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TESTING AND VALIDATING THE CERES-WHEAT MODEL IN DIVERSE ENVIRONMENTS

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CERES-Wheat is a computer simulation model of the growth, development, and yield of spring and winter wheat. It was designed to be used in any location throughout the world where wheat can be grown. The model is written in FORTRAN 77, operates on a daily time stop, and runs on a range of computer systems from micro-computers to mainframes. Two versions of the model were developed: one, CERES-Wheat, assumes nitrogen to be nonlimiting; in the other, CERES-Wheat-N, the effects of nitrogen deficiency are simulated. This report provides the comparisons of simulations and measurements of about 350 wheat data sets collected from throughout the world. Comparisons are made of model performance to predict grain yields, yield components, leaf area index and biomass, phenology, soil water balance, soil nitrogen balance and nitrogen uptake by plants. Agreement between model output and experimental results were acceptable in most instances. Statistical analysis indicated that some problems have yet to be resolved with the prediction of N uptake and grain protein concentration in some data sets.

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TESTING AND VALIDATING THE CERES-WHEAT MODEL IN DIVERSE ENVIRONMENTS

Testing and Validating the CERES-Wheat Model

in Diverse Environments

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Soil and Irrigation Research Institute - South Africa
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To be added after last paragraph of page 31 and before the first paragraph of page 32.

Dufur, Pendleton, and Madras Oregon, 1971

These experiments were reported by Ambler (1974) and involved the comparison of five varieties of winter wheat over several different rates of fertilizer at several different sites in Oregon. Data from sites where climatic data were incomplete were rejected. The three remaining sites differ in annual rainfall and altitude. Solar radiation data from Klamath Falls were used for the Madras data set. Few significant variety x N interactions were recorded and so data from only two cultivars (Hyslop and Nugaines) were utilized. At Madras four rates of N (0, 90, 180, and 270 kg N/ha) at planting with a second application of 90 kg N/ha applied at the booting stage was investigated. Initial levels of nitrate in the profile were high and the response to N was small. The experiment was irrigated. At the Dufur site, three rates of N (0, 17, and 34 kg N/ha) were used and at the Pendleton site four rates of N (0, 34, 67, and 101 kg N/ha) were used. No significant response to N was recorded at either site.

Waite Institute, 1958

These data were reported by Barley and Naidu (1962). The experiment examined the response to N of two varieties (Gabo and Bencubbin). The rates of N used were (0, 33, 67, and 174 kg N/ha) as ammonium sulfate. Solar radiation data were estimated from the recorded values of hours of sunshine. The soil was reported as a red-brown earth (Alfisol).

Bozeman, Montana, 1977

These data were reported by Christianson and Killorn (1981). This experiment examined differences in fertilizer use efficiency for applications made at different times. Nitrogen was applied as ammonium nitrate after seeding or broadcast several hours prior to a sprinkler irrigation to simulate application of fertilizer through the sprinkler system. The study investigated the effects of four rates of N applied at planting (0, 50, 100, and 150 kg N/ha) and five split-application patterns with a total application rate of either 100 or 125 kg N/ha. The soil was a deep silt loam and N responses were very marked.

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To be added to the BIBLIOGRAPHY:

Ambler, J.R. 1976. Varietal differences in response of winter wheat varieties to nitrogen fertilizer and environment. Ph.D. thesis submitted to Oregon State University.

Barley, K.P., and N.A. Naidu. 1964 The performance of three Australian wheat varieties at high levels of nitrogen supply. Aust. J. Exp. Agric. Anim. Husb. 4:3-46.

Christensen, N.W., and R.J. Killorn. 1981. Wheat and barley growth and N fertilizer utilization under sprinkler irrigation. Agron. J. 68:960-964.

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For the independent data sets, an "index of agreement" (d) was calculated according to the procedure of Willmott (1982). This calculation was only performed on yield data. All statistical computations were performed with the statistical package SAS (1982).

The second and much more extensive part of the results are graphics, showing the proximity of the time course of model output and experimental measurements. Unfortunately, most data sets provided no information available on the variance of published measurements. This would be of certain interest because observed values are not true values in a statistical sense, but are mean values of a very small sample with more or less large intrinsic error.

Results and Discussion

Summary Statistics. Tables 2 and 3 are summarized measures for the dates of anthesis and physiological maturity, yield, grain weight, grain numbers per m^2 (GPSM), ear numbers per m^2, above ground dry matter, and leaf area index (LAI). Observed and predicted means are listed to show the difference between them. Standard deviations of observed and predicted values are listed to be checked for similar ranges. The intercept and slope of the regression equation with O as an independent variable provides information about the accuracy of predictions. Tables 4 and 5 contain the difference measures for the same list of variables.

Difference Measures. While summary measures try to describe the quality of simulation, difference measures try to locate and quantify errors. Difference measures for the same variables as above are listed in Tables 4 and 5. The mean bias error (MBE) is regularly considerably smaller than the mean absolute error. The two values, being close, indicate the prediction to be biased in one direction, as is true for ear number and dry matter predictions with the independent sets.

A negative MBE occurs when predictions are smaller in value than observations. Considerable errors of this kind are found with GPSM, ear number, and dry matter predictions of the dependent data sets, and with grain weight and date of anthesis of the independent sets. For all others, predictions are larger than observed values.

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Since the value of the MBE is related to the range of values, it is not reasonable to compare across variables. However, comparisons between the two groups of data sets might show the necessity of requiring independent data sets if it could be shown that the MBE and MAE of independent data were always larger. Unfortunately, while true for yield, it does not apply for all variables; maximum error in predicting yields is smaller in the independent set.

Willmott (1982) indicated that the closer the root mean square error (RMSE) to 0, the better the model. Certainly this applies to the systematic error. The unsystematic RMSE should approach RMSE in the system:

$$MSE = MSE_s + MSE_u$$

The tendency of $RMSE_s$ toward 0 is obvious, compared to RMSE. Since the mean is involved in the computation of this measure, comparisons across groups of data sets are not advisable.

The values of $RMSE_s$ and RMSE, computed to predict yields for the dependent data set, are very similar: 25377 and 25424, respectively. Thus, compared to $RMSE_u$ of 1552, the model meets the above requirement.

Willmott (1982) also suggests the computation of d, a quality measure for models, or index of agreement:

$$d = 1 - [\sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} (|P_i'| + |O_i'|)^2], \quad 0 \le d \le 1$$

$$\text{where } P_i' = P_i - \bar{O} \text{ and } O_i' = O_i - \bar{O}$$

For a good model, d should approach 1. For CERES-Wheat yield predictions, d equals 0.8825. This quality measure is mainly used to compare different models, but it provides additional useful information of model performance when used to evaluate a single model.

Descriptive Statistics. Descriptive statistics based on the values shown in Tables 6 and 7 are reported separately for the two groups of data sets.

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Phasic Development. The accuracy of simulating the phasic development of a crop is crucial for the accurate simulation of crop growth and yield. Therefore, this part of the simulation received considerable attention. Figures 2-7 show the scatter of predicted versus measured variables, including the 1:1 line ±1 standard deviation and the matching regression.

Regression equations for anthesis and physiological maturity show an excellent fit with slopes close to 1 and high regression coefficients. Observed means are considerably different for the two groups of data sets, the independent data sets reading anthesis and maturity 12 and 19 days, respectively, later. This reflects the fact that the origin of this subset of the data base is relatively far north, where the wheat crop season is extended into the latter part of the year.

Difference measures in Tables 4 and 5 indicate small mean bias errors and mean absolute errors of five and seven days, respectively. The maximum errors for the two dates in the dependent subset occurred in the same run; therefore, the time available for grain filling was correct. When the date of anthesis was predicted too early, maturity came too early also.

Yield, Grain Weight, and Grain Numbers/m^2. The independent data set is characterized by a higher mean yield caused by higher grain weight and slightly bigger grain numbers. This confirms that the data sets came from different locations. High yields were mostly from northern wheat growing areas. However, observed and predicted mean yields are very close resulting in small mean bias errors. The mean absolute error is in the range of 22 percent of the observed mean yield and GPSM, but only 15 percent of the observed grain weight.

Figures 2-4 demonstrate the scatter of predicted versus measured data points around the regression line, the 1:1 line and within the limits of ±1 standard deviation of the observed mean. The percentage of data points outside of these limits is small as to the total number of observations. This demonstrates the model's reliability in simulating yield. Comparison of the regression to the 1:1 line proves the good fit, especially for the independent data sets. The regression coefficient, however, does not indicate a significant superiority of yield predictions over the rest of the data base (0.633 compared to 0.617).

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It is interesting to note that measured and predicted mean yields within a subset did not differ nearly as much as between the two subsets.

Final Ear Number, Final Dry Matter, and Maximum LAI. Additional variables to be checked are final ear number, final dry matter, and maximum LAI observed during the growing season. Since the average experiment had about five measurements in the season, there is no guarantee that a measurement was taken at the peak of leaf area development. There are relatively few observations in total. Therefore, observed maximum LAI has to be considered with precaution.

Despite these restrictions, the mean bias error is not very large. The mean absolute errors, however, amount to 40 percent and 95 percent of the observed mean. Also, the regression coefficient is not very high (Figure 7). (Please refer to the section where predicted and observed LAI are compared over the course of time for particular experiments to demonstrate the model's capability to simulate the canopy development.)

Leaves comprise most of the total amount of above ground dry matter (Figure 6). Since final dry matter is highly correlated to yield, it must be accurately simulated. The model overpredicts dry matter (Table 4) by about 380 g/m^2, which is considerably less than 1 standard deviation (525.5 g/m^2). In the regression, the model accounts for 41.1 percent of the variation in the real world.

For the group of independent data, simulation of final ear number (Figure 5) resulted in a very small slope (0.1398) and corresponding coefficient of determination ($r^2 = 0.014$). The regression coefficient for the dependent data sets is 0.40 and thus is higher than for dry matter.

Measured and Model Estimates of Crop Growth. To ensure accuracy, any simulation of plant parts should be checked intensively against real world observations. The appendix contains comparisons between model output with all available experimental measurements. For some, real world data were obtained by digitizing graphs in publications, which adds uncertainty to the reliability of these data. These comparisons should be viewed with a critical mind. Figures in Appendix A are in the order of locations.

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One problem with the data is that often only a few samples were taken during the growing season and for typical optimum curves like LAI or tiller number, the peak may be missing (see tiller number for Rutherglen, Australia). The experiment in Rutherglen is one of the few where root measurements were taken. It demonstrates good correspondence of compared data despite high variations in measurements and a slightly too high growth rate in the model run. Partitioning was correct for this particular experiment as shown through a large number of samplings of root, stem, and ear weight. One discrepancy is that stem weight measurements seem to include leaves or sheaths, whereas the graph of the simulation shows stem weight only.

Five, well-timed samples during the growing season demonstrated agreement with the tillering pattern at Murumbateman, Australia, in 1977. Biomass and LAI were simulated with high accuracy. The 1980 run at the same location did not perform quite as well, although the same

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by

S. Otter-Nacke, D. C. Godwin and J. T. Ritchie

INTRODUCTION

CERES-Wheat[1] is a computer simulation model of the growth, development, and yield of spring and winter wheat. It was developed through the assistance of several scientists from the United States and other countries. CERES, Crop Estimation through Resource and Environment Synthesis, is derived from the Latin word for cereal.

The model is written in FORTRAN 77, operates on a daily time step, and runs on a range of computer systems from micro-computers to mainframes (Ritchie and Otter 1985). Two versions of the model were developed: one, CERES-Wheat, assumes nitrogen to be nonlimiting; in the other, CERES-Wheat-N, the effects of nitrogen deficiency are simulated. Although the models had been intensively tested and calibrated, they had not been validated. Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from its use should be performed. Model validation in its simplest form involves a comparison between simulated values and real world values. This paper describes the validation of both models and is presented in two sections. The first section (pages 2-46) summarizes the data from all the experiments. The last section (Appendix A and B) provides detailed comparisons from individual experiments.

FEATURES OF CERES-WHEAT

CERES-Wheat was designed to be used in any location throughout the world where wheat can be grown. It describes the major environmental and edaphic factors affecting yield by way of simulating the following processes:

- Phasic development or duration of growth stages on a thermal time scale as related to plant genetics, weather, and other environmental factors.

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[1]Documentation of the CERES-Wheat model is currently in review and will be published in the same series as *CERES-Maize, A Simulation Model of Maize Growth and Development*, C. A. Jones and J. R. Kiniry, Eds.

- Apical development as related to morphogenesis of vegetative and reproductive structures.
- Extension growth of leaves and stems and senescence of leaves.
- Assimilate accumulation and partitioning.
- Soil water status and its effect on growth and development.
- Nitrogen status and its impact on growth and development.

CERES-WHEAT (NON-NITROGEN VERSION)

Calibration, validation, and sensitivity analysis are three different ways of evaluating models. Logically, validation is the last step in model testing. Although important to proper model evaluation, calibration cannot be the only or last step. Penning de Vries (de Vries and van Laar 1982) stated that calibration is a "very restricted form of evaluation," an "adjustment of some parameters such that model behavior matches one set of real world data," and that extensive calibration "degrades simulation into curve fitting."

Sensitivity analysis reflects the effects of perturbed model parameters on model output, such as biomass and yield. The information can be used to determine whether the model is overly sensitive or not sensitive enough to certain processes being simulated.

Final validation of a model can only be conducted after a calibration and a sensitivity analysis. Validation requires independent data sets to verify the behavior of the model under real world conditions. In its simplest form, it is a comparison between simulation and the real world.

Statistical methods can provide some useful information on model performance. The correlation coefficient (r) and the coefficient of determination (r^2) are of limited value. Willmott (1982) contends that r and r^2 are of little practical value in evaluating model performance, because their magnitudes are not consistently related to the accuracy of prediction. Better criteria are bias, mean bias error, variance of the distribution of differences, root mean square error (RMSE), and mean absolute error (MAE). He recommends, at minimum, reporting predicted mean (P) and observed mean (O), the standard deviation of the predicted (S_p) and observed (S_o) variable, the intercept (a) and slope (b) of the least-squares regression $P_i = a + b\ O_i$ (Willmott 1982).

Eight criteria were established by AgRISTARS for testing and evaluating crop yield models: mean square error, variance bias, proportion of years beyond a critical error limit, worst and second to worst performance during the testing period, range of accuracy, direction of change from mean yields, and correlation coefficient between actual and model predicted yields for a set of independent test years (Wilson and Sebaugh 1981). Other criteria include mean absolute difference and length of an 80% prediction interval for an observation of the difference between observed and calculated yield (Kornher and Torsell 1983). When defining the limits of acceptance for model performance, McMahon (1983) claims that 85% of the variance in crop yield should be accounted for or the predicted mean should be within one standard deviation of the observed mean.

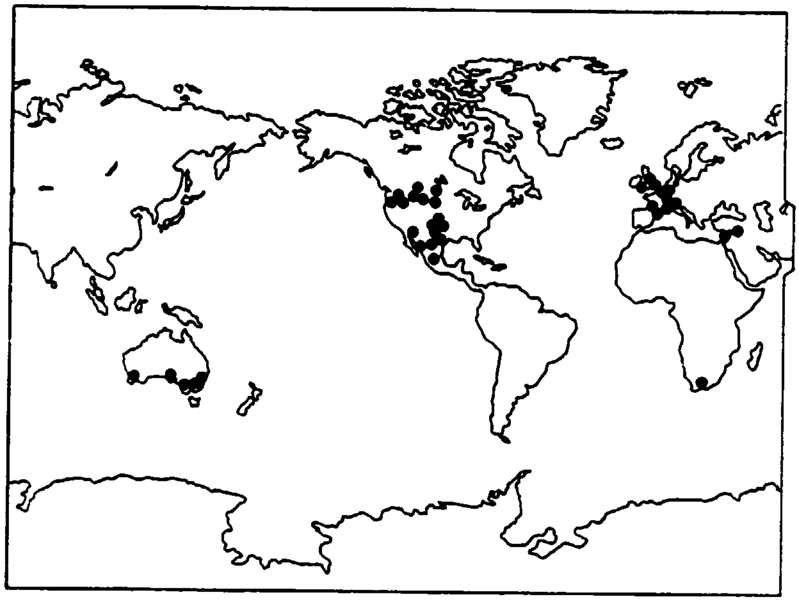
A temptation when calibrating the model is to use some of the information from data sets collected for validation. Results of these tests are of limited value, because experimental data may have been used to evaluate one particular equation in the source code. For CERES-Wheat, other data sets were run during the model's development. Thus, model weaknesses were based on more than one experiment, which allowed improvements to be made, and the same data base could be used for further validations. In the validation process discussed in this paper, the data base is divided into (1) independent data sets and (2) previously used data bases.

Data Base

A good data set should contain as much detail as possible to describe the process of plant growth. However, taking a sufficient number of measurements throughout the season can make a simple experiment expensive and location-specific. A universal model must be tested at many locations.

To test the CERES-Wheat model in the northern and southern hemisphere, a data base was assembled to represent a diversity of environments, including short growing season spring wheat crops, environments with limited water availability, subtropical wheat growing areas with little vernalization, and regions with temperature extremes. The data base of 283 data sets (collected between 1960 and 1983, from 25 different sites, includes published experimental data from the United States as well as from other countries as far south as Australia and as far north as West Germany, representing a range of latitudes from 36°S to 54°N (Figure 1).

Figure 1. Location of Experimental Sites.



Validation depends on the quality of data available. To provide a high-quality data set for wheat model testing, extensive crop measurements throughout the season are required. As most research work is for purposes other than collecting data for testing a model, published data are not as comprehensive as desired. Thus, in many instances, some compromises for model input were often necessary to fully establish the data base. Minimum input included daily weather data for the entire season, soil water information, phenological observations, yield, and yield components (Table 1).

Since several data sets in the data base had been used to calibrate and validate former versions of the CERES model, and statisticians emphasize that only truly independent data should be used for validation, the data base was divided into two groups:

1. Dependent data sets (i.e. data sets used during model development) (130). Some data were used to calibrate parts of a particular subroutine of the model. Results of their testing will be shown, however, because other parts of the model may be unaffected despite some modifications from that experiment.

Table 1. Data Source for Model Testing.

Location	Number of: Total Data Sets	Var[1]	Sow Date	Sow Den	Irr[2]	Measured Data in *: Phasic Devel	Yield + Yld Comp	DM Partg	Soil Water
ENGLAND									
Rothamsted '60[a]	4	4				*	**	***	
Rothamsted '75[b]	3	3				**	***		
Rothamsted '76[c]	3	3				**	***		
Nottingham '75[d]	1	1				**	*	***	
Nottingham '76[e]	1	1				**	*	*	
Nottingham '77[f]	1	1				**	*	*	
Cambridge '77[g]	2	2				**	**		
NETHERLANDS									
Lelystad '77[h]	7	1		7		*	**	*	
Flevoland '76[i]	1	1				**	**	**	
Flevoland '78[j]	1	1				**	**		
Wageningen '77[k]	2	2				*	***	***	
WEST GERMANY									
Ahrensburg '65-83[l]	19	1				*	*		
Weihenstephan '83[m]	9	8				*	**	(***)	
FRANCE									
Auzeville '76[n]	4	2			2	***	**		
Auzeville '78[n]	2	2				***	**		
Auzeville '79[n]	2	2				***	**		
Avignon '76[n]	6	3			2	***	**		
Avignon '77[n]	2	1			2	***	**		
Avignon '78[n]	4	4				***	***		
Avignon '79[n]	2	2				**	**		
Boigneville '76[n]	4	2			2	***	**		
Boigneville '77[n]	2	1	2			***	**		
Boigneville '78[n]	6	3	2			***	**		
Boigneville '79[n]	3	3				***	**		
ISRAEL									
Kibbutz Boker '78[o]	4	1			4	**	*	**	*
SOUTH AFRICA									
Roodeplast '78[p]	5	1			5	**	*	*	*
AUSTRALIA									
Rutherglen '71[q]	1	1				*	*	***	
Murumbateman '79[r]	1	1				*	*	***	
Murumbateman '80[r]	1	1				*	**	**	
Wagga Wagga '81[r]	1	1				*	**	**	

Table 1. Con't.

Location	Number of: Total Data Sets	Var[1]	Sow Date	Sow Den	Irr[2]	Measured Data in *: Phasic Devel	Yield + Yld Comp	DM Partg	Soil Water
MEXICO									
Ciudad Obregon '73[s]	4	1			4		*		
Ciudad Obregon '74[t]	4	1			4		*	*	
U.S.A.									
North Dakota '79[t]	5	5				*	**	**	
North Dakota '80[t]	4	4				*	*	**	
North Dakota '81[t]	4	4				*	*	**	
Sidney MN '77[v]	6	3		2			*	*	
Sidney MN '78[w]	6	3		2			*	**	
Manhattan KS '82[x]	2	1			2	**	**	***	
Hutchinson KS '80[x]	1	1				**	**	**	
Hutchinson KS '81[x]	1	1				**	**	*	
Garden City KS '81[x]	2	1			2	**	**	***	
Garden City KS '82[x]	4	1			4	**	**	***	
Bozeman MT '77[y]	1	1			1	*	*	*	
Lind WA '77[z]	2	1		2		**	**	*	
Pullman WA '73[aa]	2	1	2			*	*	**	
Pullman WA '74[aa]	2	1	2			*	**	*	
Pendleton OR '77[bb]	2	2				**	*	***	
Pendleton OR '80[bb]	8	3		3		*	**	**	
Pendleton OR '81[bb]	1	1				*	**	***	
Weston OR '81[bb]	3	3				*	**	*	
Temple TX '77[cc]	21	7	3				**		
Temple TX '83[dd]	8	2		4		**		**	
Bushland TX '78[ee]	21	2	(2)	2	4	**	**		*
Bushland TX '79[ee]	8	1			8	***	**	**	**
Bushland TX '80[ff]	1	1							
Bushland TX '81[ff]	8	1			8		**	***	
Bushland TX '82[ff]	8	2			4		**	***	
Phoenix AZ '78[gg]	12	2			6	*	**		
Phoenix AZ '79[hh]	19	1	5		4	**	*		
Phoenix AZ '80[ii]	17	1	5		4	**	*	***	***
Vernon TX '79[ff]	1	1				**	*	*	*

* Number of asterisks reflects intensity of measurements.

[1] Varieties in experiments; [2] Irrigation treatments.

[a]Watson et al. 1963; [b]Pearman et al. 1978; [c]; [d]Baker 1979; [e]Gallagher et al. 1976; [f]; [g]Brooking & Kirby 1981; [h]Darwinkel 1978; [i]Spiertz & Ellen 1978; [j]Ellen & Spiertz 1980; [k]Spiertz & v.d.Haar 1978; [l]Beinhauer, pers comm; [m]Bergermeier, pers comm; [n]Corre & Delecolle 1983; [o]Hochman 1979; [p]Meyer 1978; [q]Paltridge et al. 1972; [r]Armstrong, pers comm; [s]Sojka 1974; [t]Bauer 1980; [v]Aase 1978; [w]Black & Aase 1982; [x]Wagger 1983; [y]; [z]Johnson 1978; [aa]Thill 1976; [bb]Klepper et al. 1983; [cc]Monk et al. 1979; [dd]Otter; [ee]Musick & Dusek 1978; [ff]Dusek, pers comm; [gg]; [hh]; [ii].

2. Independent data sets (153). These were run only on the final version or, sometimes, on previous versions, but results of the run never affected the coding of the model.

Methods

This report is divided into (1) a report of the descriptive statistics to illustrate the general performance of CERES-Wheat and (2) a graphical comparison of model output with real world measurements of plant parts or growth factors over the growing season. The descriptive statistics consist of summary measures and difference measures. Criteria were selected by following the procedures recommended by Willmott (1982):

- observed mean (O)
- predicted mean (P)
- standard deviation of the observed values (S_o)
- standard deviation of the predicted values (S_p)
- the intercept (a) and slope (b) of a simple regression of the form $P = a + b * O$. The closer a to 0 and b to 1 the better the prediction
- the coefficient of determination of that regression, describing to what extent the prediction accounted for variation of observed values (r^2)

Difference measures resulted partly from the above and included:

- mean bias error (MBE)
- mean absolute error (MAE)
- maximum absolute error (MAXAE)
- minimum absolute error (MINAE)
- root mean square error (RMSE)

All of these criteria are reported for the yield and yield components as well as for the dates of anthesis and physiological maturity, because matching of phenological stages is crucial for a valid run.

