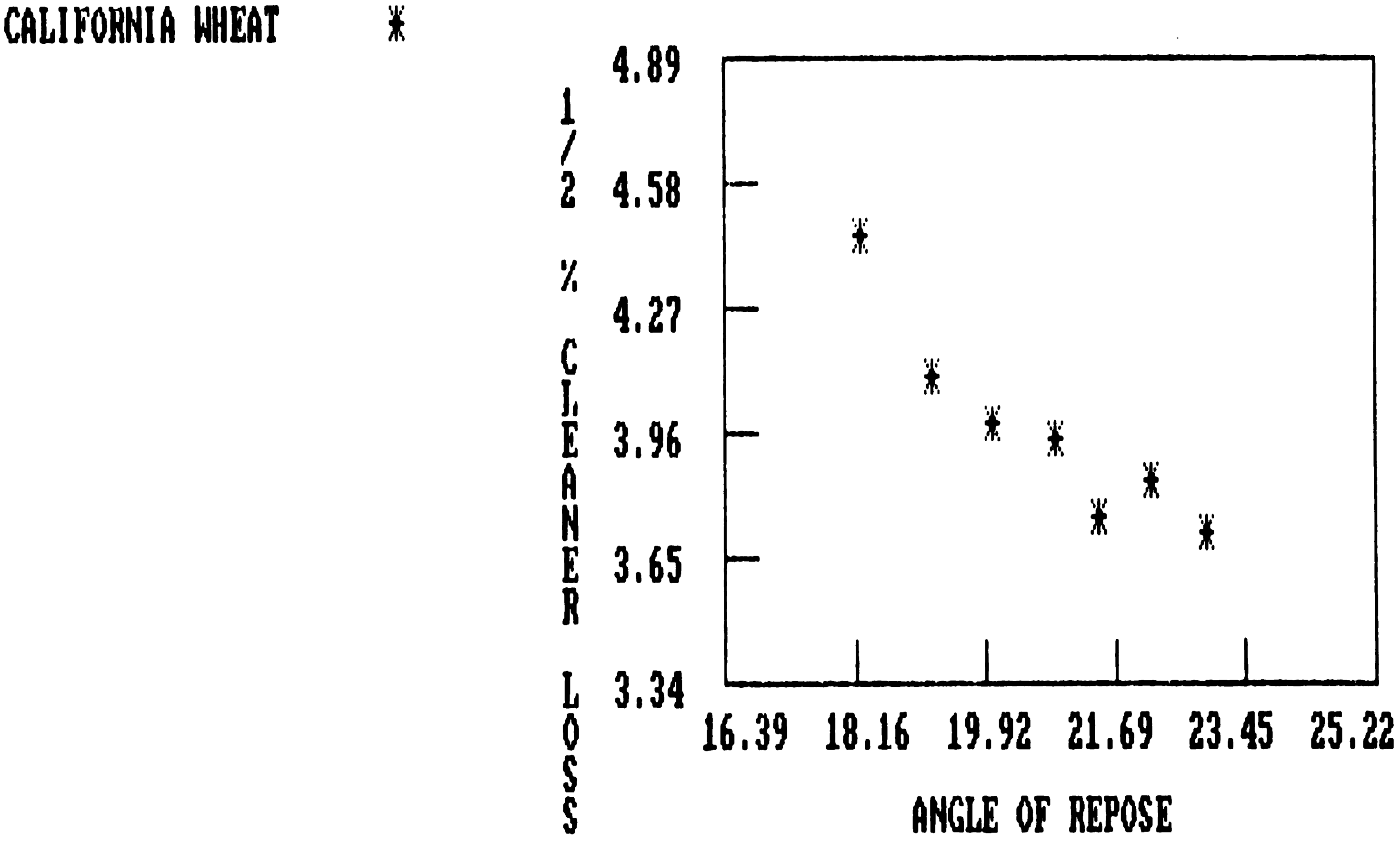


```
CALIFORNIA WHEAT      *
GRAIN  MOISTURE =  12.00047
CAPACITY =  9.318731 (T/H)
```

```
strike the space bar to exit plot
strike any other key to continue
```