For the independent data sets, an "index of agreement" (d) was calculated according to the procedure of Willmot (1982). This calculation was only performed on yield data. All statistical computations were performed with the statistical package SAS (1982).

The second and much more extensive part of the results are graphics, showing the proximity of the time course of model output and experimental measurements. Unfortunately, most data sets provided no information available on the variance of published measurements. This would be of certain interest because observed values are not true values in a statistical sense, but are mean values of a very small sample with more or less large intrinsic error.

Results and Discussion

Descriptive Statistics. Descriptive statistics based on the values shown in Tables 6 and 7 are reported separately for the two groups of data sets. Tables 2 and 3 are summarized measures for the dates of anthesis and physiological maturity, yield, grain weight, grain numbers per m^2 (GPSM), ear numbers per m^2, above ground dry matter, and leaf area index (LAI). Observed and predicted means are listed to show the difference between them. Standard deviations of observed and predicted values are listed to be checked for similar ranges. The intercept and slope of the regression equation with O as an independent variable provides information about the accuracy of predictions. Tables 4 and 5 contain the difference measures for the same list of variables.

Phasic Development. The accuracy of simulating the phasic development of a crop is crucial for the accurate simulation of crop growth and yield. Therefore, this part of the simulation received considerable attention. Figures 2-7 show the scatter of predicted versus measured variables, including the 1:1 line $\pm$1 standard deviation and the matching regression.

Regression equations for anthesis and physiological maturity show an excellent fit with slopes close to 1 and high regression coefficients. Observed means are considerably different for the two groups of data sets, the independent data sets reading anthesis and maturity 12 and 19 days, respectively, later. This reflects the fact that the origin of this subset of the data base is relatively far north, where the wheat crop season is extended into the latter part of the year.

Difference measures in Tables 4 and 5 indicate small mean bias errors and mean absolute errors of five and seven days, respectively. The maximum errors for the two dates in the dependent subset occurred in the same run; therefore, the time available for grain filling was correct. When the date of anthesis was predicted too early, maturity came too early also.

Yield, Grain Weight, and Grain Numbers/m^2. The independent data set is characterized by a higher mean yield caused by higher grain weight and slightly bigger grain numbers. This confirms that the data sets came from different locations. High yields were mostly from northern wheat growing areas. However, observed and predicted mean yields are very close resulting in small mean bias errors. The mean absolute error is in the range of 22 percent of the observed mean yield and GPSM, but only 15 percent of the observed grain weight.

Figures 2-4 demonstrate the scatter of predicted versus measured data points around the regression line, the 1:1 line and within the limits of ±1 standard deviation of the observed mean. The percentage of data points outside of these limits is small as to the total number of observations. This demonstrates the model's reliability in simulating yield. Comparison of the regression to the 1:1 line proves the good fit, especially for the independent data sets. The regression coefficient, however, does not indicate a significant superiority of yield predictions over the rest of the data base (0.633 compared to 0.617).

It is interesting to note that measured and predicted mean yields within a subset did not differ nearly as much as between the two subsets.

Final Ear Number, Final Dry Matter, and Maximum LAI. Additional variables to be checked are final ear number, final dry matter, and maximum LAI observed during the growing season. Since the average experiment had about five measurements in the season, there is no guarantee that a measurement was taken at the peak of leaf area development. There are relatively few observations in total. Therefore, observed maximum LAI has to be considered with precaution.

Despite these restrictions, the mean bias error is not very large. The mean absolute errors, however, amount to 40% and 95% of the observed mean. Also, the regression coefficient is not very high (Figure 7). (Please refer to the section where predicted and observed LAI are compared over the course of time for particular experiments to demonstrate the model's capability to simulate the canopy development.)

Leaves comprise most of the total amount of above ground dry matter (Figure 6). Since final dry matter is highly correlated to yield, it must be accurately simulated. The model overpredicts dry matter (Table 4) by about 380 g/m^2, which is considerably less than 1 standard deviation (525.5 g/m^2). In the regression, the model accounts for 41.1 percent of the variation in the real world.

For the group of independent data, simulation of final ear number (Figure 5) resulted in a very small slope (0.1398) and corresponding coefficient of determination ($r^2 = 0.014$). The regression coefficient for the dependent data sets is 0.40 and thus is higher than for dry matter.

Difference Measures. While summary measures try to describe the quality of simulation, difference measures try to locate and quantify errors. Difference measures for the same variables as above are listed in Tables 4 and 5. The mean bias error (MBE) is regularly considerably smaller th the mean absolute error. The two values, being close, indicate the prediction to be biased in one direction, as is true for ear number and dry matter predictions with the independent sets.

A negative MBE occurs when predictions are smaller in value than observations. Considerable errors of this kind are found with GPSM, ear number, and dry matter predictions of the dependent data sets, and with grain weight and date of anthesis of the independent sets. For all others, predictions are larger than observed values.

Since the value of the MBE is related to the range of values, it is not reasonable to compare across variables. However, comparisons between the two groups of data sets might show the necessity of requiring independent data sets if it could be shown that the MBE and MAE of independent data were always larger. Unfortunately, while true for yield, it doesn't apply for all variables; maximum error in predicting yields is smaller in the independent set.

Willmott (1982) indicated that the closer the root mean square error (RMSE) to 0, the better the model. Certainly this applies to the systematic error. The unsystematic RMSE should approach RMSE in the system:

$$MSE = MSE_s + MSE_u$$

The tendency of $RMSE_s$ toward 0 is obvious, compared to RMSE. Since the mean is involved in the computation of this measure, comparisons across groups of data sets are not advisable.

The values of $RMSE_s$ and RMSE, computed to predict yields for the dependent data set, are very similar: 25377 and 25424, respectively. Thus, compared to $RMSE_u$ of 1552, the model meets the above requirement.

Willmott (1982) also suggests the computation of d, a quality measure for models, or index of agreement:

$$d = 1 - [\sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} (|P_i'| + |O_i'|)^2], \quad 0 \le d \le 1$$

$$\text{where } P_i' = P_i - \bar{O} \text{ and } O_i' = O_i - \bar{O}$$

For a good model, d should approach 1. For CERES-Wheat yield predictions, d equals 0.8825. This quality measure is mainly used to compare different models, but it provides additional useful information of model performance when used to evaluate a single model.

Measured and Model Estimates of Crop Growth. To ensure accuracy, any simulation of plant parts should be checked intensively against real world observations. The appendix contains comparisons between model output with all available experimental measurements. For some, real world data were obtained by digitizing graphs in publications, which adds uncertainty to the reliability of these data. These comparisons should be viewed with a critical mind. Figures in Appendix A are in the order of locations.

One problem with the data is that often only a few samples were taken during the growing season and for typical optimum curves like LAI or tiller number, the peak may be missing (see tiller number for Rutherglen, Australia). The experiment in Rutherglen is one of the few where root measurements were taken. It demonstrates good correspondence of compared data despite high variations in measurements and a slightly too high growth rate in the model run. Partitioning was correct for this particular experiment as shown through a large number of samplings of root, stem, and ear weight. One discrepancy is that stem weight measurements seem to include leaves or sheaths, whereas the graph of the simulation shows stem weight only.

Five, well-timed samples during the growing season demonstrated agreement with the tillering pattern at Murumbateman, Australia, in 1977. Biomass and LAI were simulated with high accuracy. The 1980 run at the same location did not perform quite as well, although the same variety was grown. Data from Wagga Wagga, Australia, 1981, also showed excellent fit.

The pattern of dry matter accumulation in response to different irrigation treatments was generally correctly simulated in Kibbutz Boker, Israel. The point of highest water stress is equally marked in the observations and the model simulations, although the differences between the two tend to increase toward the end of the growing period, causing the simulated LAI to increase too early and too much. Partitioning of assimilates to the ear, however, is very close to observations for those crops under late water stress.

An irrigation experiment in Roodeplaat, RSA, shows considerable differences between the modelled and observed LAI. Plots receiving higher amounts of water (Irr. 3 and 5) produced much denser canopies which could be simulated well. In the dryland run (Irr. 1), the modelled LAI was too high, and it developed too late.

In Ciudad Obregon, Mexico, another site where wheat is highly stressed by lack of water, the reverse effect was observed: LAI was generally underestimated, except for the plots experiencing the highest water stress where amount and timing were correct.

In Bushland, Texas (1981 and 1982), several different irrigation treatments for three varieties demonstrate excellent simulation of wheat growth and development with respect to dry matter, LAI, and tiller number. LAI shows the typical pattern for this area where wheat tillers vary greatly before winter due to warm fall temperatures, hence producing more coverage than further north where frosts usually kill many tillers and thus reduce leaf area. Therefore, these curves have two peaks. Some of the outliers in tiller number can be explained by the counting technique used, which includes every initiated tiller, even if not emerged yet.

An experiment in Temple, Texas, in 1984 focused on the influence of sowing density on plant growth and tillering under restricted water conditions. The biomass simulation was excellent. LAI was sometimes larger than observed due to some problems in measuring leaf area before the leaves were fully dried. The model maintained a higher tiller number than observed in low sowing densities, but did not simulate the peak in the highest sowing density (640 plants/m^2). One hundred sixty plants/m^2, a common population for the area, gave excellent results.

A comparison with a similar experiment in a location with very different soil water availability in Lelystad, Netherlands, reveals interesting facts. The polder area of the Netherlands is characterized by almost unlimited water availability. In the model, the simulated crop produced an extremely high number of tillers, but were drastically reduced about 180 days after emergence. In reality, this decline in tiller number is in the same range, but it occurs earlier with higher populations.

Other locations with the same climatic characteristics, like Flevoland and Wageningen, The Netherlands, demonstrate the excellent performance of CERES in cooler climates as well, though several runs suggested that it might perform better in the warm-to-subtropical climatic range. All of the biomass samples (5) taken at Flevoland in 1976, agree with the model's output. Biomass partitioning and LAI are represented by late season samples only, making profound comparison impossible, especially for LAI. Stem and ear weights agree reasonably well. Unusually high differences between simulated and measured leaf weights indicate a problem either with the definition of plant parts or units or something else.

The same phenomena occurs in an experiment conducted the following year with the same variety, Lely, grown in Wageningen, The Netherlands. All the other details of this run show an excellent fit, as well as those with the variety, Maris Hobbit. With both, LAI simulation agreed perfectly with reality, including the timing of development, which is of particular interest, because Maris Hobbit was used in a series of experiments in France focusing on phenology. The French series was conducted for four years, with five varieties, at three locations. The growth details showed good fit with the model, which is a profound test of the stability of the model's phenological predictions. This confirms how valuable experiment series are for model testing.

Phenological observations complete with detailed measurements were taken in a three-year (1975-1977) series of experiments in Nottingham, England. Root weight measurements were considerably less than what the model had partitioned to the root system. Since root measurements are very difficult to take and therefore highly erratic, the model's functions, which work well for other locations, were not adjusted. Total biomass and its fractions gave excellent agreement with measurements. However, leaf weight was severely over-estimated in 1975, and in 1977 the crop developed too early and too fast in the model.

The less recent data sets are from Rothamsted, England, 1960. The varieties Jufy and Atle are older, tall varieties; Capelle Desprey and Squarehead Master are new releases with a short culm. Therefore, only total dry matter and LAI could be compared, but with good results. The observed decrease in biomass at the end of the growing period does not appear in the simulations. The peak of LAI was generally underestimated, except for Atle.

The same tendency can be found in another highly productive crop in Weihenstephan, Germany, in a record year: 1983. For most of the growing season, coincidence between measured and modelled LAI prevailed, accompanied by excellent simulation of above-ground dry matter and tiller number.

Several test runs were conducted with data from the main U.S. wheat producing areas: the Midwest and the Pacific Northwest. Experiments in Kansas (at Manhattan and at Garden City) focused on nitrogen fertilization; the irrigation aspect can also be checked with the non-nitrogen version of the model. In the Manhattan 1982 runs, the model recognized no water deficit for the non-irrigated crop. Therefore, model output was identical with the field. Measurements of details of the irrigated plots were slightly higher in the model, but they did not exceed estimated measurement variations. General agreement and timing is acceptable. Measured stem and leaf weights decreased more rapidly towards the end of the season than what the model allowed. Total measured biomass is larger, however, suggesting that a fraction, probably senesced leaves, is lacking.

The 1981 Garden City experiment included two irrigation treatments; 1982 four. The results with the model are encouraging; dry matter was only slightly overestimated, but LAI and tiller development were on target. There were hardly any differences between irrigation treatments two to four of the 1982 experiment in the model as well as in reality. In the tillering pattern there was no difference at all.

The Sidney, Montana, series consists of two years of data for three varieties of Russian origin planted at two densities. The initial development of biomass was ahead in denser crops throughout winter and spring with the final results being identical. The model crop had 50%-80% more biomass, however, producing a much denser crop canopy than observed. The typical two-peak curve of leaf area development in the area with heavy winter-kill could not be checked, because observations started only in spring. Despite this lack of information, it is a very useful data set for testing the winter-kill and cold-hardiness routines of the CERES model.

The test runs for Lind, Washington, 1977, with two crop densities, produced a very unusual pattern of leaf area development. Despite double the initial population, the course of tiller development in the model was almost identical to the low density crop where final tiller number coincided with measurements. The high density crop produced a considerably higher number of tillers than simulated. Since few late measurements were taken, validation of the LAI component is difficult. It seems the model was overestimating LAI at this location, as winter temperatures killed most of the leaf cover.

Similar results, although less pronounced, were found for Pullman, Washington. With the 1973 data, CERES' simulations coincided perfectly with observations for early and late sowing; for 1974 the simulation was good only for the late sowing data. There is some confusion, though, with the data, as observed LAI and dry matter of the early sowing were unusually high.

The Experiment Station at Pendleton, Oregon, furnished valuable data from diverse experiments. Detailed measurements from 1977 allowed us to check the correct simulation for different plant parts. For unknown reason, however, ear weight was far below the field-observations. Leaf area was simulated to be twice as high as reality. The tiller number comparison is impressive, although it is not certain that plotted tiller counts represent the peak of tillering. The final increase in tiller number is a very unusual phenomena.

Biomass weights from a 1980 experiment in Pendleton and Weston (Oregon) with two sowing dates and three sowing densities, though few, confirm the accuracy of simulation. This was reinforced by the 1981 Pendleton run. The differences between the modelled and measured values are acceptable.

The CERES model, developed from a soil water balance subroutine, had been tested and validated. Thus, few tests were done with soil water measurements.

Figure 2. Predicted Versus Measured Yield.

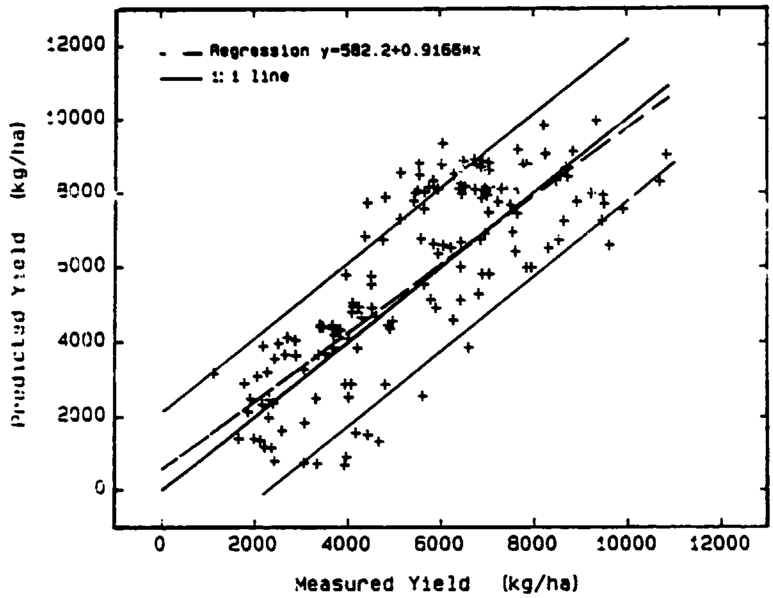


Figure 3. Predicted Versus Measured Grain Weight.

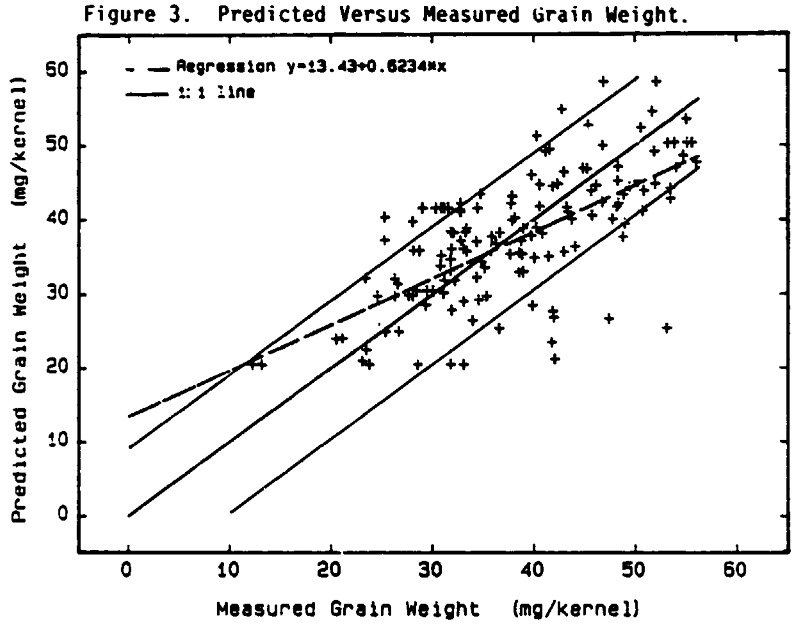


Figure 4. Predicted Versus Measured Number of Grains.

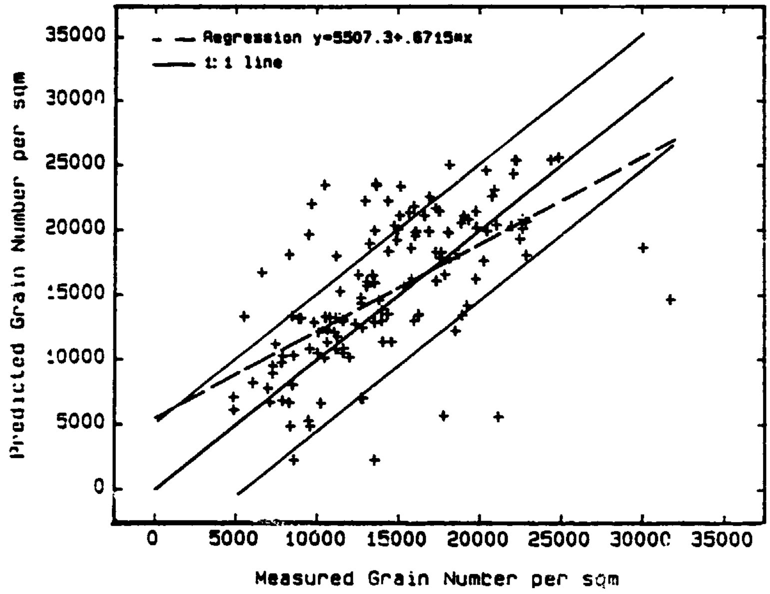


Figure 5. Predicted Versus Measured Number of Ears.

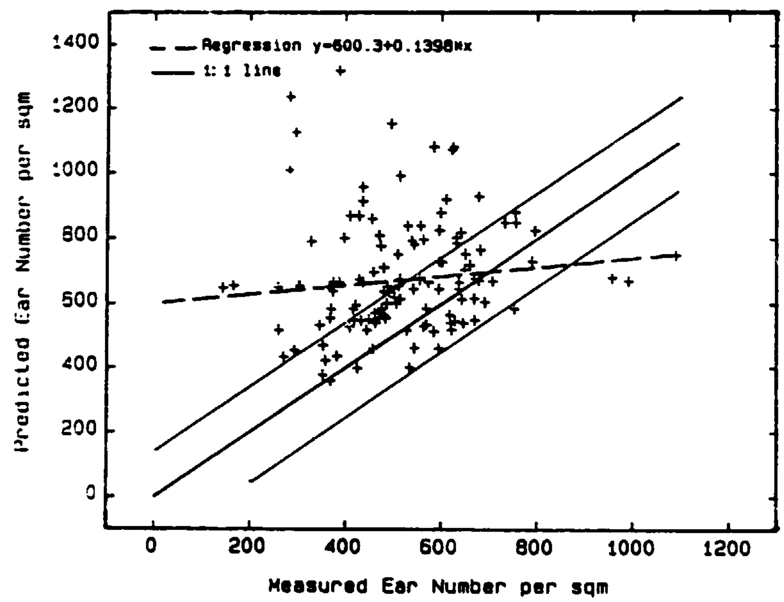


Figure 6. Predicted Versus Measured Above Ground Dry Matter.

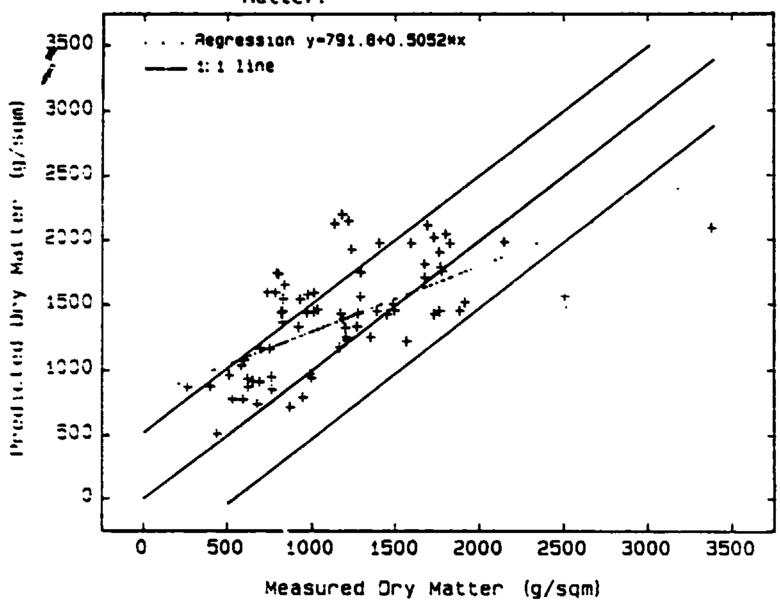


Figure 7. Predicted Versus Measured Leaf Area Index.

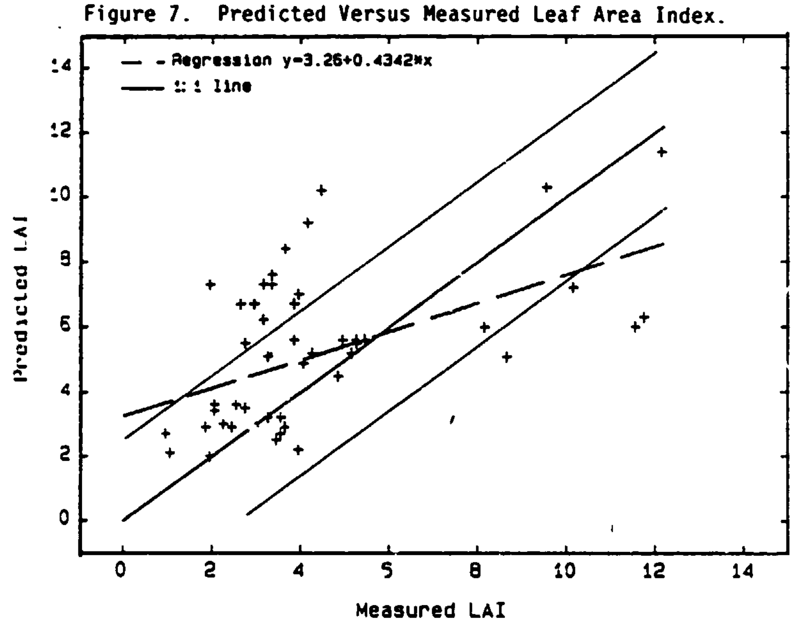


Table 2. Summary Measures for Independent Data Sets.

Variable	Unit	n	O	P	S_o	S_p	P = a + b*O a	P = a + b*O b	Reg Coeff
Anthesis	days	82	144.6	144.2	30.3	28.4	14.6	0.8960	.912
Phys Mat	days	76	176.0	176.6	28.4	28.5	4.7	0.9763	.947
Yield	kg/ha	157	5547.0	5646.8	2219.0	2578.2	582.2	0.9166	.633
Grain Wt	mg/kernel	144	38.3	36.4	9.3	9.4	13.4	0.6234	.448
GPSM	#	138	14594.6	15161.2	5115.2	5811.9	5507.3	0.6715	.376
Ear #	#	122	524.0	648.7	152.9	190.2	600.3	0.1398	.014
Dry Matter	g/m^2	76	1179.2	1559.1	525.5	412.2	791.8	0.5052	.411
LAI	--	54	4.4	5.2	2.6	1.6	3.3	0.4342	.260

Table 3. Summary Measures for Dependent Data Sets.

Variable	Unit	n	Meas Mean	Pred Mean	S_m	S_p	P = a + b*O a	P = a + b*O b	Reg Coeff
Anthesis	days	113	132.9	135.7	62.1	62.8	2.46	1.0021	.9834
Phys Mat	days	111	157.2	151.9	50.3	54.0	1.56	0.9735	.9416
Yield	kg/ha	130	4359.6	4376.0	1892.7	1892.9	950.7	0.7857	.6171
Grain Wt	mg/kernel	91	31.9	33.1	6.2	8.4	8.3	0.7598	.3467
GPSM	#	91	13837.9	1301[illegible].8	4144.3	4477.1	5705.8	0.5596	.3167
Ears	#	77	558.2	527.3	192.2	270.1	185.3	0.7818	.3998
Dry Matter	g/m^2	85	1396.4	1359.6	529.9	418.4	1033.1	0.3296	.33[illegible]5
LAI	--	37	4.0	4.9	1.9	2.4	8.26	-0.2957	.0395

Table 4. Difference Measures for Independent Data Sets.

Variable	Unit	n	MBE	MAE	Max Error	Min Error	$RMSE_u$
Anthesis	days	82	-0.4	5.67	32.0	0.	8.5
Phys Mat	days	76	0.6	5.1	18.0	0.	6.6
Yield	kg/ha	157	99.8	1272.8	3468.0	6.	1552.0
Grain Wt	mg/kernel	144	-1.9	5.8	28.4	0.	6.5
GPSM	#/m^2	138	566.6	3444.1	17446.0	17.	4437.5
Ear #	#/m^2	122	124.7	196.0	938.0	1.	179.6
Dry Matter	g/m^2	76	379.9	352.0	1324.0	2.	320.0
LAI	--	54	0.8	1.8	5.7	0.	1.9

Table 5. Difference Measures for Dependent Data Sets.

Variable	Unit	n	MBE	MAE	Max Error	Min Error	$RMSE_u$
Anthesis	days	113	2.8	6.8	24.0	0.	8.1
Phys Mat	days	111	-5.4	7.7	24.0	0.	12.2
Yield	kg/ha	[illegible]	16.4	948.3	4066.0	19.	1175.8
Grain Wt	mg/kernel	91	1.2	5.1	22.2	0.1	6.5
GPSM	#/m^2	91	-821.1	2907.1	11059.0	72.	3425.6
Ears	#/m^2	77	-30.9	150.4	563.0	1.	185.3
Dry Matter	g/m^2	85	-36.8	354.0	1314.0	1.	247.8
LAI	--	37	0.9	3.8	9.6	0.	2.8

Table 6. Listing of Final Results of Independent Data Sets.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
1700.	1319.	23.3	20.5	7205.	6430.	275.	422.	1.1	2.0	448.	486.
3575.	3600.	32.0	34.2	11281.	10521.	357.	365.	4.0	2.1	775.	826.
2110.	2994.	26.5	31.6	7945.	9479.	373.	348.	2.0	1.9	543.	752.
1826.	2803.	29.0	35.4	6169.	7914.	298.	443.	0.0	2.8	409.	850.
1180.	3068.	20.7	23.5	5636.	13056.	0.	463.	1.0	2.6	275.	845.
2933.	3550.	29.6	28.1	9946.	12623.	0.	513.	3.0	2.8	662.	891.
2564.	3879.	28.7	30.0	8995.	12935.	0.	461.	1.9	2.8	523.	935.
2484.	3464.	31.1	34.7	8017.	9989.	0.	402.	3.5	2.4	635.	845.
2239.	3799.	24.8	29.3	9145.	12945.	0.	517.	2.3	2.9	595.	1010.
3424.	3578.	26.5	29.3	12945.	12225.	0.	473.	3.6	2.6	999.	945.
2760.	4031.	23.6	31.7	11726.	12710.	0.	530.	2.8	3.4	611.	1053.
2330.	3111.	26.8	30.9	8689	10052.	0.	414.	3.7	2.8	631.	908.
6960.	8762.	0.0	43.3	0.	20219.	518.	604.	0.0	5.5	0.	1892.
5470.	7679.	0.0	44.7	0.	17165.	480.	575.	0.0	5.2	0.	1690.
6540.	8755.	0.0	41.8	0.	20945.	0.	567.	0.0	5.6	0.	1945.
6340.	8404.	48.6	41.7	0.	20138.	0.	609.	0.0	5.2	0.	1920.
5620.	6660.	48.0	39.6	0.	16788.	485.	554.	0.0	4.7	0.	1505.
7080.	7369.	51.0	40.7	0.	18094.	425.	585.	0.0	4.7	0.	1568.
6990.	7966.	0.0	44.2	0.	18023.	623.	530.	0.0	4.5	0.	1678.
5810.	8054.	38.4	39.8	0.	20227.	474.	564.	0.0	4.8	0.	1756.
6500.	7872.	36.1	37.3	0.	21128.	646.	603.	0.0	5.4	0.	1799.
8300.	8969.	53.7	43.7	0.	20533.	467.	530.	0.0	5.4	0.	1932.
7810.	8042.	49.0	37.2	16138.	21597.	492.	642.	0.0	5.6	0.	1980.
8690.	7132.	44.3	35.9	19918.	19882.	574.	575.	0.0	5.0	0.	1743.
10760.	8203.	48.4	41.3	22784.	19862.	640	655.	0.0	6.1	0.	1988.
10900.	8930.	52.2	44.3	21164.	20157.	674.	539.	0.0	5.4	0.	1904.
9560.	7600.	54.3	46.5	17970.	16344.	599.	450.	0.0	3.8	0.	1526.
9540.	7836.	42.1	44.0	23004.	17818.	695.	595.	0.0	5.7	0.	1791.
9510.	7144.	48.5	44.7	19880.	15994.	568.	520.	0.0	4.7	0.	1642.
9960.	7455.	49.1	42.9	20376.	17384.	532.	508.	0.0	4.4	0.	1479.
9280.	7879.	40.8	41.3	22616.	19079.	574.	525.	0.0	5.6	0.	1856.
3361.	2403.	.0	20.0	0.	12017.	264.	507.	[illegible]	2.8	773.	922.
4213.	1476.	.0	20.0	0.	7381.	484.	626.	3.2	6.1	1576.	1197.
4474.	1427.	.0	20.0	0.	7136.	515.	645.	4.2	9.1	1497.	1478.
4712.	1244.	.0	20.0	0.	6222.	711.	659.	9.6	10.2	2518.	1541.
0.	1170.	.0	20.0	0.	5851.	374.	574.	2.1	3.3	955.	860.
3102.	659.	.0	20.0	0.	3296.	560.	664.	4.0	6.9	1178.	1151.
3391.	637.	.0	20.0	0.	3186.	960.	670.	4.5	10.1	1505.	1434.
3972.	595.	.0	20.0	0.	2975.	995.	660.	12.2	11.3	1922.	1494
3116.	1745.	32.1	37.8	9707.	4620.	0.	593.	3.3	3.1	1008.	913.
4561.	4822.	32.3	37.8	14121.	12768.	0.	620.	3.6	3.1	1285.	1406.
2633.	1538.	31.0	33.3	8494.	4620.	0.	593.	3.3	3.1	957.	768.
5945.	4822.	36.9	37.8	16111.	12768.	0.	620.	3.6	3.1	1184.	1406.
3102.	3181.	26.9	24.5	11532.	12979.	0	802.	2.6	3.5	1217.	1203
4145.	4853.	21.3	23.6	19460.	20576.	0.	902.	3.9	6.4	1303.	1723.
2277.	1104.	23.7	22.0	9608.	5028.	0.	794.	2.1	3.5	687.	713.

Table 6. Continued.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
5833.	5043.	25.6	24.5	22785.	20576.	0.	902.	3.9	6.6	1771.	1881.
2477.	704.	28.4	35.4	8721.	1990.	0.	726.	2.8	5.4	606.	751.
3752.	4095.	25.5	36.8	14713.	11119.	0.	826.	5.3	5.5	838.	1342.
4124.	2778.	31.8	41.1	12968.	6761.	0.	726.	5.3	5.4	762.	1136.
4009.	818.	29.3	41.1	13682.	1990.	0.	726.	5.3	5.4	700.	884.
4550.	5456.	31.4	41.1	14490.	13277.	0.	826.	5.3	5.5	796.	1569.
4337.	4569.	30.6	41.1	14173.	11119.	0.	826.	5.3	5.5	838.	1426.
3991.	2778.	31.1	41.1	12832.	6761.	0.	726.	5.3	5.4	706.	1139.
5689.	5456.	34.7	41.1	16394.	13277.	0.	826.	3.9	5.5	746.	1569.
8967.	7662.	47.1	58.1	19042.	13197.	422.	540.	.0	4.6	0.	1772.
8351.	6406.	43.2	45.9	19350.	13951.	386.	425.	.0	4.6	0.	1740.
7694.	7333.	25.5	39.9	30197.	18381.	466.	561.	.0	4.6	0.	1766.
4950.	4267.	38.0	41.7	11720.	10228.	0.	267.	.0	3.8	0.	1345.
2920.	3963.	35.0	43.0	7390.	9226.	0.	279.	.0	3.7	0.	1255.
3720.	4267.	33.0	41.7	10180.	10228.	0.	267.	.0	3.8	0.	1292.
3830.	4219.	32.0	38.0	10760.	11110.	0.	277.	.0	3.4	0.	1243.
5650.	2461.	53.3	24.9	10600.	9871.	0.	518.	0.0	5.5	1212.	1298.
6640.	3761.	47.6	26.2	13950.	14356.	0.	505.	0.0	5.8	1198.	1368.
5500.	7899.	43.0	54.4	12825.	14514.	475.	546.	10.2	7.1	1233.	2121.
6100.	9232.	44.0	39.6	13775.	23342.	475.	798.	11.6	5.9	1195.	2173.
5900.	8231.	40.0	45.5	14520.	18102.	440.	903.	8.2	5.9	1151.	2100.
4062.	2428.	42.0	23.0	9672.	10578.	372.	545.	3.7	8.3	851.	1628.
4072.	4009.	42.3	20.7	9628.	19395.	332.	779.	3.4	7.2	802.	1720.
4250.	3750.	36.8	24.9	11550.	15041.	350.	523.	3.2	7.2	814.	1711.
6794.	7991.	33.0	40.6	20587.	19686.	673.	606.	0.0	6.1	2158.	1958.
6922.	8599.	40.5	38.5	17091.	22330.	794.	720.	0.0	6.1	1[illegible]40.	1994.
7050.	7834.	43.6	40.6	16170.	19292.	652.	694.	0.0	6.1	1834.	1948.
4865.	7783.	28.3	39.3	15106.	19811.	506.	609.	11.8	6.2	1415.	1951.
6000.	7996.	32.9	40.9	18215.	19539.	600.	720.	0.0	6.1	1602.	1950.
7886.	5886.	35.6	29.3	22102.	20070.	682.	661.	0.0	4.7	1891.	1428.
7088.	5722.	38.8	32.5	18270.	17605.	599.	635.	0.0	4.7	1739.	1405.
6930.	5722.	39.2	32.5	17661.	17605.	546.	635.	0.0	4.7	1460.	1405.
7991.	5890.	34.8	28.8	22995.	[illegible]422.	640.	635.	0.0	4.7	1772.	1428.
6570.	8067.	46.0	40.1	14900	20098.	429.	387.	4.3	5.1	1682.	1789.
7590.	6835.	50.8	51.9	164[illegible]	13167.	462.	450.	5.2	5.1	1683.	1685.
8580.	6619.	42.1	27.2	20552.	24340.	538.	390.	0.0	5.4	1787.	1737.
8260.	9731.	41.4	48.7	19970.	20000.	635.	775.	0.0	5.7	1810.	2020.
9390.	9857.	56.3	47.2	16775.	20880.	510.	591.	5.0	5.5	1700.	2088.
4480.	7535.	52.3	58.1	8619.	13140.	650.	530.	3.3	5.0	940.	1516.
6310.	4492.	53.7	42.3	11761.	10611.	420.	574.	0.0	5.5	980.	1417.
74[illegible]0.	8147.	49.2	39.0	15229.	20880.	490.	591.	0.0	5.5	1250.	1901.
7090.	8702.	38.8	35.1	18277.	24773.	518.	981.	0.0	7.8	0.	2320.
5560.	7963.	40.3	34.4	13810.	23163.	440.	946.	0.0	7.4	0.	2037.
6810.	8661.	49.7	43.9	13696.	19716.	391.	1308.	0.0	7.5	0.	2298.
5710.	7925.	50.5	44.6	11313.	17762.	288.	1226.	0.0	7.4	0.	2038.
6440.	8008.	33.6	38.4	19163.	20878.	645.	808.	0.0	6.7	0.	2042.
6930.	7758.	41.8	[illegible]9.0	17431.	15844.	635.	792.	0.0	7.0	0.	2009.

Table 6. Continued.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
5920.	8049.	33.5	37.9	17668.	21242.	568.	786.	0.0	6.0	0.	1953.
5180.	7200.	40.8	44.2	12669.	16284.	543.	782.	0.0	5.9	0.	1874.
8740.	8594.	35.1	33.9	24979.	25341.	760.	838.	0.0	6.7	0.	2159.
7720.	7995.	34.6	31.8	22304.	25158.	562.	828.	0.0	5.9	0.	2020.
6460.	5027.	28.8	20.0	22405.	25111.	737.	838.	0.0	6.7	0.	1757.
5010.	4474.	24.0	20.0	20905.	22371.	534.	828.	0.0	5.9	0.	1626.
7910.	8671.	46.4	44.1	17039.	19667.	629.	1071.	0.0	6.3	0.	2117.
6850.	5190.	42.2	26.4	16241.	19665.	589.	1071.	0.0	6.3	0.	1758.
5191.	8448.	39.2	38.4	13100.	21999.	413.	858.	0.0	6.0	0.	2082.
5590.	8700.	38.1	39.5	14502.	21999.	433.	858.	0.0	6.0	0.	2107.
8890.	9021.	40.0	37.4	22225.	24093.	759.	870.	0.0	6.6	0.	2190.
8290.	8935.	52.1	48.7	15911.	18362.	499.	1143.	0.0	6.3	0.	2148.
8630.	8418.	48.5	46.6	17794.	18050.	603.	868.	0.0	6.9	0.	2143.
8530.	8221.	47.0	41.9	18149.	19630.	626.	1062.	0.0	6.6	0.	2111.
7546.	7559.	43.2	35.2	17467.	21452.	683.	918.	0.0	6.7	0	2017.
6992.	6804.	51.1	43.4	13677.	15687.	614.	909.	0.0	6.8	0.	1968.
4810.	6632.	33.3	28.6	10589.	23223.	460.	849.	0.0	6.1	0.	1843.
4550.	5667.	34.2	26.0	9792.	21760.	401.	790.	0.0	5.1	0.	1503.
4420.	6725.	41.1	37.7	8423.	17862.	300.	1115.	0.0	5.9	0.	1833.
4010.	5697.	41.7	34.6	6715.	16453.	288.	997.	0.0	4.8	0.	1458.
5600.	8381.	36.5	36.3	15263.	23117.	478.	766.	0.0	5.4	0.	1877.
5700.	7463.	36.0	35.4	15814.	21108.	548.	772.	0.0	5.1	0.	1724.
6780.	8795.	45.1	46.4	15013.	18961.	391.	655.	0.0	6.6	0.	2066.
6080.	8665.	45.5	46.3	13367.	18701.	377.	628.	0.0	5.1	0.	1770.
7710.	9064.	38.1	42.7	19922.	21208.	686.	755.	0.0	6.6	0.	2079.
7830.	8657.	38.1	42.6	18976.	20311.	606.	718.	0.0	5.1	0.	1794.
7090.	8495.	45.6	52.2	13553.	16260.	513.	740.	0.0	6.7	0.	2048.
6480.	8148.	40.5	50.8	15980.	16034.	664.	708.	0.0	5.1	0.	1744.
7360.	7999.	42.6	44.3	17446.	18067.	494.	628.	0.0	5.2	0.	1674.
7010.	8058.	43.5	41.2	16168.	19571.	463.	686.	0.0	4.7	0.	1599.
7280.	7652.	47.0	49.5	15479.	15459.	484.	701.	0.0	5.1	0.	1626.
4910.	4356.	39.0	36.7	11190.	11880.	0.	326.	0.0	4.4	0.	1440.
4130.	4706.	33.0	40.8	11350.	11535.	0.	286.	0.0	3.5	0.	1363.
3730.	4356.	33.0	36.7	10210.	11880.	0.	326.	0.0	4.4	0.	1409.
2710.	3574.	32.0	32.7	7570.	10946.	0.	295.	0.0	4.3	0.	1262.
1950.	2386.	39.1	34.9	4987.	6839.	148.	638.	0.0	3.5	0.	887.
1900.	2042.	37.9	34.9	5015.	5854.	170.	644.	0.0	3.6	0.	892.
2372.	2366.	32.1	27.4	7390.	8637.	263.	639.	0.0	3.5	0.	892.
2217.	2234.	31.3	29.7	7084.	7518.	308.	643.	0.0	3.6	0.	896.
2450.	2281.	28.3	29.4	8641.	7766.	370.	642.	0.0	3.4	0.	890.
2352.	1885.	27.9	29.4	8433.	6417.	499.	640.	0.0	3.8	0.	889.
3455.	4304.	32.1	35.6	10763.	12088.	379.	655.	0.0	4.0	829.	1414.
3460.	4378.	33.3	35.6	10651.	12297.	433.	664.	0.0	4.7	842.	1520.
4277.	4848.	32.4	31.4	13200.	15451.	440.	656.	0.0	4.0	1044.	1439.
4147.	4953.	31.4	31.4	13209.	15786.	518.	667.	0.0	4.9	1024.	1566.
3888.	4228.	30.3	30.0	12831.	14109.	578.	656.	0.0	4.0	1022.	1421.
3520.	4320.	29.7	30.0	31862.	14416.	674.	667.	0.0	4.9	986.	1553.

Table 6. Continued.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
4850.	2772.	40.1	28.0	12125.	9900.	548.	452.	0.0	2.2	883.	693.
2172.	1278.	32.0	20.0	10353.	6388.	1094.	740.	2.0	7.2	1279.	1309.
2032.	1316.	33.3	20.0	8008.	6579.	654.	742.	3.4	7.5	931.	1305.
3738.	3763.	0.0	20.0	0.	18813.	621.	555.	5.5	5.5	1300.	1537.
4642.	4597.	0.0	20.0	0.	22985.	625.	509.	4.1	4.8	1400.	1426.
8778.	8339.	35.4	33.1	24520.	25161.	757.	575.	8.7	5.0	3389.	2065.
7109.	8063.	33.6	35.3	21038.	22866.	589.	504.	4.9	4.4	1778.	1766.
2420.	1070.	13.4	20.0	21270.	5351.	600.	814.	3.0	6.6	1361.	1228.
2250.	1087.	12.5	20.0	17900.	5436.	800.	814.	2.7	6.6	1215.	1227.
7649.	6315.	55.9	49.9	13683.	12662.	449.	508.	0.0	4.0	0.	1605.
6104.	6483.	54.1	49.9	11277.	12999.	467.	542.	0.0	5.1	0.	1761.
5897.	6523.	55.4	49.9	10648.	13078.	488.	545.	0.0	5.5	0.	1814
6900.	6639.	55.3	53.1	12485.	12502.	357.	459.	0.0	3.7	0.	1462.
6259.	6414.	53.4	49.8	11718.	12879.	413.	518.	0.0	4.4	0.	1545.
5992.	6265.	55.0	48.1	10905.	13024.	454.	541.	0.0	4.7	0.	1596.
6466.	5912.	45.9	43.4	14102.	13615.	362.	411.	0.0	4.4	0.	1530.
6472.	6564.	34.6	36.6	18835.	17939.	437.	537.	0.0	4.4	0.	1544.
9665.	6485.	51.9	54.1	18622.	11993.	632.	536.	0.0	5.0	0.	1781.

Table 7. Listing of Final Results of Dependent Data Sets.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
4825.	7843.	45.4	64.5	10670.	12164.	485.	465.	7.7	6.1	1500.	1914.
2320.	3002.	37.0	40.3	5867.	7442.	402.	546.	7.9	7.1	1250.	1847.
4070.	4800.	43.2	45.5	9325.	10543.	374.	400.	5.1	4.0	1135.	1382.
2710.	3585.	32.3	36.4	8175.	9859.	415.	499.	4.8	5.0	1050.	1521.
6450.	6469.	0.0	32.2	0.	20064.	0.	701.	4.0	5.3	1252.	1725.
3400.	3594.	0.0	20.8	0.	17263.	0.	689.	0.0	6.5	0.	1543.
5030.	7961.	0.0	39.1	0.	20379.	413.	733.	0.0	5.3	0.	1909
2820.	5058.	40.3	38.3	6997.	13220.	118.	155.	0.0	1.6	707.	884.
6440.	7065.	41.7	39.2	15443.	18020.	272.	264.	0.0	3.2	1531.	1331
7200.	7574.	44.6	39.9	16143.	18996.	322.	311	0.0	4.0	1647.	1480.
8430.	7893.	44.1	40.4	19115.	19534.	430.	359.	0.0	4.7	1968.	1616.
8340.	8065.	42.3	40.8	19716.	19788.	490.	383.	0.0	5.2	2024.	1753.
8480.	8078.	41.0	40.8	20683.	19809.	582.	400.	0.0	5.2	2181.	1814.
8900.	8180.	39.0	41.1	22820.	19898.	777.	800.	0.0	5.7	2376.	1870.
4440.	3125.	38.2	25.6	11642.	12227.	433.	564.	4.0	4.8	1094.	1196.
2580.	2349.	35.5	25.9	7319.	9060.	308.	587.	2.2	5.0	717.	1107.
3350.	1752.	21.3	20.0	15830.	8761.	581.	577.	4.9	4.9	1115.	1093.
4344.	4707.	34.0	39.1	12800.	12053.	466.	374.	6.5	5.0	1492.	1545.
8711.	6876.	44.0	43.2	19934.	15906.	511.	728.	0.0	5.6	0.	1692.
3537.	1992.	24.0	20.0	14738.	9960.	391.	714.	0.0	4.8	0.	1096.
2508.	1368.	20.6	20.0	12175.	6840.	372.	680.	0.0	5.2	0.	980.
3009.	1654.	23.0	20.0	10260.	8271.	510.	711.	0.0	5.3	0.	1112.
3414.	1470.	33.7	55.9	9987.	2629.	304.	549.	0.0	4.0	0.	732.
3800.	5516.	23.4	36.7	16239.	15043.	0.	829.	3.6	4.2	1657.	1396.
3823.	5516.	23.1	36.7	16549.	15243.	0.	829.	3.6	4.2	1716.	1396
2372.	3099.	20.4	28.7	11627.	10804.	220.	629.	0.0	4.3	979.	1095.
4098.	3983.	31.7	27.7	12927.	14379.	716.	961.	4.6	5.9	1211.	1490.
4012.	3451.	33	35.4	12012.	9754.	1069.	1022.	0.0	5.4	1124.	1332.
4381.	6233.	35.0	35.4	12517.	17615.	1098.	982.	0.0	6.3	1329.	1835.
5400.	6403.	31.5	31.8	17142.	20128.	0.	942.	6.1	3.8	1215.	1502.
5440.	6784.	29.6	33.7	18378.	20128.	0.	942.	5.3	3.8	1312.	1599.
5948.	6784.	30.1	33.7	19760.	20128.	0.	942.	5.3	3.8	1308.	1599.
5353.	6784.	28.2	33.7	18982.	20128.	0.	942.	6.1	3.8	1304.	1599.
4417.	4332.	27.6	32.3	16026.	13427.	706.	616.	3.4	11.0	2449.	1894.
3387.	4323.	25.5	32.3	13278.	13399.	635.	614.	2.5	7.8	1474.	1607.
4749.	4110.	30.3	30.9	15672.	13297.	777.	624.	1.4	5.7	2067.	1394.
3789.	3652.	23.4	27.3	16216.	13383.	819.	713.	3.1	12.7	1393.	1976.
3134.	3651.	22.9	27.3	10804.	13378.	507.	713.	4.4	10.1	2628.	1740.
4208.	3644.	26.7	27.3	14992.	13352.	705.	712.	3.7	7.8	1950.	1508.
4057.	4497.	26.2	32.3	15382.	13931.	836.	750.	2.3	11.4	1953.	1900.
4138.	4489.	30.0	32.3	13788.	13906.	743.	749.	3.0	8.0	2373.	1643.
4746.	4499.	29.4	32.5	16139.	13840.	777.	734.	4.5	6.1	1621.	1433.
3825.	3885.	31.3	35.0	12224.	11114.	640.	520.	3.1	12.5	2818.	1940.
2625.	3883.	33.8	35.0	7765.	11108.	472.	520.	2.4	9.3	1696.	1672.
3407.	3889.	32.7	35.3	10414.	11027.	556.	514.	3.7	7.3	1784.	1475.
4201.	4656.	36.4	44.7	11637.	10412.	619.	510.	1.6	10.8	2264.	1882.