FIGURE 50

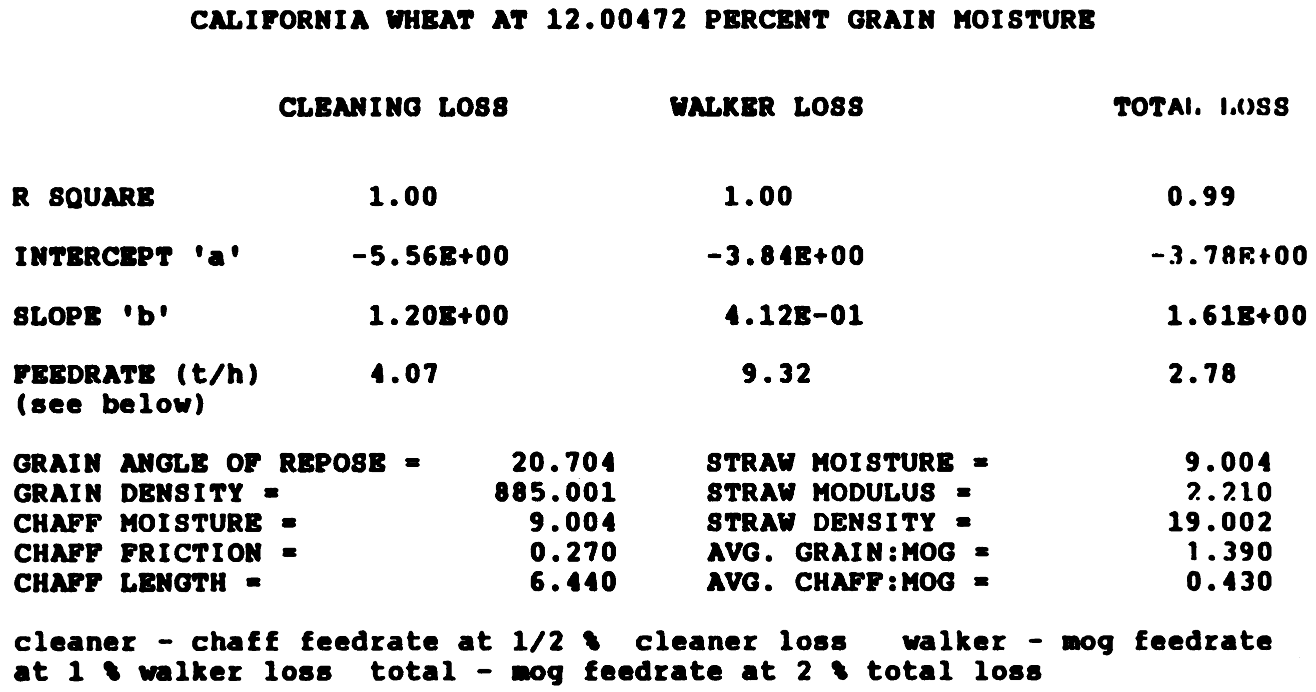
EXAMPLE OF WALKER LOSS CURVE DISPLAYED ON SCREEN
BY PRESSING THE F3 FUNCTION KEY



strike any key to continue

FIGURE 51

SCATTER PLOT DISPLAYED ON SCREEN
BY PRESSING F4 FUNCTION KEY
THE OPTION PROMOTS THE USER FOR TWO CROP
PROPERTIES OR MACHINE PARAMETERS



```
                    CALIFORNIA WHEAT AT 12.00472 PERCENT GRAIN MOISTURE

                        CLEANING LOSS          WALKER LOSS              TOTAL LOSS

R SQUARE                  1.00                  1.00                    0.99

INTERCEPT 'a'           -5.56E+00             -3.84E+00               -3.78E+00

SLOPE 'b'                1.20E+00              4.12E-01                1.61E+00

FEEDRATE (t/h)            4.07                  9.32                    2.78
(see below)

GRAIN ANGLE OF REPOSE =         20.704     STRAW MOISTURE =           9.004
GRAIN DENSITY =                885.001     STRAW MODULUS =            2.210
CHAFF MOISTURE =                 9.004     STRAW DENSITY =           19.002
CHAFF FRICTION =                 0.270     AVG. GRAIN:MOG =           1.390
CHAFF LENGTH =                   6.440     AVG. CHAFF:MOG =           0.430

cleaner - chaff feedrate at 1/2 % cleaner loss  walker - mog feedrate
at 1 % walker loss  total - mog feedrate at 2 % total loss
```

FIGURE 52

EXAMPLE OF SIMULATION STATISTICS DISPLAYED
BY PRESSING THE F6 FUNCTION KEY

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