Table 7. Continued.

YIELD O	YIELD P	GRAIN WT. O	GRAIN WT. P	GRAINS/SQM O	GRAINS/SQM P	EARS/SQM O	EARS/SQM P	MAX. LAI O	MAX. LAI P	DRY MATTER O	DRY MATTER P
3236.	4452.	41.6	42.8	8250.	10408.	438.	522.	1.4	7.8	1312.	1617.
3602.	4388.	42.4	42.8	8493.	10259.	443.	517.	1.2	5.2	0.	1366.
5529.	5282.	32.2	37.8	17270.	13975.	642.	510.	8.8	11.1	3245.	1931.
3793.	5274.	33.0	37.8	11493.	13953.	536.	510.	2.8	8.2	1662.	1663.
4397.	5005.	33.9	36.2	22609.	13834.	530.	518.	2.9	5 7	1019.	1436.
4399.	4506.	29.7	30.5	14794.	15118.	804.	546.	4.8	12.0	1883.	1949.
3783.	4370.	28.9	29.1	13090.	15029.	605.	539.	2.3	9.0	1827.	1691.
3655.	4184.	31.3	29.1	11637.	14389.	531.	532.	2.0	6.0	990.	1432.
4992.	5741.	37.4	41.1	13349.	13969.	383.	290.	0.0	5.1	1510.	1612.
3552.	5741.	29.3	41.1	12124.	13969	348.	290.	0.0	5.1	1420.	1556
6556.	5741.	43.2	41.1	15176.	13969.	364.	290.	0.0	5.1	1650.	1612.
5436.	5741.	37.9	41.1	14344.	13969.	350.	290.	0.0	5.1	1300.	1612.
2676.	4418.	22.5	31.6	11893.	13969.	361.	290.	0.0	5.1	1100.	1397.
4709.	5741.	36.7	41.1	12831.	13969.	330.	290.	0.0	5.1	1690.	1593.
4437.	5278.	31.9	34.7	13908.	15229.	506.	321.	0.0	5.4	1140.	1645.
4386.	5278.	27.4	34.7	16007.	15228.	484.	321.	0.0	5.4	620.	1594.
5427.	5278.	32.3	34.7	16853.	15229.	511.	321.	0.0	5.4	640.	1645.
4862.	5278.	31.1	34.7	15633.	15229.	492.	321.	0.0	5.4	710.	1645.
2682.	3982.	20.3	26.1	13210.	15228.	499.	321.	0.0	5.4	620.	1404.
4354.	5278.	30.8	34.7	14137.	15228.	462.	321.	0.0	5.4	560.	1608.
9108.	6917.	0.0	41.9	0.	16546.	0.	300.	0.0	4.2	0.	1562.
5389.	6720.	0.0	40.6	0.	16566.	0.	303.	0.0	4.2	0.	1543.
6232.	7279.	0.0	44.0	0.	16556.	0.	301.	0.0	4.2	0.	1602.
8777.	7286.	0.0	44.0	0.	16573.	0.	304.	0.0	4.2	0.	1610.
3471.	1810.	0.0	20.0	0.	9048.	0.	265.	0.0	3.9	0.	937.
4893.	4418.	0.0	30.6	0.	14417.	0.	278.	0.0	4.1	0.	1281.
6100:	5077.	0.0	33.5	0.	15176.	0.	267.	0.0	4.0	0.	1348.
9158.	5092.	0.0	33.5	0.	15219.	0.	272.	0.0	4.0	0.	1379.
2810.	2682.	0.0	31.3	0.	8580.	0.	201.	0.0	2.9	0.	806.
5438.	3641.	0.0	33.9	0.	10756.	0.	207.	0.0	3.0	0.	941.
1389.	1595.	0.0	20.0	0.	7977.	0.	202.	0.0	2.9	0.	681.
2281.	3483.	0.0	33.9	0.	10290.	0.	183.	0.0	2.7	0.	862.
2281.	2043.	0.0	30.2	0.	6760.	0.	133.	0.0	1.7	0.	550.
1422.	1713.	0.0	25.1	0.	6829.	0.	139.	0.0	1.7	0.	525.
1488.	1786.	0.0	28.9	0.	6179.	0.	118.	0.0	1.4	0.	481.
17.	316.	0.0	26.9	0.	1176.	0.	85.	0.0	0.5	0.	110.
149.	332.	0.0	26.9	0.	1237.	0.	92.	0.0	0.5	0.	116.
149.	273.	0.0	26.9	0.	1016.	0.	68.	0.0	0.4	0.	93.
364.	281.	0.0	26.9	0.	1046.	0.	71.	0.0	0.4	0.	96.
4774.	5818.	0.0	45.4	0.	12828.	0.	194.	0.0	2.5	0.	1099.
4695.	5978.	0.0	45.5	0.	13148.	0.	208.	0.0	2.7	0.	1143.
4496.	6162.	0.0	45.6	0.	13512.	0.	229.	0.0	2.9	0.	1198.
8133.	6503.	0.0	49.2	0.	13231.	0.	268.	0.0	4.0	0.	1467.
8926.	6483.	0.0	49.1	0.	13191.	0.	263.	0.0	3.9	0.	1447.
7124.	6499.	0.0	49.1	0.	13223.	0.	266.	0.0	4.0	0.	1460.
3885.	6584.	0.0	45.4	0.	14487.	0.	269.	0.0	4.0	0.	1504.
6893.	6635.	0.0	45.4	0.	14601.	0.	270.	0.0	4.3	0.	1602.

Table 7. Continued.

YIELD		GRAIN WT.		GRAINS/SQM		EARS/SQM		MAX. LAI		DRY MATTER	
O	P	O	P	O	P	O	P	O	P	O	P
3736.	6589.	0.0	45.4	0.	14498.	0.	270.	0.0	4.0	0.	1511.
2992.	3223.	0.0	20.6	0.	15645.	0.	318.	0.0	4.6	0.	1307
6348.	6188.	0.0	36.6	0.	16906.	0.	318.	0.0	4 6	0.	1624.
5058.	5444.	0.0	32.5	0.	16733.	0.	318.	0.0	4.6	0.	1544.
4853.	3224.	0.0	20.6	0.	15649.	0.	319.	0.0	4.6	0.	1310.
3091.	1470.	0.0	20.0	0.	7350.	0.	285.	0.0	4.8	0.	949.
7108.	4254.	0.0	37.0	0.	11493.	0.	283.	0.0	4.9	0.	1276.
3554.	3391.	0.0	29.9	0.	11346.	0.	284.	0.0	4.8	0.	1148.
5091.	3515.	0.0	32.8	0.	10720.	0.	282.	0.0	4.8	0.	1177
2746.	2853.	23.2	24.4	13310.	11698.	587.	930.	0.0	5.9	1048.	1338
4886.	4733.	28.0	24.7	17590.	19140.	800.	904.	0.0	5.9	1388.	1781
2746.	1594.	31.6	23.4	10360.	6822.	583.	959.	0.0	4.1	858.	851.
3246.	3618.	23.4	24.7	13390.	14632.	935.	957.	0.0	4.1	1029.	1322.
4649.	4738.	22.8	24.7	20570.	19160.	806.	906.	0.0	6.0	1531.	1803.
4991.	4738.	25.9	24.7	19060.	19160.	780.	906.	0.0	6.0	1590.	1803.
2554.	2613.	27.8	24.9	9210.	10504.	390.	953.	0.0	4.4	712.	1217.
1974.	2312.	26.1	24.9	7520.	9297.	497.	827.	0.0	2.1	530.	811.
3719.	4356.	27.3	24.9	13760.	17512.	535.	895.	0.0	5.3	1028.	1536.
3719.	4413.	25.0	24.9	15140.	17743.	644.	895.	0.0	5.3	1052.	1543.
644.	148.	31.8	24.7	2090.	599.	0.	230.	0.0	0.1	0.	69.
4895.	4733.	35.2	24.7	14040.	19140.	798.	904.	0.0	5.9	1424.	1781.
3325.	1594.	34.3	23.4	10020.	6822.	516.	959.	0.0	4.1	844.	851.
3404.	3618.	35.4	24.7	9710.	14632.	756.	957.	0.0	4.1	1154.	1322.
4684.	4738.	35.6	24.7	13990.	19160.	867.	906.	0.0	6.0	1497.	1803.
4798.	4738.	35.8	24.7	13510.	19160.	847.	906.	0.0	6.0	1571.	1803.
2684.	2613.	36.7	24.9	7300.	10504.	412.	953.	0.0	4.4	688.	1217.
2289.	2312.	30.8	24.9	7500.	9297.	531.	827.	0.0	2.1	693.	811.
3114.	4356.	34.5	24.9	9120.	17512.	513.	895.	0.0	5.3	966.	1536.
3632.	4413.	32.9	24.9	11150.	17743.	617.	895.	0.0	5.3	1144.	1543.
3793.	1434.	32.9	2..0	13252.	7169.	0.	650.	0.0	2.4	979.	817.
5359.	4066.	32.0	35.7	19250.	11401.	0.	650.	0.0	2.4	1286.	1166.
4367.	2961.	32.2	35.7	15590.	8301.	0.	650.	0.0	2.4	1258.	1067.
3985.	1756.	34.5	21.1	13275.	8301.	0.	650.	0.0	2.4	1076.	849.
5672.	4066.	31.1	35.7	20964.	11401.	0.	650.	0.0	2.4	1479.	1225.
5455.	4066.	30.6	35.7	20490.	11401.	0.	650.	0.0	2.4	1462.	1225.
5002.	2961.	29.6	35.7	19360.	8301.	0.	650.	0.0	2.4	1228.	1071.
5664.	4066.	30.3	35.7	21485.	11401.	0.	650.	0.0	2.4	1620.	1225.

Summary

The enormous diversity of the data base used for testing the CERES-Wheat model allowed us to compare every important aspect of the model's features. The most important are phasic development and developing timing for which almost all data sets could be used. The next most important data for comparison between the model and experimental results are above-ground dry matter production, leaf area development, and tillering pattern. We found that measurements of tillering were limited, perhaps because tillering occurs shortly before or after winter. When more detailed measurements were taken, they usually were for dry matter partitioning.

These were the most valuable data sets, because subroutines or parts of subroutines for CERES-Wheat can only be validated when their specific output is compared with stem, leaf, ear, and root weight measurements. More detailed information from experiments would have been valuable.

Generally, agreement between model output and experimental results was acceptable or excellent. When discrepancies grew too large, usually a conflict could be detected, such as heavy diseases or pests in the crops, differing definitions of plant parts or units, etc.

Acceptance of a model's performance remains a personal decision and a matter of defining limits. Models restricted to certain locations can easily be more accurate when regionally applied. CERES, however, was designed for universal application--and it meets the requirements of being able to simulate wheat growth and development at any site where wheat can be grown.

CERES-WHEAT NITROGEN

Some of the important objectives in developing the CERES-Wheat-N model were:

1. To predict response or nonresponse to N fertilizer in a diversity of environments.

2. To predict crop N uptake and N utilization.

3. To account for the N balance components in the soil-crop system.

4. To predict the time course of biomass accumulation and N uptake by the crop.

Since model development and testing is somewhat of an iterative process in the early stages, most of the data sets have been utilized during the development phase and are not truly independent. Since development of CERES-Wheat-N has necessarily lagged behind the development of CERES-Wheat, the opportunity to rigorously test the model with a large base of truly independent data sets has not yet arisen. Development and testing of the CERES-Maize-N model (Jones and Kiniry 1986) has proceeded in parallel with the work on the wheat model. Because the soil N transformation components of both models are identical and since the basic structure of the CERES-Wheat model dictates the nature of biomass production, yield component determination, and water balance, the testing data base can be inferred as having some degree of independence from model development. Thus, in the analyses that follow, no attempt has been made to separate truly independent data sets from those used for model development.

In addition to those test criteria used for testing the CERES model, several other procedures were examined:

1. An approach suggested by Dent and Blackie (1979) testing the null hypothesis that the intercept coefficients (a) and slope coefficient (b) simultaneously are not different from zero and unity, respectively. An F statistic appropriate for testing this hypothesis was calculated.

2. Upper and lower confidence intervals about the slope and intercept were also determined such that either slope or intercept could be identified as significantly departing from the 1:1 line.

3. A statistic to determine model accuracy as defined by Freese (1960).

4. A 5% critical error as defined by Reynolds (1984).

Data Base

Data sets of wheat production from several places in the world were assembled for testing and improving the CERES-Wheat-N model. Most of the data came from published sources and some from unpublished Ph.D. dissertations and other unpublished sources. As a complete minimum data set was rarely available, the additional climatic and soils information was obtained from other reports or personal communication. When a few key data were unavailable, certain model inputs were estimated using the best available local information.

Comparisons of the predicted and observed time course of biomass accumulation of N uptake by the crop and N balance components depicted where appropriate observed data were available.

The test data base spans the wheat-growing environments from 53 degrees N latitude in the United Kingdom and the Netherlands with a 10-month growing season to the spring wheat-growing areas of Canada and the northern United States with growing seasons of 90-120 days to the winter-planted spring wheat-growing areas of the Middle East and Australia. A diversity of soil types and fertilizer application patterns, sources, and timings is also represented in the data base.

Individual Data Sets

Garden City, Kansas, U.S.A. (1980 and 1981). The experimental design was six N rates (0, 28, 56, 84, 112, and 140 kg N/ha) with four irrigation timing strategies (preplant irrigation only, preplant + irrigation at jointing, preplant + irrigation at flowering, irrigation at all three times). The soil was a clay loam (Aridic Argiustoll) and fertilizers were applied broadcast at preplanting followed by incorporation. The variety was Newton. The experiment was conducted by Dr. Mark Hooker; data were obtained by personal communication and are reported in Wagger (1983).

Manhattan, Kansas, U.S.A. (1981). The experimental design was three N rates (0, 60, and 180 kg N/ha) and a plus and minus irrigation treatment. The 180 kg N/ha rate was divided; half was applied at planting and the other half at x days after planting (Wagger 1983). Additional data were obtained by personal communication (Drs. M. Wagger and D. Kissel, Kansas State University).

Hutchinson, Kansas, U.S.A. (1979 and 1980). The experimental design was six N rates (0, 28, 56, 84, 112, and 140 kg N/ha) applied preplant followed by incorporation. In 1979, the variety was Centurk; in 1980, Newton was used.

Swift Current, Saskatchewan, Canada (1975). The experiment comprised seven N rates (0, 20.5, 41, 61.5, 82, 123, and 164 kg N/ha) with a plus and a minus irrigation treatment (Campbell et al. 1977 a,b). Following planting, 15 cm diameter lysimeters were driven into the soil to a depth of 120 cm. Five harvests during the growing season were made. The variety was Manitou. Climate and soils data were obtained from the authors. The instrument gathering solar radiation data malfunctioned for three weeks during the early grain filling stage. The missing data were estimated by fitting a function to radiation of maximum and minimum temperature, presence or absence of rainfall, and the day of the year. The reliability of these estimates is not known.

Northwest Syria (1979 and 1980). Experiments were conducted at four sites in Aleppo province by Dr. M. Stapper. At three of the sites (Brida, Jindiress, and Kafr Antoon), two N rates (0 and 60 kg N/ha) were applied. At each site, three spring wheat varieties (Mexipak, Sonalika, and Novi Sad) were compared. At the fourth site, additional irrigation treatments were added. At Kafr Antoon, a late frost was suspected, and at Jindiress, the variety Mexipak suffered from rust (Dr. H. C. Harris, personal communication, ICARDA). Data are reported in Stapper (1984).

Wongan Hills, Western Australia (1966). The experiment, using the spring wheat variety Gamenya, was designed to examine the fate of anhydrous ammonia and urea applied to a loamy sand (Mason and Rowley 1969). Since the model simulates both of these fertilizer materials as identical ammoniacal sources, comparisons were made with the mean of these two treatments. The experiment showed no significant differences between the sources. The rates of N applied were 0 and 61 kg N/ha applied preplant. Solar radiation data were estimated from recorded hours of sunshine.

Lancelin, Western Australia (1967). The experiment was on a very coarse, siliceous sand and was designed to examine the fate of urea applied at various intervals after planting (Mason et al. 1972). Urea was applied at 77 kg N/ha either at planting or at 2, 4, or 8 weeks after planting. Delaying the application resulted in an almost threefold increase in grain yield. Solar radiation for Perth, 100 km distant, was used as part of the climatic data.

Rothamsted, England (1975). The experiment compared three varieties of winter wheat (Maris Huntsman, Capelle Desprez, and Maris Fundin) over either rates of N (0, 30, 60, 90, 120, 150, 180, and 210 kg N/ha) (Pearman et al. 1978). The fertilizer was applied 163 days after planting. Few significant variety X N interactions were recorded. The initial soil mineral N values and soil water contents were interpolated from estimates provided by the authors.

Flevopolder, The Netherlands (1975). The experiment was designed to test the effects of late applications of N on leaf area duration, assimilation nutrient uptake, and growth of grains (Spiertz and Ellen 1978). A zero N treatment was not included, thus comparisons of apparent fertilizer recovery were not made. The soil was a marine clay in a reclaimed polder; the winter wheat variety was Lely. A water table was present during the course of the growing season. This was simulated by assuming that layers in the profile below 1 m deep were filled to saturation. Without this assumption, the model predicted considerable moisture stress. Soil mineral N analyses were made after the crop was planted, thus estimates based on these were used for the initial mineral N input values supplied to the model.

Wageningen, The Netherlands (1977). These data are reported by Ellen and Spiertz (1980). The experiment examined various strategies of splitting fertilizer applications on uptake and yield of grain. The variety used was the winter wheat Donata. The soil was reported as a river clay with 45% silt.

Carrington, North Dakota, U.S.A. (1969-73). These data were reported by Bauer (1980). The experiments involved a comparison of several varieties of hard, red spring wheats over several rates of nitrogen and over five years. Half of the experiment was irrigated and the remainder dryland. Since this experiment yielded a massive data set, only selected contrasting years were utilized in the testing data base to avoid biasing the data base with to many points from one location. Straw yields and straw N percent were not reported in some instances and were estimated from the grain yields and grain protein concentrations using the regression procedures described in the publication. This may lead to some errors in estimation of observed biomass and N uptake.

Wagga Wagga, N.S.W., Australia (1962). The experiment, reported by Storrier (1966), used four rates of N. Half of the experiment was irrigated; the other half was dryland. As a split plot treatment, a later application of 45 kg N/ha as sodium nitrate was made to half of the plots. Storrier (1966) reports a negative response to applied N, but examination of the variation in the experiment indicates more of a case of nonresponse to N. Some lodging was reported in the high N plots, which the model would not have been able to account for. The initial mineral N in this experiment was very high. Several gaps existed in the weather record for this experiment. Solar radiation was estimated from hours of sunshine data recorded from the site or nearby. Where the record was blank for both sites, mean values for that time of year were used.

Results and Discussion

Validation: Difference Measures and Summary Statistics

Grain Yield. Simulated grain yields are tabulated against observed counterparts (Table 10). The means and standard error of predictions closely approached those of the observations (Table 8). The degree of scatter around the 1:1 line (Figure 8a) is very small. Thirty yield predictions from 240 deviated more than one standard deviation from their observed counterparts. Data sets, where predictions were poor, were those from Carrington, North Dakota, U.S.A. (1969), Hutchinson, Kansas, U.S.A. (1980), Flevopolder, The Netherlands (1975), Jindiress, Syria (1980), and some individual treatments from some of the remaining data sets.

The regression line (Figure 8a) has a slope greater than unity (1.033) which differs from unity by slightly more than 5% confidence interval (0.030). The F statistic for the regression is significant at the 5% level due to the slope. This slope of greater than unity and the small positive intercept (145.6 kg/ha) implies that the model has some tendency to overpredict yields across the range of observations. This is further indicated by the small positive MBE (Table 8). This finding is not surprising and it is not sufficient cause to reject the model since the assumption is made that all nutrients other than N were present in nonlimiting quantities and that other factors not accounted for by the model (pests and diseases, crop lodging effects, frost induced sterility, etc.) had no influence on yield. As mentioned in the description of the data sets, these assumptions may not always have been entirely fulfilled. No quantitative data were available to suggest that some of the test data sets should have been eliminated from the testing data base.

All other statistical criteria for model evaluation (correlation coefficient, chi-square test, and modified Freese statistic) indicated the model was acceptable. The critical error term of Reynolds (1984) indicates that the model will predict grain yield within an error of 1,865 kg.ha with a 95% confidence.

Biomass. Simulated biomass is tabulated against its observed counterparts (Table 10). Means and standard error for predicted biomass closely resemble those from the observed data (Table 8). More scatter about the 1:1 line occurred for biomass predictions (Figure 8b) than for grain yield. The greater spread is generally from a poorer simulation of straw yield. Most of the 55 points falling outside the bounds of the ± 1.0 standard deviation were from whole data sets rather than from individual treatments across a range of data sets. Data sets where simulation of biomass was generally poor were Wageningen, 1977; the variety Nugaines at Pendleton and Dufur, Oregon, 1971; various treatments within the Jindiress, 1980; Tel Hadya, 1980; Kafr Antoon, 1980; and Garden City, 1981. The simulated biomass for the Hutchinson 1980 data set was consistently low.

The slope of the regression line significantly deviated from the 1:1 line indicating a tendency of the model to overpredict biomass particularly at the high end of the range. This is also indicated by an MBE of 1,406 kg/ha. The correlation coefficient, chi-square, and modified Freese statistic all indicated model predictions were acceptable.

Total N Uptake, Grain N Uptake, and Grain Protein. Performance of the model in predicting these parameters was generally poorer than the simulation of grain yield. Forty-four points from a total of 223 fell outside of the bounds of ± standard deviation of the 1:1 line for total N uptake for grain protein and grain N uptake: 31 from 215 and 60 from 215, respectively. The slope of the regression line (1.042) for total N uptake was just beyond the 5% interval for slope (1.039). Similarly, the intercept (7.0) lies beyond the 5% confidence interval for the intercept (6.34). There is a tendency for the simulations to exceed the observations although the correlation coefficient, chi-square test, and modified Freese procedure all indicate the simulations are acceptable.

Total N uptake was consistently underpredicted for the Swift Current, Canada, data, and consistently overpredicted for the Waite Institute, Dufur, and Pendleton data sets. Grain N uptake was simulated fairly closely (Figure B.1). Much of the error involved in simulation of total N uptake arose from poor simulation of the concentration of N in the straw at harvest.

The range of simulation values was consistently less than that observed (0.1 to 1.3%). Some of these differences may occur due to differences in harvesting technique and time of harvest. If significant amounts of chaff or leaf materials are not included in the sample, the reported straw N concentration also will be low. The model makes no attempt to account for losses of N from the vegetative material through leaching of N compounds from harvest ripe straw or via volatile losses from senescing leaves. Several data sets had less N in plant top tissue at harvest than at anthesis, indicating some losses.

The scatter of points around the 1:1 line (Figure 8) was much higher for grain protein (grain N percent multiplied by 5.7) than for many other parameters. Both slope and intercept of the regression line are significantly different from the 1:1 line. The chi-square test also indicates the simulations are significantly different from the observations, but the modified Freese statistic indicates the model is still acceptable.

The simulation of grain protein concentration has been to date one of the most difficult components in the whole model to get working satisfactorily. In several of the data sets, grain protein concentration was consistently overpredicted or underpredicted. It was difficult to determine if in any of these cases a genotypic factor was involved. Adding a further genetic coefficient to the model input data requirements to help explain cultivaral differences in grain protein accumulation has so far been avoided. Further investigation of this aspect of the model is warranted.

Dry Weight and N Uptake at Anthesis. In many of the studies, harvests were made at or near anthesis. The simulated data used for the comparisons were the corresponding values for N uptake and biomass on the date of harvest (i.e., not necessarily on the simulated date of anthesis). Biomass was generally overestimated at anthesis. The regression line significantly deviates from the 1:1 line (Figure 8g) and 72 points of the 161 fell outside the bounds of ± 1.0 standard deviation of the 1:1 line. The chi-square test indicated the predicted biomass differed significantly from that observed. The simulated N uptake at anthesis showed much less scatter than the predictions for biomass. The simulations were acceptable within all of the statistical criteria examined. The model substantially underestimated the anthesis N uptake of several of the treatments from the experiments at Wagga Wagga, 1962. The resulting slope of the regression line thus is a little less than 1.0. Some compensating errors in the simulation of plant N concentration may occur if the simulated biomass is incorrect and the simulated N uptake is correct. The MBE terms (Table 8) also indicate a large overestimate of biomass at anthesis and a slight underestimate of N uptake at anthesis.

Kernel Weight and Kernels Per Square Meter. Overall, the model had a slight tendency to underestimate the number of grains per square meter and overestimate the weight of individual kernels. The model consistently overestimated kernel weight for the variety Capelle Desprez in the Rothamsted 1975 experiments. For the final determination of grain yield, small errors in either of these components are of no consequence provided compensation occurs (i.e., low kernel number is compensated by a high kernel weight). These two yield components are, however, important indications to timing of certain stresses, and for the model to be useful, they should be reasonably correct. For both parameters, the slope of the regression line significantly differs from the 1:1 line, but the intercepts were within the confidence interval. There was a noticeable tendency for the model not to display the same sensitivity in kernel weight to rates of applied N as the observed data did.

Apparent Recovery. Apparent recovery (AR) is a parameter often used in fertilizer research to indicate the efficiency of fertilizer use. From a modelling standpoint, it is a particularly challenging parameter on which to test the model, since AR depends on the accurate simulation of two treatments simultaneously. It is calculated:

$$AR = \frac{NUP_f - NUP_u}{Rate} \times 100$$

where NUP_f = N uptake from a fertilized treatment
NUP_u = N uptake from an unfertilized treatment
Rate = rate of fertilizer applied.

Since AR depends on the N uptake from two different treatments, small errors in the prediction of either can lead to quite spurious values for the calculated AR. This is indicated in Table 9 where 10% errors in prediction of both the fertilized and unfertilized treatment leads to errors in the calculated AR of 33% and 38%.

Table 9. Effect of Errors in N Uptake Simulation on Errors and Apparent Recovery.

	NUP_f	NUP_u	Rate	AR	Error (%)
Sample Obs	60	40	30	67	-
10% Error 1	66	36	30	100	33
10% Error 2	54	44	30	33	-34

The means and standard errors of the predictions closely approximated those of the observed. Most of the statistical parameters (Table 8) indicate a significant difference between predicted and observed values. The modifiees to N in both years at Garden City, Kansas, were not apparent in any of the irrigation treatments. The simulations reasonably approximated the observations across the range of treatments.

Predicted N responses for the Syrian data sets were generally very good. Yields for some of the varieties were overestimated at Jindiress and Kafr Antoon, but the simulations were consistent with the remarks noted in the above section "Description and Testing Data Base." Yields for the longer duration variety Novi Sad were overestimated at Tel Hadya, 1979, and small underestimates of yield occurred for the zero N treatments at Brida.

Responses to N applied either at planting or in split applications were not apparent at Madras, Oregon, or for single applications at Dufur. Simulations for these treatments were very close to the observations. The model underestimated yields for the variety Hyslop at Pendleton, but overestimated yields across the range of N rates for the variety Nugaines.

The model underestimated the grain yield at low N rates in the Swift Current, 1975, experiment, but simulations for the remainder of the response curve were excellent. Excellent yield simulations were also recorded for the Rothamsted data sets.

The sensitivity of the model to differences in fertilizer application pattern (timing) is well illustrated by the data sets from Lancelin, Wageningen, and Bozeman.

Grain protein concentration generally was well simulated across the range of N rates, except for the cases noted above (section "Total N Uptake, Grain N Uptake, and Grain Protein"). These exceptions rendered the simulation of grain protein to be unacceptable statistically when all data sets were combined. Given the constraints noted above in model development and the proximity of most of the simulations depicted in Figure B.6, there is insufficient evidence to reject the model for the applications for which it was designed.

The model tended to overestimate total N uptake, but there was no consistent pattern of overestimation or underestimation. Despite these problems, the model captures most of the observed effects of N uptake for most of the data sets. Some further study is required to elucidate the problems with the North Dakota and Syrian data sets.

Seasonal Patterns of Biomass and N Uptake Accumulation

Across the range of data sets, predicted biomass was slightly out of phase with observed biomass. The model tended to predict higher biomass accumulations earlier in the season than the observations would indicate. While there was a noticeable trend, the errors were not large and were consistent with those observed for the non-nitrogen version. Errors were large, however, at the low N rates for the Swift

Current data set and for some treatments in the Tel Hadya 1980 data set.

A similar pattern in seasonal N uptake to that of biomass was observed (early overestimation of N uptake). Seasonal patterns of N uptake were poorly simulated at the low N rates in the Swift Current data set, but reasonably simulated in the Kansas data sets.

Seasonal Patterns of N Balance

When attempting the validation of the soil N components of the model, it was originally intended to attempt a layer-by-layer comparison of each of the predicted nitrate and ammonium concentrations with those observed. Analysis of the observed data in most instances first indicated very large standard errors and other seeming anomalies were sometimes apparent. In some of the data sets, mineral N concentrations were low after fertilizer addition and increased as the crop grew and withdrew N from the soil. While this may be indicative of turnover occurring within the soil systems due to microbial activity or ammonium adsorption/desorption on clay surfaces, the anomalies in the individual layers were so gross as to discard many of them. The errors associated with the layer data for most data sets were such that the simulations may have been in error by some 200% and yet still be within the error bounds of the observations.

To provide some meaningful validation of these components of the model, total mineral N in the soil at various times was used as a test criterion. While many of the error conditions noted above will still affect this total soil pool, the values obtained were more consistent with what could be reasonably expected.

Across the range of data sets studied, some within-season differences in predicted and observed balances occur, but given the magnitude of the errors cited, the N balance simulations are plausible.

Figure 8. Comparison of Predictions of the CERES-Wheat-N Model with Observed Data from Field Experiments.

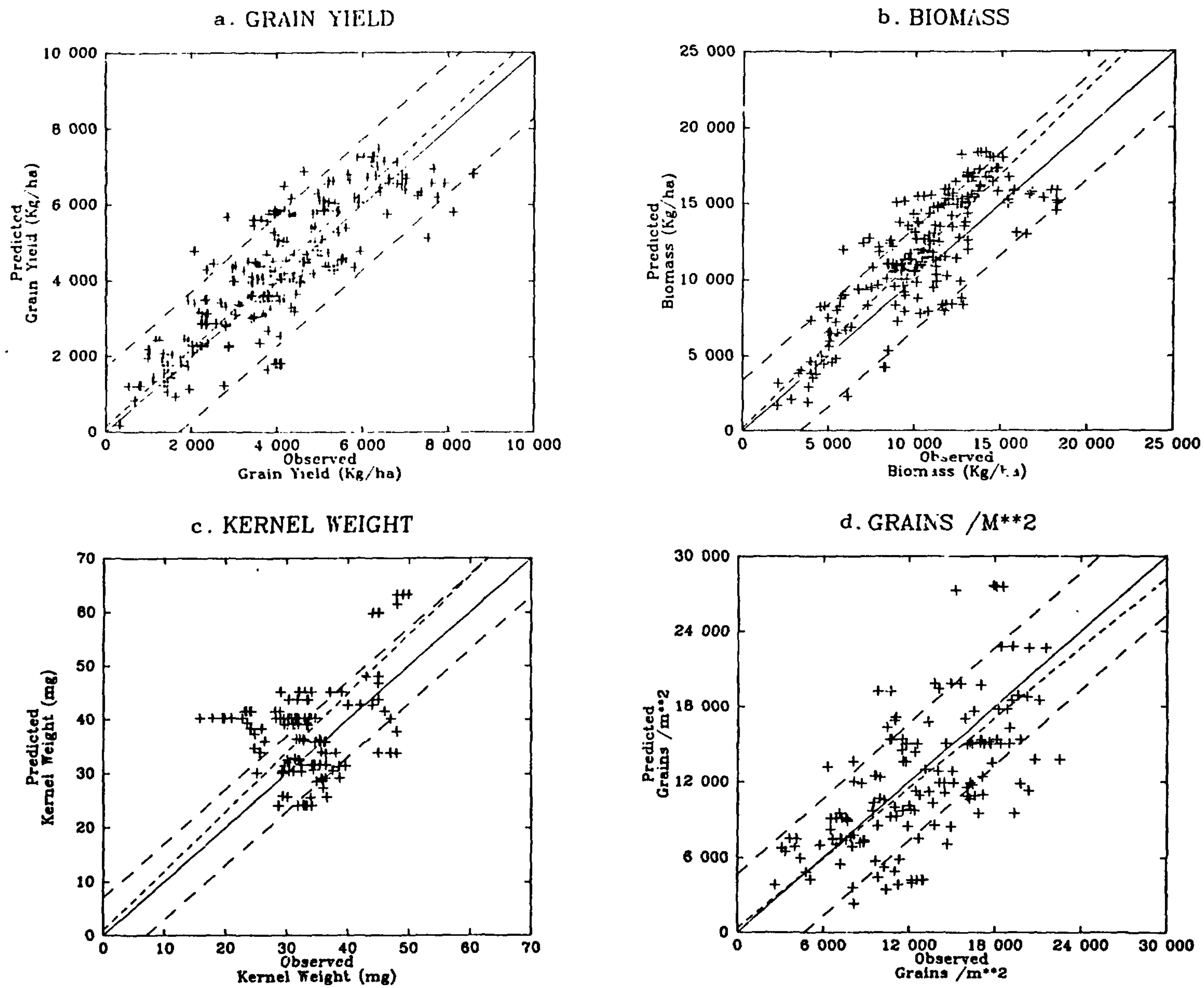


Figure 8. Continued.

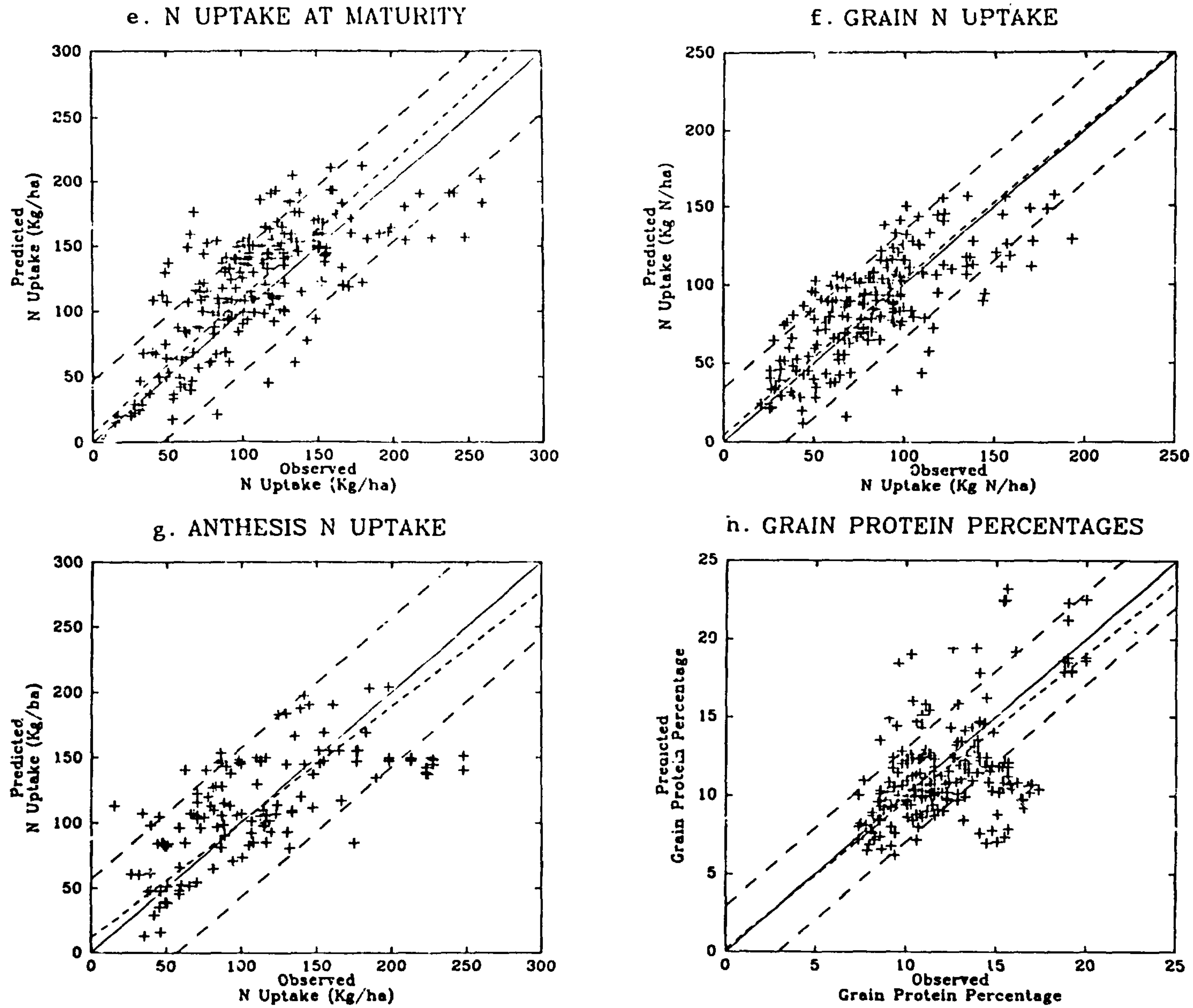


Table 8. Summary Measures for all Data Sets.

Variable	Units	N	$\bar{O}$	$\bar{P}$	SO	SP	a	b	R	D	F
Biomass	kg/ha	222	10,313	11,719	3,375	3,897	189.3	1.118	0.82	0.86	15.907
Grain yield	kg/ha	240	3,953	4,227	1,716	1,719	145.6	1.033	0.84	0.91	3.263
Total N uptake	kg N/ha	223	110	121	47	45	7.0	1.042	0.72	0.83	7.8438
Grain N uptake	kg N/ha	215	84	87	34	31	4.4	0.996	0.74	0.85	1.298
Grain protein	%	215	12.3	11.7	2.95	3.55	0.198	0.939	0.55	0.74	2.933
Anthesis DW	kg/ha	161	7,254	8,681	2,166	2,818	261.7	1.161	0.58	0.70	22.771
Anthesis N uptake	kg N/ha	151	118	116	57.1	39.31	11.66	0.887	0.67	0.78	2.3370
GPSM	NO	152	12,381	11,861	4,668	5,324	362	0.929	0.63	0.78	1.080
Kernel weight	mg	134	33.6	37.9	7.02	8.40	0.998	1.096	0.34	0.59	18.69
App recovery	%	137	45.7	43.4	29.4	25.68	8.37	0.[illegible]7	0.37	0.65	6.24

Variable	Units	N	P	CISLOP	CIINT	χ^2	MAE	MBE	RMSE	RT	E*
Biomass	kg/ha	222	0	0.028	423.6	136.01	2,248.1	1,405.590	2,648.19	13.06	480.9
Grain yield	kg/ha	240	0.0400	0.030	173.9	85.08	806.08	274.43	1,024.16	15.39	186.5
Total N uptake	kg N/ha	223	0.0005	0.0392	6.34	133.03	28.55	11.535	36.27	22.43	65.9
Grain N uptake	kg N/ha	215	0.2752	0.0354	4.344	105.13	19.4	3.491	24.040	18.64	43.6
Grain protein	%	215	0.0554	0.0330	0.582	250.832	2.363	-0.550	3.192	18.65	5.8
Anthesis DW	kg/ha	161	0	0.0509	533.22	259.72	2,159.6	1,426.76	2,759.73	19.26	494.6
Anthesis N uptake	kg N/ha	151	0.1002	0.0467	8.239	82.46	34.36	-1.660	42.352	23.62	75.7
GPSM	NO	152	0.3422	0.0516	362.30	131.43	3,462.3	-520.78	4,355.36	22.43	778.6
Kernel weight	mg	140	0	0.0452	2.1724	274.77	8.091	4.2286	9.8738	12.00	17.6
App recovery	%	137	0.0026	0.0850	6.032	152.20	23.460	-2.281	31.177	69.48	55.5

N = Number of observations.
$\bar{O}$ = Mean of observations.
$\bar{P}$ = Mean of predictions.
SO = Standard deviation of observations.
SP = Standard deviation of predictions.
a = Intercept term from regression of predicted on observed.
b = Slope term from regression of predicted on observed.
R = Regression coefficient.
D = Index of agreement (Willmott 1982).
F = F statistic calculated as per Dent and Blackie (1979).
P = Probability of exceeding F.
CISLOP = 5% confidence interval about slope of regression line.
CIINT = 5% confidence interval about intercept of regression line.
χ^2 = Chi-square.
MAE = Mean absolute error (Willmont 1982).
MBE = Mean bias error (Willmont 1982).
RMSE = Root mean square error.
RT = Model accuracy (Freese 1960).
E* = 5% critical error as defined by Reynolds (1984).

Table 10. Listing of N-Model Testing Data Base (O = Observed Value and P = Predicted Value).

GRAIN YIELD		BIOMASS		N UPTAKE		GRAIN N NUPTAKE		GRAIN PROTEIN		ANTHESIS N UPTAKE	
O	P	O	P	O	P	O	P	O	P	O	P
4064.	3727.	9230.	9518.	72.9	102.7	61.3	78.5	8.6	12.0	58.6	106 1
5329.	3923.	11475.	10326.	122.1	123.0	98.2	82.6	10.5	12.0	97.3	126.7
5126.	4201.	11014.	11035.	127.8	142.9	104.3	88.4	11.6	12.0	92.5	147.0
3949.	5090.	8911.	12349.	63.3	135.1	51.3	107.2	7.4	12.0	62.4	138.9
5080.	5521.	11772.	13740.	104.3	164.2	83.8	116.2	9.4	12.0	84.8	169.2
5082	6011.	11916.	15384.	127.5	218.8	103.4	126.5	11.6	12.0	116.3	224.9
4624.	4118.	10338.	10402.	91.2	103.6	75.4	83.1	9.3	11.5	72.8	106.1
5018.	4360.	11084.	11295.	116.5	122.5	91.6	91.8	10.4	12.0	87.3	126 7
4948.	4575.	11127.	11981.	119.6	143.0	96.4	96.3	11.1	12.0	15.3	147 0
4175.	5090.	9386.	12349.	76.1	134.7	63.0	107.2	8.6	12.0	76.6	138.9
5211.	5521.	12187.	13740.	115.0	164.2	92.3	116.2	10.1	12.0	98.1	169.2
4988.	6011.	11916.	15386.	129.9	218.8	101.5	126.5	11.6	12.0	109.9	224 9
4585.	3799.	10005.	9776.	90.7	106.5	74.0	80.0	9.2	12.0	0.0	0.0
5185.	3935.	11216.	10284.	123.8	121.6	99.2	82.8	10.9	12.0	0.0	0.0
5400.	4030.	12416.	10523.	138.9	129.2	111.8	84.8	11.8	12.0	0.0	0.0
5119.	5269.	11501.	12831.	97.7	144.6	80.8	110.9	9.0	12.0	0.0	0.0
5185.	5764.	12897.	14287.	125.7	183.9	95.5	121.3	10.5	12.0	0.0	0.0
5440.	5923.	13118.	14851.	135.9	202.5	110.7	124.7	11.6	12.0	0.0	0.0
4756.	4208.	10427.	10614.	103.4	106.2	84.3	84.9	10.1	11.5	0.0	0.0
5188.	4381.	11412.	11203.	124.5	121.0	100.1	92.2	11.0	12.0	0.0	0.0
5948.	4457.	13079.	11438.	148.4	129.2	117.9	93.8	11.3	12.0	0.0	0.0
5079.	5269.	11904.	12831.	100.0	144.6	82.9	110.9	9.3	12.0	0.0	0.0
5109.	5764.	12187.	14287.	122.6	183.9	96.8	121.3	10.8	12.0	0.0	0.0
5353.	5923.	13043.	14851.	137.7	202.5	108.9	124.7	11.6	12.0	0.0	0.0
2317.	2226.	5994.	4964.	59.2	46.3	44.3	37.9	10.9	9.7	50.9	46.5
3330.	3011.	10178.	7245.	103.2	72.8	63.7	58.6	10.9	11.1	101.0	74.1
4521.	3717.	12649.	9088.	166.6	112.8	99.9	74.3	12.6	11.4	175.0	115.7
1438.	1646.	3926.	3873.	37.7	31.1	26.7	24.5	10.6	8.5	45.5	32.9
3025.	2769.	9424.	6760.	87.8	61.3	56.8	49.1	10.7	10.1	81.5	66.3
4695.	4168.	13064.	10689.	166.5	131.0	95.5	83.4	11.6	11.4	147.6	133.9
1828.	2075.	6347.	5215.	66.6	58.0	38.5	50.2	12.0	13.8	58.9	61.7
2224.	2379.	8918.	6165.	97.1	72.7	50.7	62.2	13.0	14.9	86.7	76.2
[illegible]	2577.	7483.	7095.	79.6	89.4	52.2	76.9	12.8	17.0	84.1	93.7
2164.	2759.	8375.	8103.	98.3	111.6	50.5	89.5	13.3	18.5	112.8	117.6
2365.	2958.	9202.	9026.	107.5	129.1	59.3	99.6	14.3	19.2	123.2	136.2
2372.	3079.	9540.	9440.	119.7	139.0	58.7	103.7	14.1	19.2	100.4	146.6
5017.	1584.	9376.	5513.	80.1	70.8	67.3	37.2	10.9	13.4	0.0	73.1
4060.	2021.	11225.	6430.	107.7	91.3	86.9	47.5	12.2	13.4	115.1	84.0
3396.	2334.	8864.	7086.	92.4	90.4	79.2	54.9	13.3	13.4	117.1	92.5
3999.	2495.	11223.	7422.	119.3	96.3	94.7	58.7	13.5	13.4	134.0	98.6
3786.	2579.	10289.	7598.	117.1	99.9	93.7	60.6	14.1	13.4	133.8	102.3
3417.	2628.	9205.	7699.	105.4	101.7	86.9	61.8	14.5	13.4	114.8	104.2
3839.	2422.	10592.	6987.	83.6	86.1	70.0	56.9	10.4	13.4	130.7	88.4
4140.	3201.	11451.	8643	95.3	103.5	78.4	75.3	10.8	13.4	123.9	106.1
4415.	3812.	12727.	10006.	103.2	122.0	89.1	89.6	11.5	13.4	147.9	124.8
4368.	4198.	13278.	10913.	121.0	134.3	94.3	98.7	12.3	13.4	152.2	137.1
4288	4355.	13634.	11298.	147.0	139.1	103.1	102.4	13.7	13.4	176.6	142.7
3819.	4445.	11694.	11525.	114.9	142.1	90.4	104.5	13.5	13.4	154.7	145.5

Table 10. Continued.

GRAIN YIELD		BIOMASS		N UPTAKE		GRAIN N NUPTAKE		GRAIN PROTEIN		ANTHESIS N UPTAKE	
O	P	O	P	O	P	O	P	O	P	O	P
3464.	1593.	9324.	5531.	80.9	70.8	67.5	37.4	11.1	13.4	132.2	73.3
3789.	2021.	10079.	6430.	101.3	81.4	82.4	47.5	12.4	13.4	115.1	84.0
3685.	2336.	9734.	7111.	99.7	90.4	83.4	54.9	12.9	13.4	117.1	92.5
3819.	2497.	10815.	7480.	116.3	96.3	91.8	58.7	13.7	13.4	134.0	98.6
3886.	2583.	10501.	7685.	127.3	99.9	98.2	60.7	14.4	13.4	133.8	102.5
3678.	2629.	10148.	7798.	113.6	101.8	91.0	61.8	14.1	13.4	114.8	104.2
3946.	2424.	11047.	6991.	100.2	86.1	80.3	57.0	11.6	13.4	130.7	88.4
4221.	3201.	12837.	8644.	115.0	103.5	87.4	75.3	11.8	13.4	123.9	106.1
4288.	3812.	13448.	10006.	117.3	122.0	92.5	89.6	12.3	13.4	147.9	124.8
3959.	4198.	[illegible]791.	10913.	132.1	134.3	91.0	98.7	13.1	13.4	152.2	137.1
4026.	4355.	[illegible]	11298.	134.5	139.1	99.6	102.4	14.1	13.4	176.6	142.7
3933.	4445.	13723.	11525.	131.4	142.1	95.2	104.5	13.8	13.4	154.7	145.5
1617.	788.	3781.	1398.	52.9	15.9	44.0	14.4	15.5	10.4	35.8	11.8
1578.	1279.	3957.	2754.	53.8	24.9	43.5	20.9	15.7	9.3	42.1	24.1
1754.	1528.	4603.	3903.	65.7	36.2	51.1	29.5	16.6	11.0	49.6	36.6
1732.	1832.	5042.	5016.	70.2	45.8	51.4	36.6	16.9	11.4	59.0	51.7
2028.	2067.	5063.	5842.	78.9	63.3	61.9	41.7	17.4	11.5	58.9	65.2
2192.	2332.	5151.	6497.	81.9	74.5	64.6	47.0	16.8	11.5	65.6	77.1
2367.	2465.	5540.	6776.	88.7	80.9	70.6	49.7	17.0	11.5	60.1	83.6
2754.	602.	6121.	1096.	82.3	11.6	68.1	10.4	14.1	9.8	46.4	9.5
3792.	1872.	8494.	3406.	116.7	36.0	96.5	32.2	14.5	9.8	50.6	32.2
4154.	2875.	9031.	5297.	134.6	55.5	110.0	49.4	15.1	9.8	70.5	50.4
4395.	3906.	9431.	7295.	142.5	74.9	114.1	66.5	14.8	9.7	94.7	70.6
4395.	4583.	10122.	8911.	148.5	91.0	116.4	80.4	15.1	10.0	105.3	90.0
5425.	5305.	9946.	10435.	170.5	111.3	144.7	97.7	15.2	10.5	108.2	113.3
4883.	5523.	10142.	10794.	165.8	118.8	134.5	104.6	15.7	10.8	116.8	124.2
1420.	949.	4735.	3853.	48.9	52.0	32.1	21.3	12.9	12.8	46.5	54.0
1430.	1327.	5010.	5768.	62.3	97.1	40.4	29.8	16.1	12.8	48.9	100.5
1940.	1223.	5430.	4463.	57.6	51.6	42.5	32.4	12.5	15.1	38.0	53.3
1910.	1811.	5430.	6723.	64.2	96.0	47.2	48.0	14.1	15.1	50.2	99.9
1360.	1100.	5200.	3898.	44.0	51.3	26.5	39.8	11.1	20.6	39.9	54.3
1340.	1434.	5107.	5730.	61.4	97.1	36.7	51.8	15.6	20.6	51.2	101.0
2510.	4735.	7000.	11537.	49.4	113.9	37.9	92.2	8.6	11.1	39.8	111.6
3950.	5511.	10925.	14101.	106.9	155.8	75.5	107.3	10.9	11.1	110.7	156.5
2840.	5291.	7350.	10495.	46.4	104.8	38.9	91.0	7.8	9.8	62.5	49.8
4330.	6270.	11160.	13806.	101.1	151.6	76.7	132.0	10.1	12.0	120.2	95.5
2070.	3617.	5816.	10970.	40.2	115.0	28.0	95.2	7.7	15.0	34.2	117.7
3890.	4258.	10167.	13586.	82.7	164.0	63.5	120.3	9.3	16.1	86.5	167.5
4410.	3151.	12710.	8241.	0.0	88.8	0.0	75.7	0.0	13.7	0.0	91.1
4090.	4112.	12560.	11246.	0.0	133.1	0.0	102.4	0.0	14.2	0.0	136.9
4320.	3648.	11270.	9724.	0.0	82.4	0.0	65.9	0.0	10.3	0.0	91.1
4880.	4922.	13050.	13243.	0.0	132.8	0.0	101.9	0.0	11.8	0.0	136.9
4710.	4865.	11850.	9676.	0.0	86.4	0.0	73.4	0.0	8.6	0.0	89.8
4000.	5992.	10180.	12672.	0.0	130.5	0.0	112.5	0.0	10.7	0.0	134.1
3760.	4865.	9340.	9710.	0.0	87.2	0.0	74.3	0.0	8.7	0.0	89.8
4960.	5992.	12120.	13023.	0.0	130.2	0.0	111.4	0.0	10.6	0.0	134.1
3590.	2363.	10790.	7323.	0.0	89.5	0.0	77.1	0.0	18.6	0.0	91.6
3670.	2972.	11760.	10059.	0.0	134.3	0.0	112.6	0.0	21.6	0.0	138.3

Table 10. Continued.

GRAIN YIELD		BIOMASS		N UPTAKE		GRAIN N NUPTAKE		GRAIN PROTEIN		AN[illegible]S N UPTAKE	
O	P	O	P	O	P	O	P	O	P	O	P
4070.	2794.	11050.	9196.	0.0	84.0	0.0	67.2	0.0	13.7	0.0	91.6
4440.	3728.	12170.	12667.	0.0	134.1	0.0	110.5	0.0	16.9	0.0	138.3
3220.	4415.	10700.	10036.	89.5	106.3	56.5	92.9	10.0	12.0	45.3	109.7
3940.	4855.	11701.	12443.	112.9	149.5	73.3	113.3	10.6	13.3	86.7	154.6
3940.	4963.	7905.	10480.	63.4	104.2	58.8	90.6	8.5	10.4	75.3	103.4
4840.	5954.	11335.	13761.	104.9	156.5	88.3	136.8	10.4	13.1	93.1	156.4
3840.	3348.	9600.	9451.	83.7	111.0	67.4	95.2	10.0	16.2	70.7	110.4
4360.	3837.	10847.	12030.	104.3	152.9	83.4	131.9	10.9	19.6	98.7	157.4
5040.	4742.	12642.	12979.	118.9	144.1	92.8	96.[illegible]	10.5	11.6	0.0	0.0
4030.	4742.	11060.	12979.	112.6	143.7	78.5	96.5	11.1	11.6	0.0	0.0
3420.	3934.	9790.	11247.	98.3	144.0	68.4	89.7	11.4	13.0	0.0	0.0
1920.	2524.	4950.	6366.	41.9	65.5	31.0	51.4	9.2	11.6	0.0	0.0
4930.	5620.	12900.	12059.	127.1	136.6	97.7	119.3	11.3	12.1	0.0	0.0
4080.	5620.	10124.	12010.	101.1	133.9	81.6	117.3	11.4	11.9	0.0	0.0
3470.	5288.	9582.	11624.	90.6	128.8	68.2	112.3	11.2	12.1	0.0	0.0
1920.	2987.	4800.	6310.	39.7	64.6	31.7	56.1	9.4	10.7	0.0	0.0
4540.	3798.	10344.	12764.	95.1	146.8	78.1	115.9	9.8	17.4	0.0	0.0
4280.	3798.	9909.	12764.	94.4	146.4	77.3	115.9	10.3	17.4	0.0	0.0
3150.	3131.	8600.	10354.	85.9	143.9	62.4	98.3	11.3	17.9	0.0	0.0
1540.	1923.	3968.	5950.	33.4	65.9	25.9	55.3	9.6	16.4	0.0	0.0
7520.	5360.	16460.	11593.	179.6	123.6	143.8	107.2	10.9	11.4	166.5	132.8
8120.	5828.	18230.	13883.	198.6	178.3	156.7	157.5	11.0	15.4	212.6	184.5
7280.	5876.	17430.	13940.	237.6	185.1	178.8	161.8	14.0	15.7	0.0	184.5
7360.	6652.	16640.	15856.	218.0	223.1	169.2	196.1	13.1	16.8	225.6	229.6
6990.	7018.	16750.	16481.	258.6	244.3	182.7	206.8	14.9	16.8	247.7	252.2
6570.	5335.	15870.	11319.	152.4	125.1	118.7	110.4	10.3	11.8	139.7	125.4
7750.	6588.	18180.	14314.	208.4	177.1	150.9	157.2	11.1	13.6	189.9	180.6
7650.	6614.	18180.	14330.	259.6	181.4	178.5	161.3	13.3	13.9	0.0	180.6
6910.	7247.	15380.	15286.	207.8	201.9	154.0	181.8	12.7	14.3	224.3	204.9
6340.	7317.	15380.	15425.	240.8	206.0	155.7	184.9	14.0	14.4	247.7	209.1
1100.	692.	2060.	1366.	27.5	14.4	25.5	12.7	13.2	10.5	0.0	0.0
2310.	2881.	4540.	6049.	48.3	63.4	40.9	55.1	10.1	10.9	0.0	0.0
3890.	4221.	7170.	9365.	90.0	103.4	77.8	89.6	11.4	12.1	0.0	0.0
4850.	4332.	8830.	9790.	118.0	114.3	105.5	100.3	12.4	13.2	0.0	0.0
3530.	3781.	6730.	8182.	90.3	89.3	76.2	77.6	12.3	11.7	0.0	0.0
3550.	3781.	6690.	8155.	95.2	87.9	74.7	76.3	12.0	11.5	0.0	0.0
2960.	2990.	5800.	6137.	87.5	67.3	69.1	58.8	13.3	11.2	0.0	0.0
2990.	2990.	5930.	6137.	92.5	67.4	77.6	59.3	14.8	11.3	0.0	0.0
4160.	4221.	7860.	9368.	105 9	103.8	84.7	90.3	11.6	12.2	0.0	0.0
6290.	8171.	15720.	16500.	147.0	186.4	108.1	166.3	9.8	11.6	90.0	187.0
6910.	8228.	15710.	16578.	183.0	187.9	138.2	167.4	11.4	11.6	100.0	187.7
8560.	8229.	18210.	16579.	226.0	187.9	171.2	167.5	11.4	11.6	130.0	188.9
8580.	8229.	17870.	16579.	248.0	187.9	192.7	167.5	12.8	11.6	142.0	188.9
4170.	6132.	9100.	11896.	71.0	114.7	54.1	100.0	7.4	9.3	0.0	0.0
5640.	7043.	12200.	13781.	105.0	140.9	81.1	123.6	8.2	10.0	0.0	0.0
6020.	7933.	13000.	15857.	126.0	175.5	94.0	153.1	8.9	11.0	0.0	0.0
6260.	8297.	13000.	17169.	162.0	207.3	114.2	165.9	10.4	11.4	0.0	0.0
4620.	6949.	10500.	13363.	89.0	135.1	66.5	118.3	8.2	9.7	0.0	0.0

Table 10. Continued.

GRAIN YIELD		BIOMASS		N UPTAKE		GRAIN N NUPTAKE		GRAIN PROTEIN		ANTHESIS N UPTAKE	
O	P	O	P	O	P	O	P	O	P	O	P
5870.	7626.	13000.	15188.	118.0	162.9	87.5	141.8	8.5	10.6	0.0	0.0
5230.	8167.	13400.	16715.	147.0	195.1	104.9	161.9	9.6	11.3	0.0	0.0
6360.	8511.	[illegible]	17773.	166.0	224.9	121.6	170.2	10.9	11.4	0.0	0.0
3400.	2975.	8680.	9343.	74.3	124.1	56.7	84.0	9.5	16.1	81.9	129.3
3730.	3022	9190.	9854.	76.0	134.6	69.4	88.5	10.6	16.7	79.5	140.0
3460.	[illegible]	8910.	10206.	86.3	135.8	66.2	91.8	10.9	17.3	88.7	147.9
3410.	[illegible]	7920.	10353.	68.4	123.4	60.4	106.5	10.1	15.5	70.6	128.3
3660.	[illegible]	8690.	10857.	74.1	134.3	68.7	116.2	10.7	17.0	77.8	138.3
3650.	[illegible]	8550.	11287.	92.2	141.8	69.8	122.6	10.9	17.3	70.5	146.9
5810.	[illegible]	14470.	13888.	121.7	211.0	97.9	161.5	9.6	21.5	129.7	220.6
5600.	4377.	14370.	14410.	133.2	222.8	101.2	165.1	10.3	21.5	141.8	237.9
5490.	4301.	14670.	14876.	158.7	238.8	121.4	169.0	12.6	22.4	185.1	254.2
5530.	4414.	14770.	15406.	179.6	257.8	134.9	173.5	13.9	22.4	197.9	272.2
5190.	6532.	12660.	16305.	111.5	213.3	89.2	186.8	9.8	16.3	124.8	221.4
5690.	6976.	14100.	17216.	137.9	232.0	107.8	203.2	10.8	16.6	139.5	240.7
5310.	6897.	13780.	17835.	159.8	251.6	118.3	216.6	12.7	17.9	145.3	260.7
5190.	7117.	13600.	18460.	158.1	271.2	122.0	224.7	13.4	18.0	161.0	280.8
2070.	2252.	5694.	3973.	71.0	46.6	50.8	42.3	14.0	10.7	0.0	0.0
3772.	4409.	8412.	8349.	129.7	95.3	100.6	85.1	15.2	11.0	0.0	0.0
3450.	5057.	8459.	9469.	116.7	107.6	87.2	95.8	14.4	10.8	0.0	0.0
3470.	4899.	8736.	9074.	127.4	104.7	93.8	93.7	15.4	10.9	0.0	0.0
3631.	5069.	9292.	9481.	136.9	109.1	100.0	96.9	15.7	10.9	0.0	0.0
804.	313.	2821.	543.	32.8	6.6	20.7	6.0	14.7	11.0	0.0	0.0
992.	1141.	4286.	1959.	50.5	24.6	25.8	22.4	14.8	11.2	0.0	0.0
1159.	1558.	8241.	2682.	77.5	33.8	31.5	30.6	15.5	11.2	0.0	0.0
1240.	1727.	8322.	2976.	90.8	37.7	34.2	34.2	15.7	11.3	0.0	0.0
1521.	777.	3829.	1449.	53.7	17.5	39.0	15.8	14.6	11.6	0.0	0.0
1307.	1067.	4086.	2001.	65.1	24.0	37.6	21.5	16.4	11.5	0.0	0.0
978.	1161.	3264.	2178.	58.3	26.1	28.3	23.4	16.5	11.5	0.0	0.0
1005.	1258.	3403.	2270.	60.9	27.1	29.1	24.5	16.5	11.1	0.0	0.0
2352.	3437.	0.	9420.	48.2	88.9	35.5	62.7	8.6	10.4	0.0	90.6
3024.	4090.	0.	12657.	73.9	139.8	48.3	74.6	9.1	10.4	0.0	143.5
3696.	4202.	0.	13874.	96.3	169.4	67.4	76.7	10.4	10.4	0.0	174.4
3584.	4375.	0.	14936.	132.2	204.3	91.2	79.8	14.5	10.4	0.0	209.7
2240.	2978.	0.	10871.	50.4	131.0	33.8	56.4	8.6	10.8	0.0	133.1
2800.	3145.	0.	12223.	65.0	163.4	44.7	59.6	9.1	10.8	0.0	[illegible]
2688.	3254.	0.	13201.	67.2	184.8	49.0	61.7	10.4	10.8	0.0	195.7
2352.	3375.	0.	14663.	118.7	235.9	59.8	63.9	14.5	10.8	0.0	243.2
670.	447.	2016.	869.	14.6	9.6	0.0	8.5	0.0	10.9	0.0	0.0
1337.	2041.	4256.	4140.	31.3	47.8	0.0	42.6	0.0	11.9	0.0	0.0
2866.	2101.	10416.	10035.	154.5	178.7	95.5	53.4	19.0	14.5	222.9	186.3
2240.	2209.	9744.	10996.	155.7	214.1	60.5	58.1	15.4	15.0	227.4	222.1
2128.	2281.	9632.	11332.	150.1	234.4	57.9	60.0	15.5	15.0	198.2	242.6
2016.	2273.	9408.	11313.	151.2	241.2	70.7	59.8	20.0	15.0	212.8	249.2
2800.	2619.	10864.	11367.	154.5	178.6	94.3	66.6	19.2	14.5	222.9	190.2
2576.	2820.	10528.	12342.	155.7	214.3	85.0	71.7	18.8	14.5	227.4	223.2
2352.	2891.	10080.	12670.	150.1	234.6	78.4	73.5	19.0	14.5	198.2	243.4
2240.	2878.	10080.	12620.	151.1	241.3	78.6	73.2	20.0	14.5	212.8	251.1

Table 10. Continued.

GRAIN YIELD		BIOMASS		N UPTAKE		GRAIN N NUPTAKE		GRAIN PROTEIN		ANTHESIS N UPTAKE	
O	P	O	P	O	P	O	P	O	P	O	P
2866.	2108.	10416.	10087.	154.5	184.6	95.5	53.6	19.0	14.5	222.9	192.3
2240.	2204.	9744.	10997.	155.7	218.3	60.5	58.0	15.4	15.0	227.4	226.4
2128.	2275.	9632.	11318.	150.1	237.6	57.9	59.9	15.5	15.0	198.2	245.6
2016.	2265.	9408.	11297.	151.2	243.1	70.7	59.6	20.0	15.0	212.8	251.5
2800.	2621.	10864.	11406.	154.5	184.8	94.3	66.7	19.2	14.5	222.9	195.6
2576.	2815.	10528.	12327.	155.7	218.5	85.0	71.6	18.8	14.5	227.4	227.4
2352.	2884.	10080.	12647.	150.1	237.7	78.4	73.4	19.0	14.5	198.2	246.9
2240.	2869.	10080.	12605.	151.1	243.3	78.6	73.0	20.0	14.5	212.8	252.6
329.	139.	0.	265.	8.3	2.3	0.0	1.9	0.0	7.8	0.0	0.0
531.	1043.	0.	2077.	16.2	15.6	0.0	12.8	0.0	7.0	0.0	0.0
766.	888.	0.	1749.	25.2	13.2	0.0	10.9	0.0	7.0	0.0	0.0
1082.	1270.	0.	2492.	27.4	19.2	0.0	16.0	0.0	7.2	0.0	0.0
1344.	1425.	0.	2642.	30.8	20.8	0.0	17.8	0.0	7.1	0.0	0.0
3400.	3787.	5650.	7488.	49.0	60.0	47.1	50.5	7.9	7.6	40.0	65.9
4000.	4943.	7550.	9904.	57.0	87.3	51.9	74.6	7.4	8.6	40.0	90.8
5400.	5803.	10000.	11845.	83.0	108.2	76.7	92.6	8.1	9.1	0.0	115.6
6400.	6398.	12430.	13576.	107.0	133.7	96.6	115.6	8.6	10.3	96.0	137.6
6600.	7162.	13250.	15281.	123.0	160.0	110.0	138.2	9.5	11.0	96.0	163.8
7000.	7754.	14250.	16608.	153.0	179.6	136.3	156.4	11.1	11.5	0.0	185.0
6600.	8018.	13000.	17629.	149.0	207.6	134.3	177.2	11.6	12.6	172.0	211.8
7000.	8105.	14060.	17751.	197.0	220.7	158.4	182.0	12.9	12.8	172.0	225.2
3600.	3788.	7300.	8039.	62.0	60.6	59.4	47.2	9.4	7.1	40.0	67.0
4200.	4739.	8950.	10355.	69.0	89.7	64.1	67.3	8.7	8.1	40.0	92.2
4800.	5409.	10000.	12066.	72.0	113.1	67.4	76.9	8.0	8.1	0.0	117.4
5800.	5821.	12700.	13314.	98.0	134.3	87.5	82.7	8.6	8.1	96.0	138.2
6100.	6209.	13000.	14457.	111.0	156.3	98.5	88.2	9.2	8.1	96.0	161.6
6800.	6610.	15050.	15564.	153.0	181.9	126.5	93.9	10.6	8.1	0.0	186.6
6200.	6991.	14300.	16582.	150.0	207.4	121.8	99.3	11.2	8.1	172.0	212.1
6500.	7111.	14500.	17384.	172.0	230.4	138.0	103.5	12.1	8.3	172.0	236.0
3100.	3549.	5500.	7572.	52.0	59.5	50.0	47.9	9.2	7.7	40.0	65.9
4600.	4482.	8800.	9808.	71.0	81.9	67.0	66.1	8.3	8.4	40.0	90.8
5600.	5260.	10800.	11960.	88.0	112.2	80.6	92.3	8.2	10.0	0.0	115.6
5900.	5798.	11300.	13473.	88.0	134.3	77.6	108.8	7.5	10.7	96.0	137.6
6400.	6371.	12300.	14904.	107.0	160.2	98.8	122.9	8.8	11.0	96.0	163.8
7600.	6850.	13400.	16063.	151.0	179.7	134.7	132.2	10.1	11.0	0.0	185.0
7900.	7269.	15400.	16918.	191.0	207.7	170.5	140.3	12.3	11.0	172.0	211.8
6800.	7146.	13300.	17016.	172.0	220.9	153.9	140.4	12.9	11.2	172.0	225.2
2358.	1515.	0.	2684.	0.0	31.6	63.7	28.4	15.4	10.7	0.0	0.0
2955.	2560.	0.	4712.	0.0	53.5	82.4	48.1	15.9	10.7	0.0	0.0
3490.	3004.	0.	5618.	0.0	62.5	94.3	55.9	15.4	10.6	0.0	0.0
3538.	2815.	0.	5227.	0.0	59.3	98.1	53.3	15.8	10.8	0.0	0.0
3316.	3015.	0.	5638.	0.0	63.5	94.2	56.6	16.2	10.7	0.0	0.0
3774.	1293.	10330.	5982.	100.1	92.2	0.0	25.2	0.0	11.1	89.1	95.5
4075.	1334.	11740.	6100.	120.8	95.8	0.0	26.0	0.0	11.1	106.9	99.2
4056.	1448.	11632.	6410.	114.1	103.4	0.0	28.2	0.0	11.1	88.6	107.0
4098.	1509.	12190.	6682.	127.9	112.7	0.0	29.4	0.0	11.1	116.4	116.4
3982.	1577.	11841.	6990.	124.4	123.0	0.0	30.7	0.0	11.1	107.1	127.1
3937.	1619.	12845.	7208.	127.0	131.3	0.0	31.5	0.0	11.1	119.0	135.6

Summary

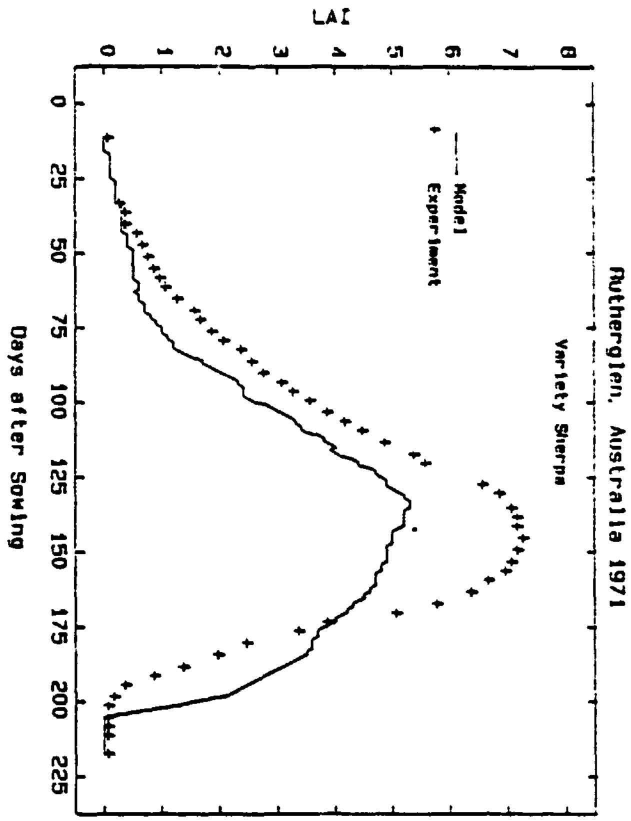
CERES-Wheat-N is designed to be used as a management-oriented model for a diversity of applications in many environments. To make the model useful for such a wide audience, the inputs must be minimal and they must be reasonably easy to attain or estimate from standard agricultural experimental practice. Given these constraints, the model simulates crop growth and response to fertilizer reasonably reliably. The rigorous statistical analysis indicated that some problems have yet to be resolved with the prediction of N uptake and grain protein concentration in some data sets. Some tendency to overpredict biomass and N uptake early in the season was also noted. Further testing and refinement of this area of the model may be beneficial. Further data sets are required to test more reliably the soil N components of the model.

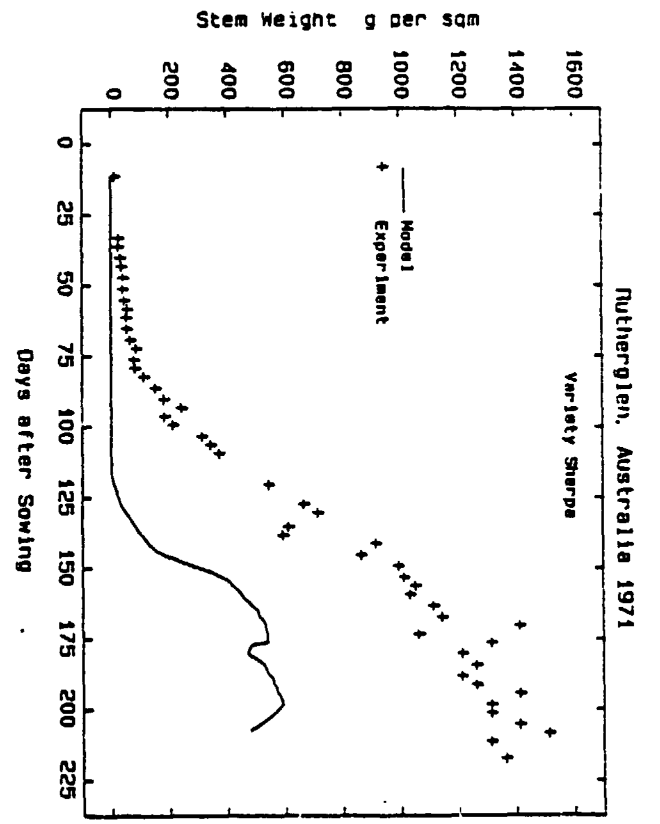
APPENDIX A

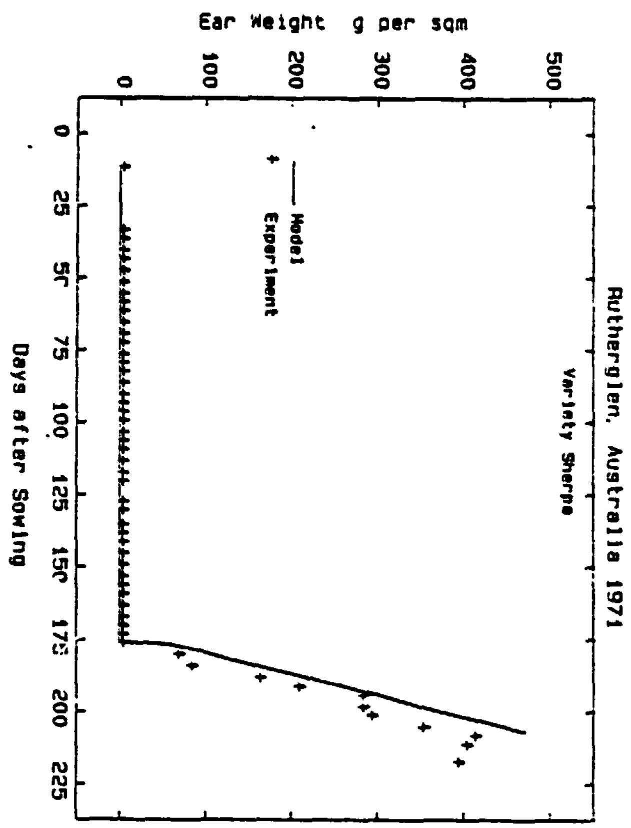
CERES-WHEAT (non-nitrogen) MODEL VALIDATION

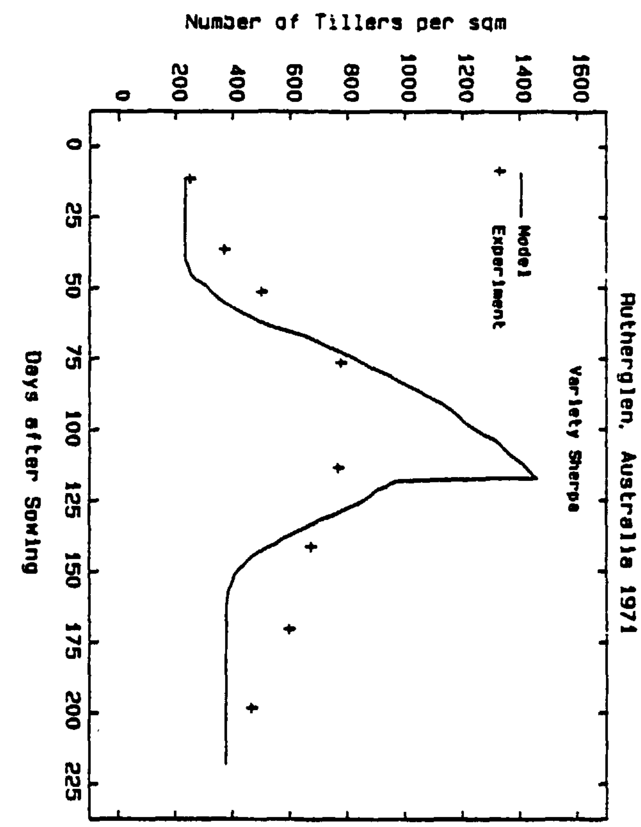
RESULTS FROM INDIVIDUAL EXPERIMENTS

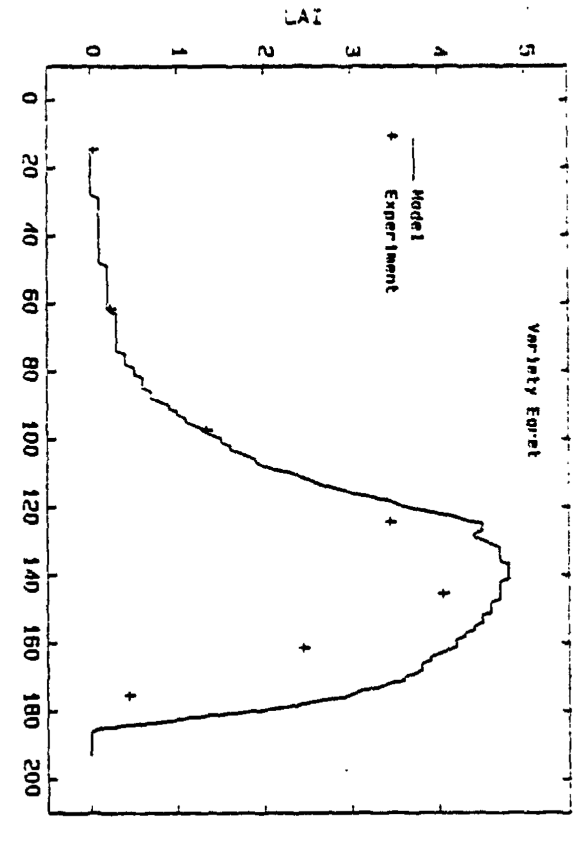
PREDICTED VS. OBSERVED

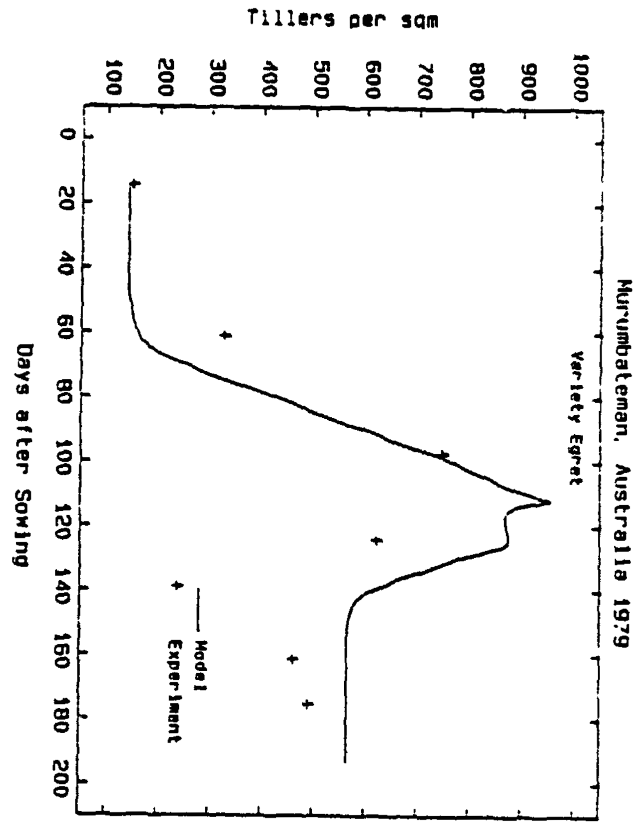

Rutherglen, Australia 1971
Variety Sherpa
Model
Experiment
LAI
0
1
2
3
4
5
6
7
8
Days after Sowing
0
25
50
75
100
125
150
175
200
225

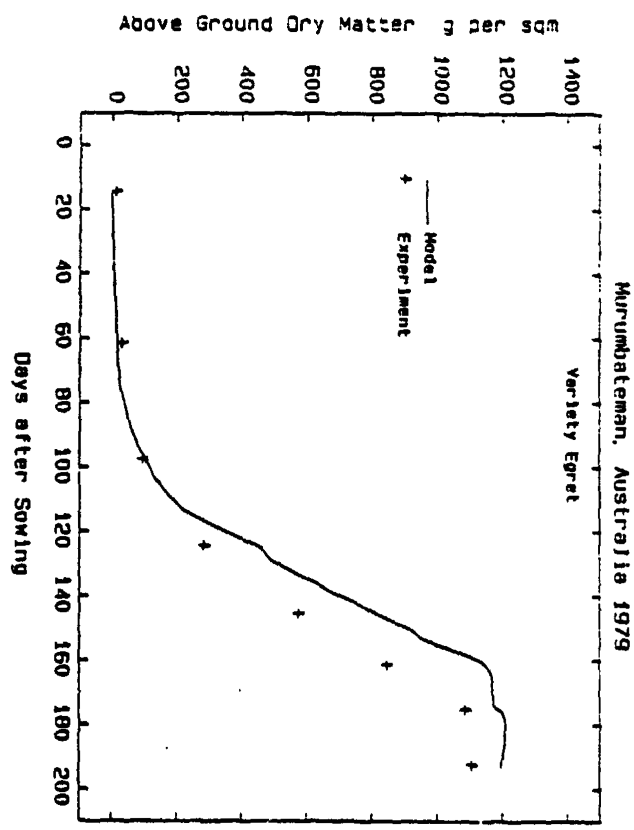

Rutherglen, Australia 1971
Variety Sherpa
Model
Experiment
Stem Weight g per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
25
50
75
100
125
150
175
200
225

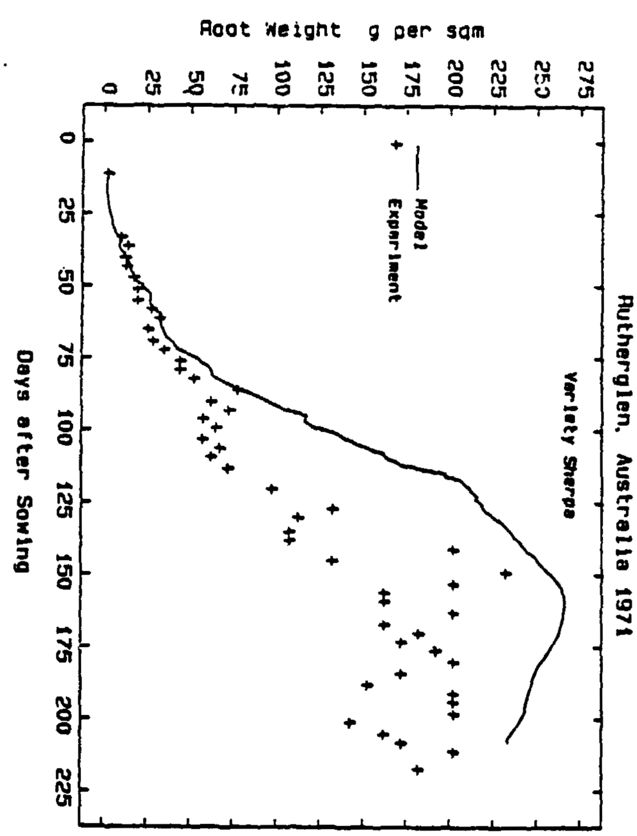

Rutherglen, Australia 1971
Variety Sherpa
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
Days after Sowing
0
25
50
75
100
125
150
175
200
225


Rutherglen, Australia 1971
Variety Sherpa
Model
Experiment
Number of Tillers per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
25
50
75
100
125
150
175
200
225

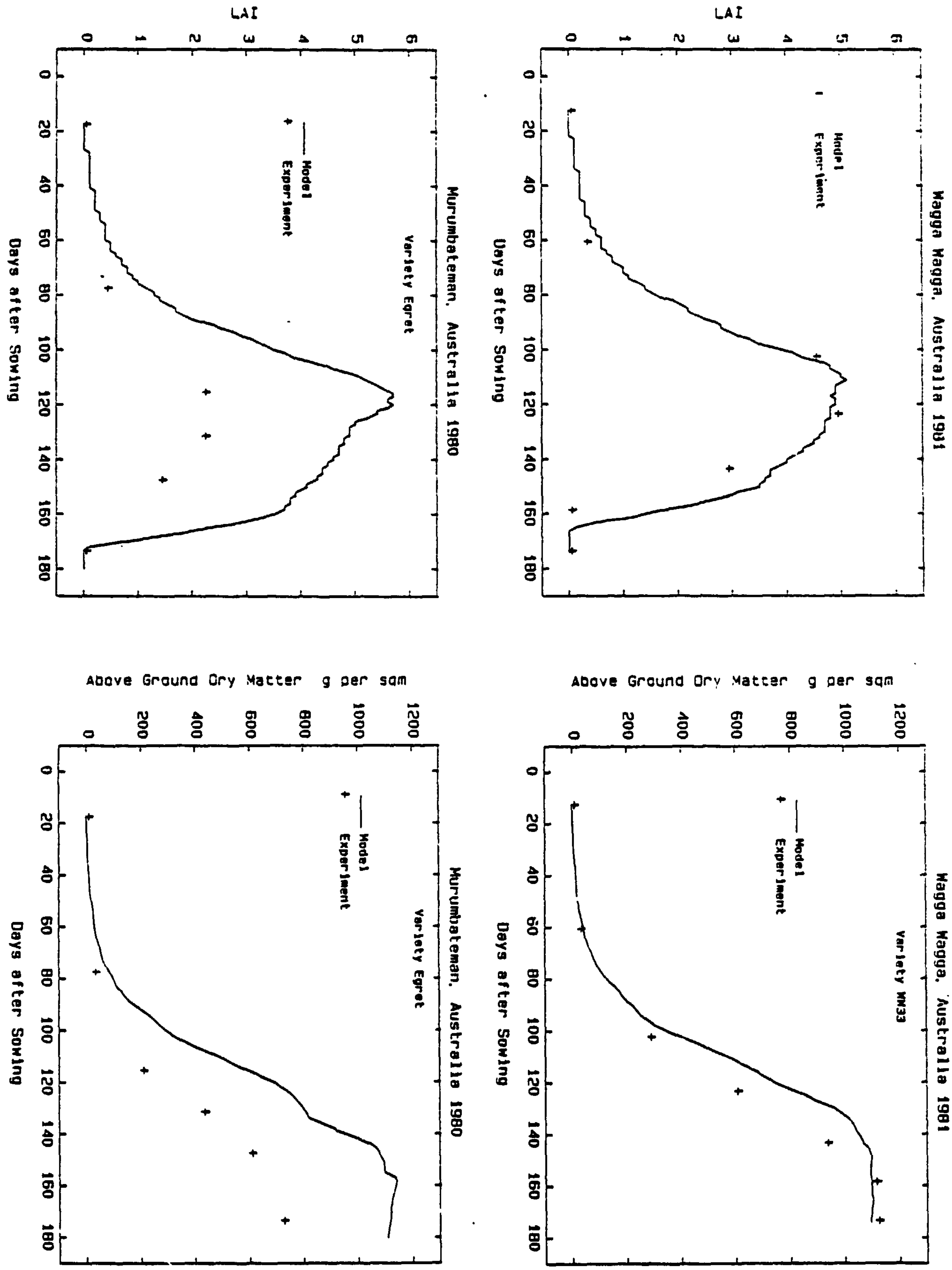

Murumbateman, Australia 1979
Variety Egret
Model
Experiment
LAI
Days after Sowing

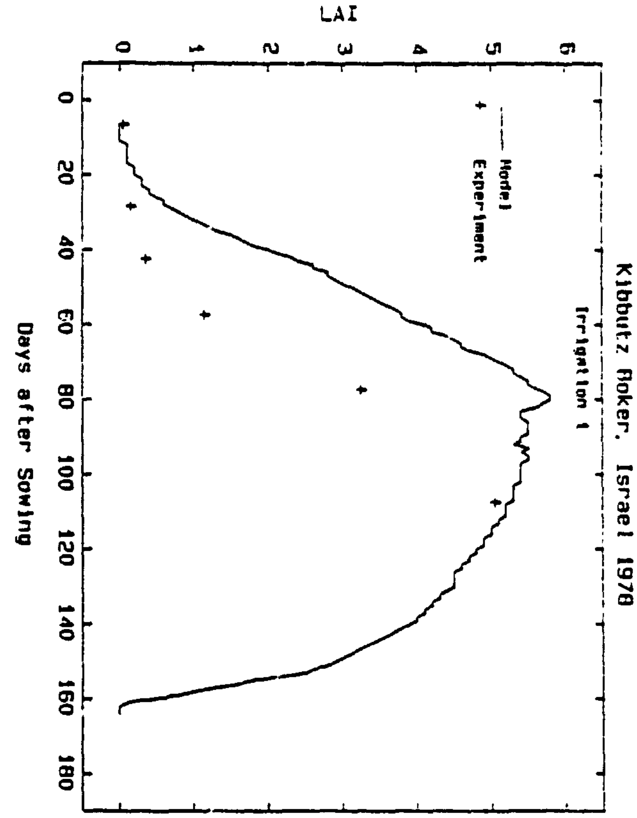

Murumbateman, Australia 1979
Variety Egret
Model
Experiment
Tillers per sqm
Days after Sowing

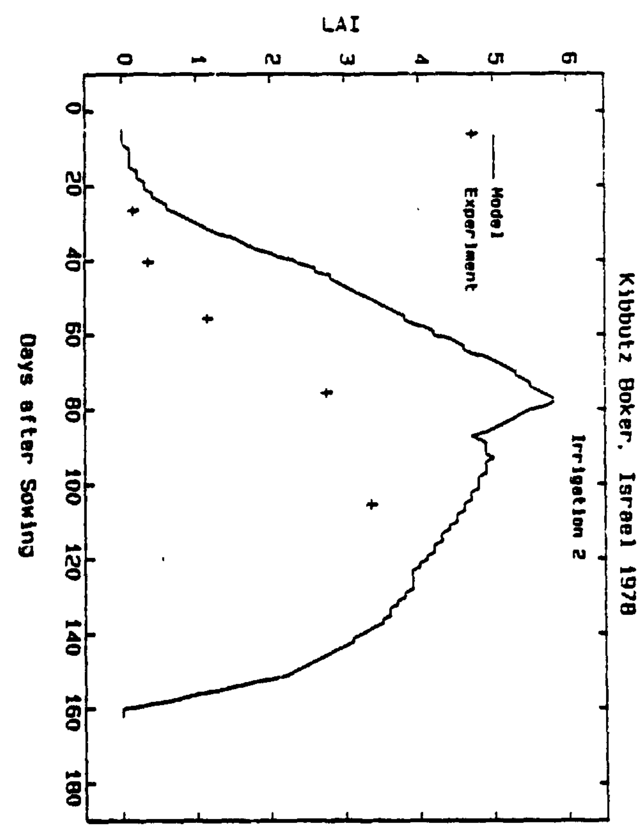

Murumbateman, Australia 1979
Variety Egret
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

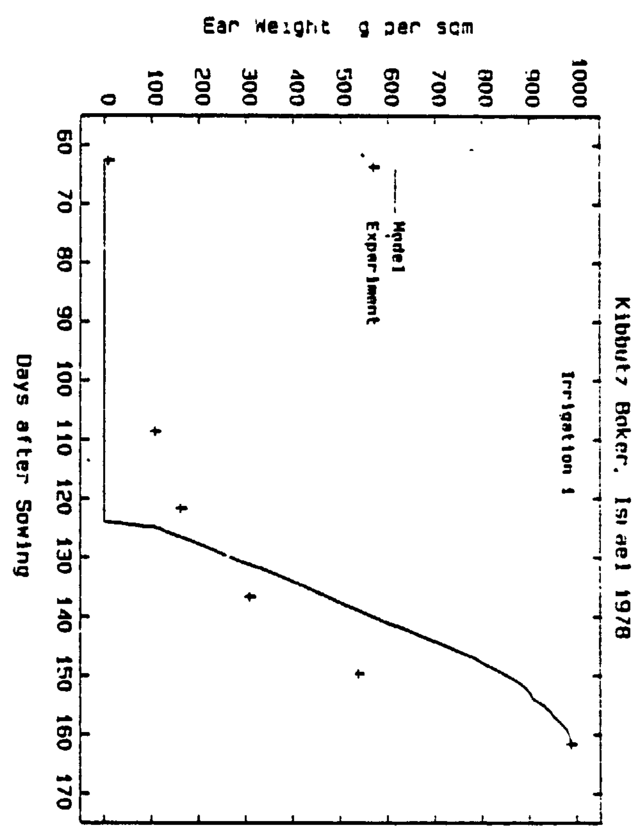

Rutherglen, Australia 1971
Variety Sharpe
Model
Experiment
Root Weight g per sqm
Days after Sowing

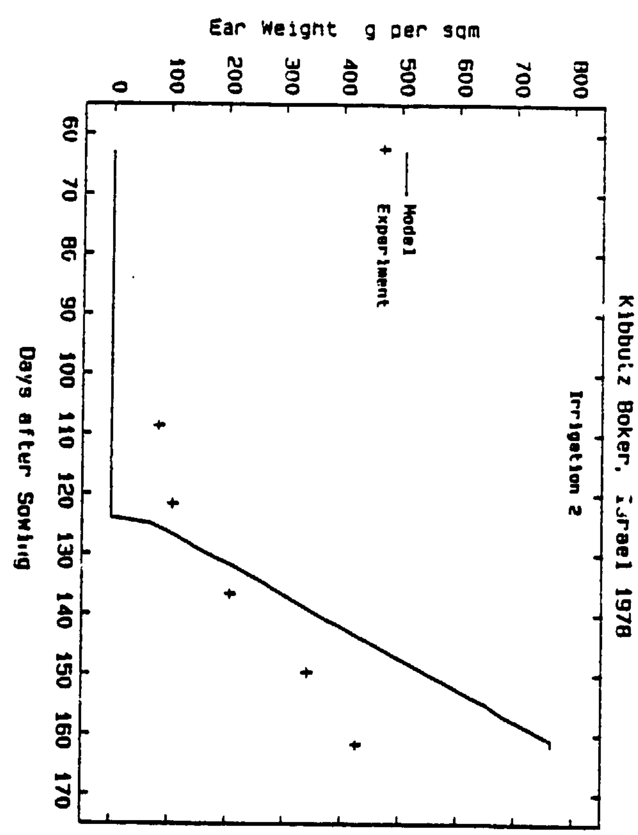
Wagga Wagga, Australia

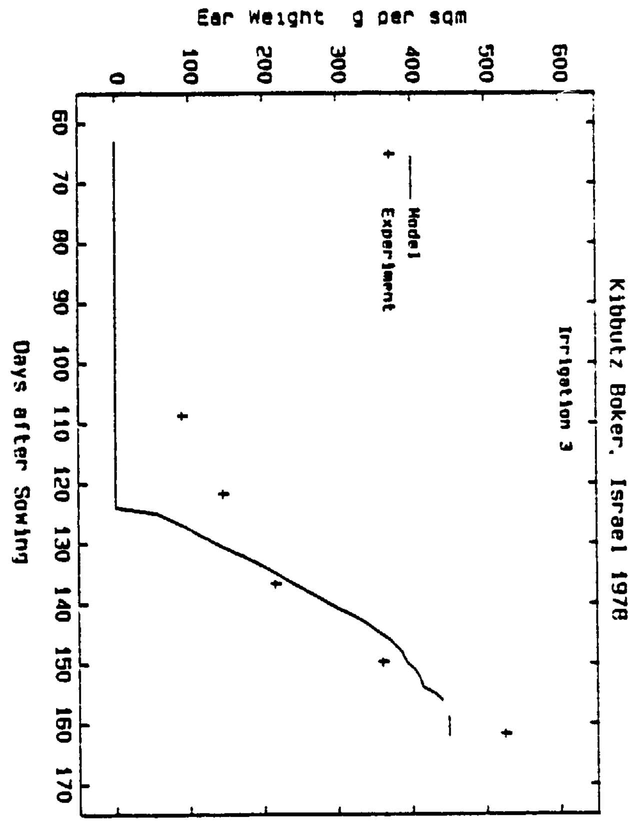


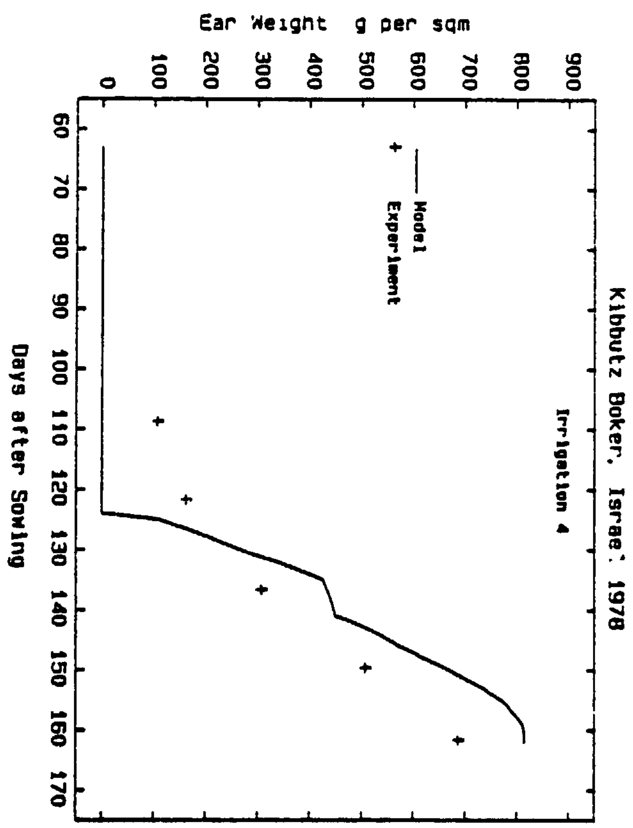

Kibbutz Boker, Israel 1978
Irrigation 1
LAI
Days after Sowing
Model
Experiment
0 1 2 3 4 5 6
0 20 40 60 80 100 120 140 160 180

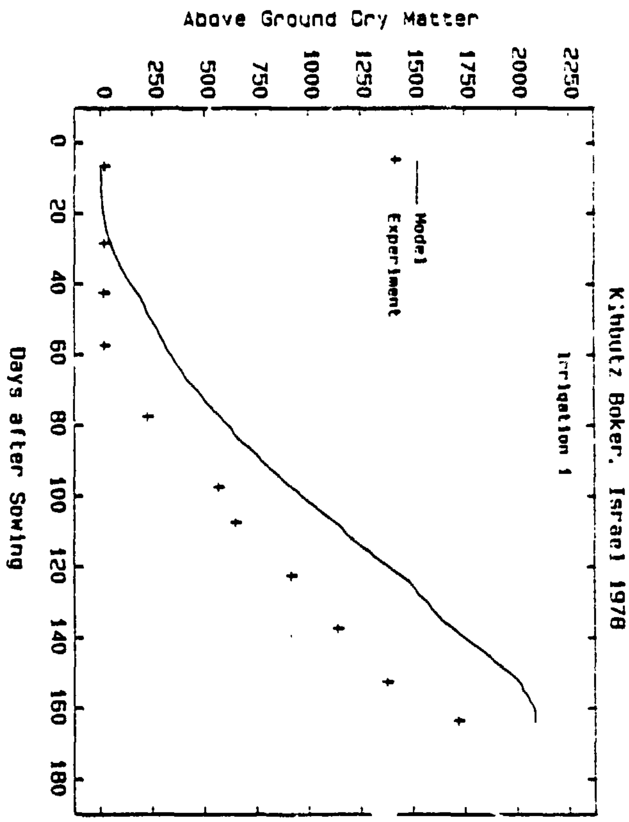

Kibbutz Boker, Israel 1978
Irrigation 2
LAI
Days after Sowing
Model
Experiment
0 1 2 3 4 5 6
0 20 40 60 80 100 120 140 160 180

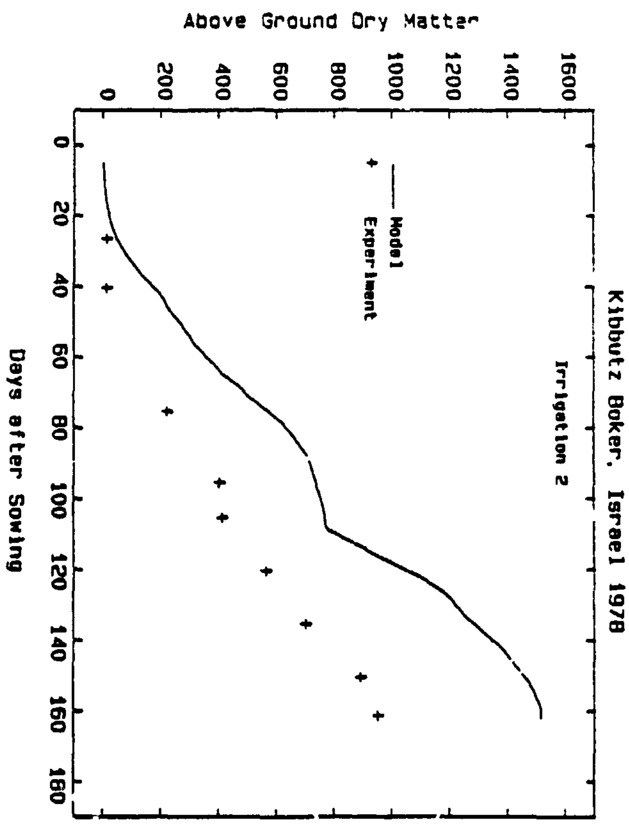

Kibbutz Boker, Israel 1978
Irrigation 1
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
600
700
800
900
1000
Days after Sowing
60
70
80
90
100
110
120
130
140
150
160
170

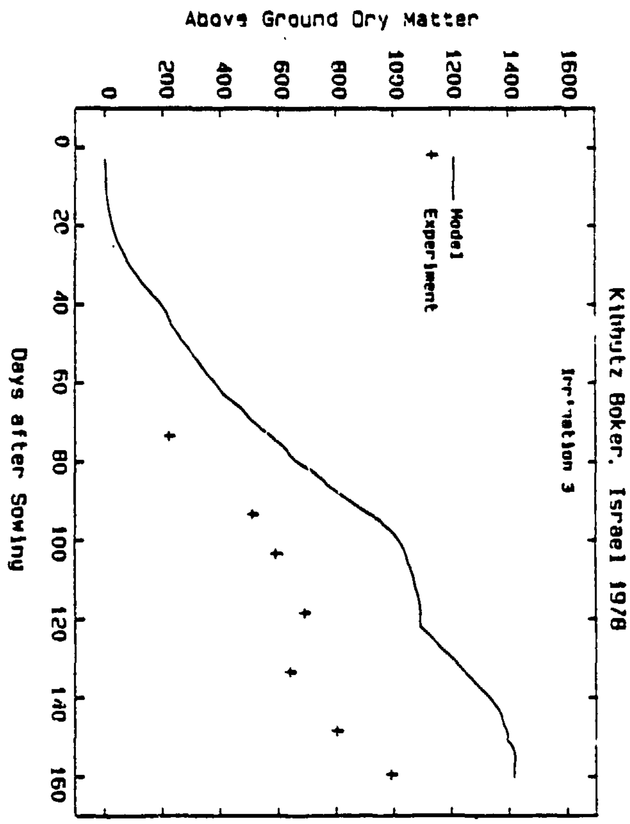

Kibbutz Boker, Israel 1978
Irrigation 2
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
600
700
800
Days after Sowing
60
70
80
90
100
110
120
130
140
150
160
170

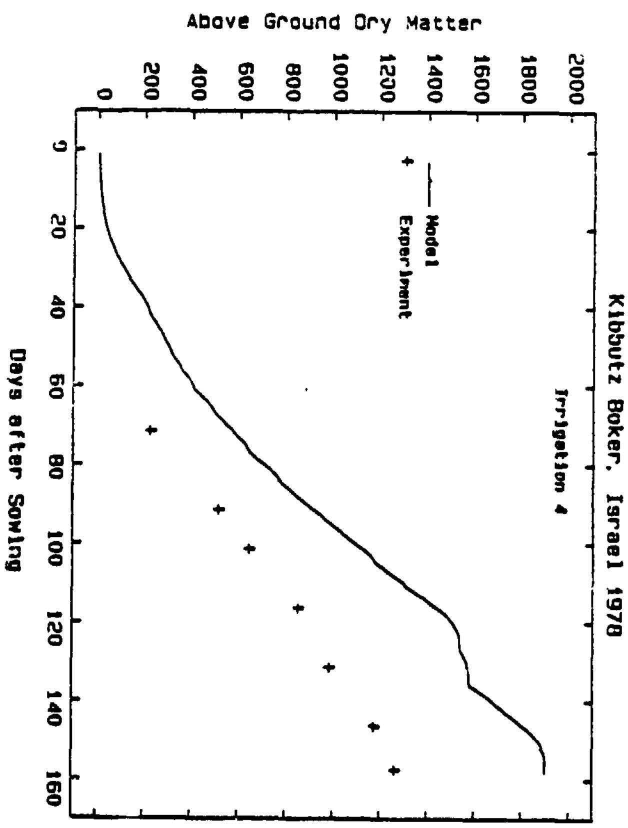

Kibbutz Boker, Israel 1978
Irrigation 3
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
600
Days after Sowing
60
70
80
90
100
110
120
130
140
150
160
170

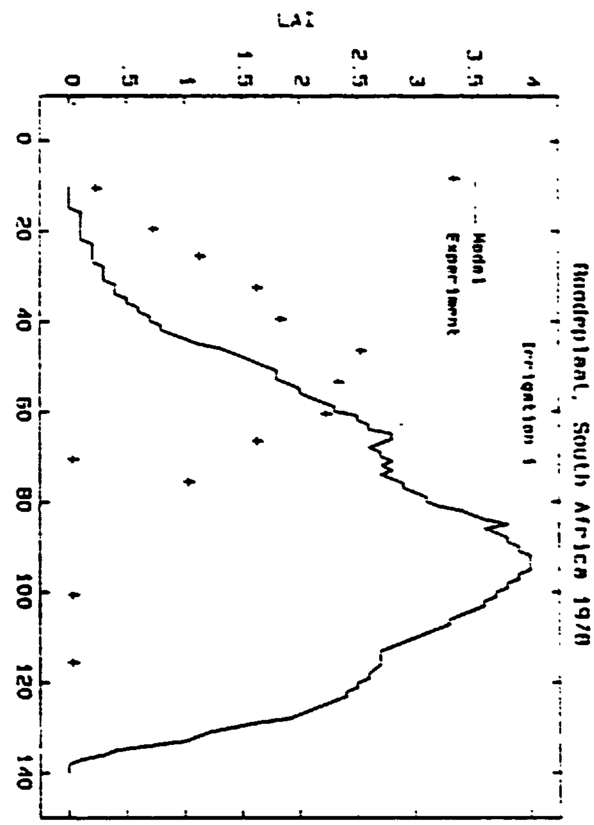

Kibbutz Boker, Israel 1978
Irrigation 4
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
600
700
800
900
Days after Sowing
60
70
80
90
100
110
120
130
140
150
160
170

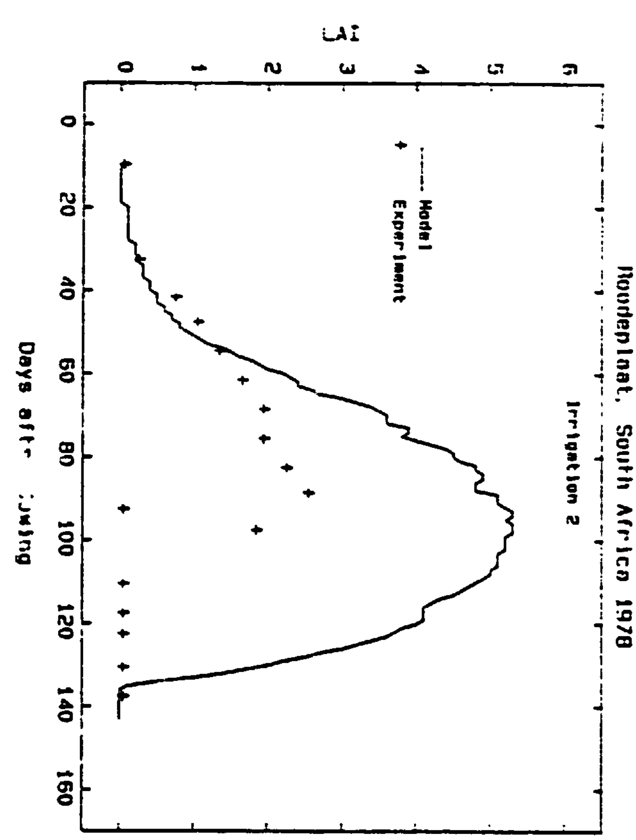

Kibbutz Boker, Israel 1978
Irrigation 1
Model
Experiment
Above Ground Dry Matter
0
250
500
750
1000
1250
1500
1750
2000
2250
Days after Sowing
0
20
40
60
80
100
120
140
160
180

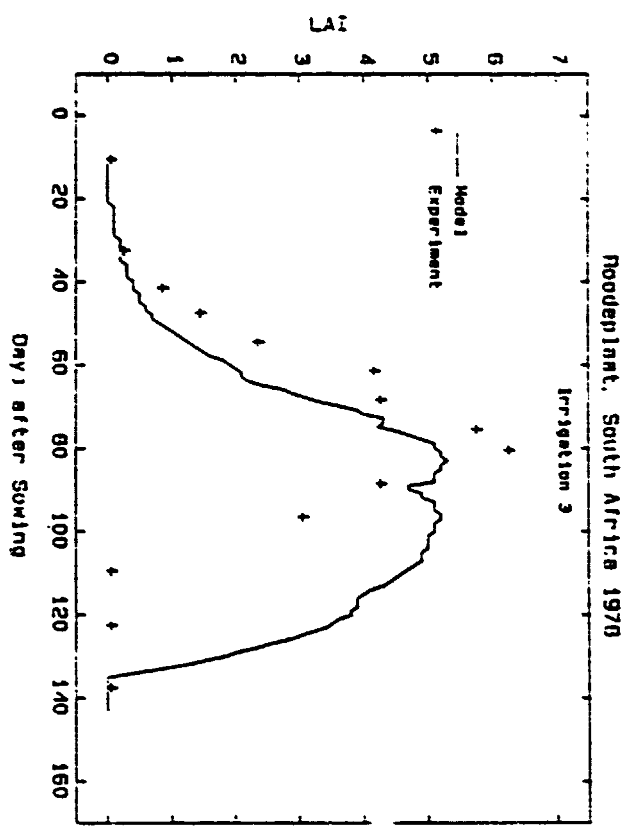

Kibbutz Boker, Israel 1978
Irrigation 2
Model
Experiment
Above Ground Dry Matter
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
20
40
60
80
100
120
140
160
180

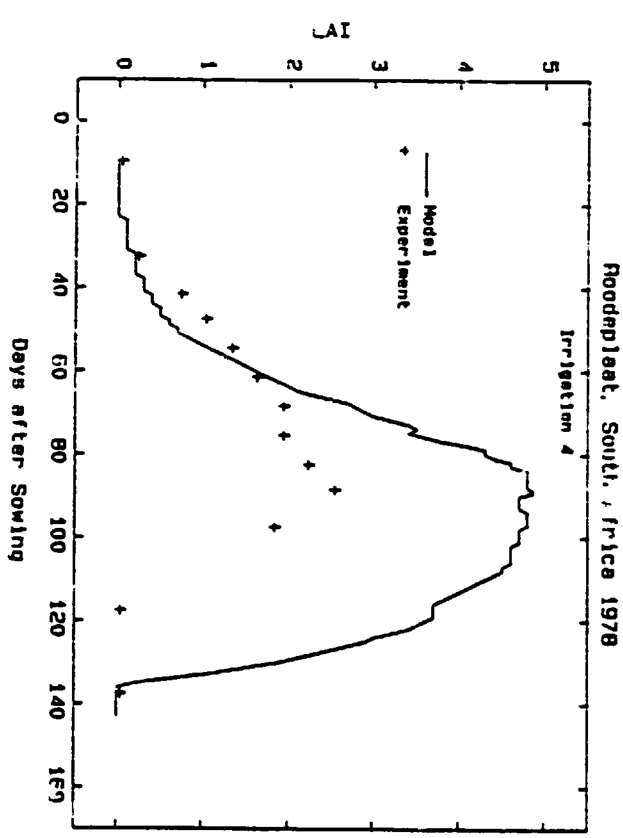

Kibbutz Boker, Israel 1978
Model
Experiment
Above Ground Dry Matter
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
20
40
60
80
100
120
140
160

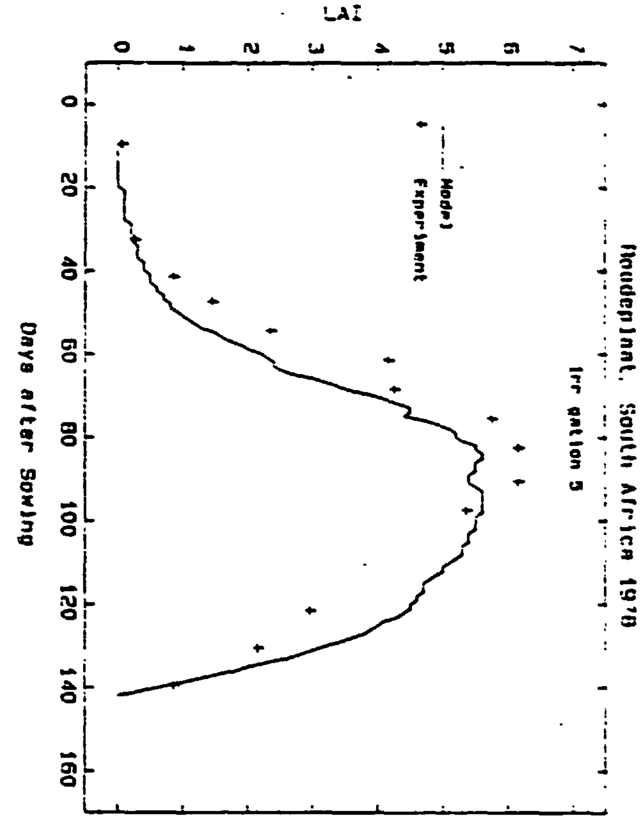

Kibbutz Boker, Israel 1978
Irrigation 4
Model
Experiment
Above Ground Dry Matter
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Days after Sowing
20
40
60
80
100
120
140
160

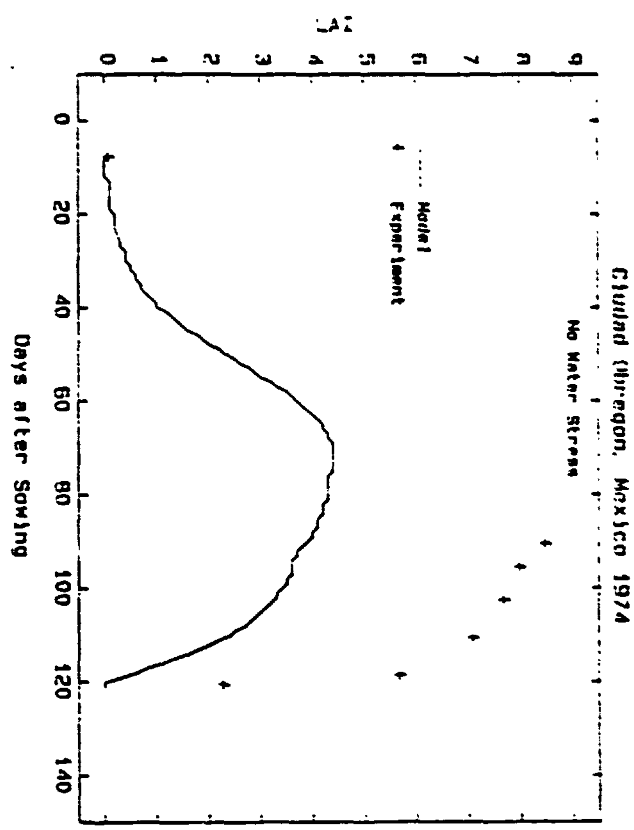

Roodeplaat, South Africa 1978
Irrigation 1
Model
Experiment
LAI
Days after Sowing

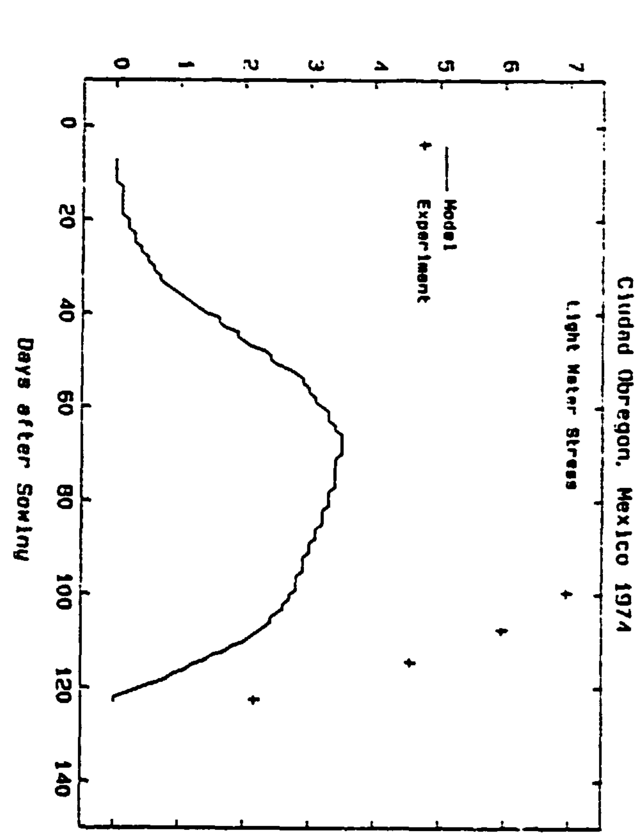

Roodeplaat, South Africa 1978
Irrigation 2
Model
Experiment
LAI

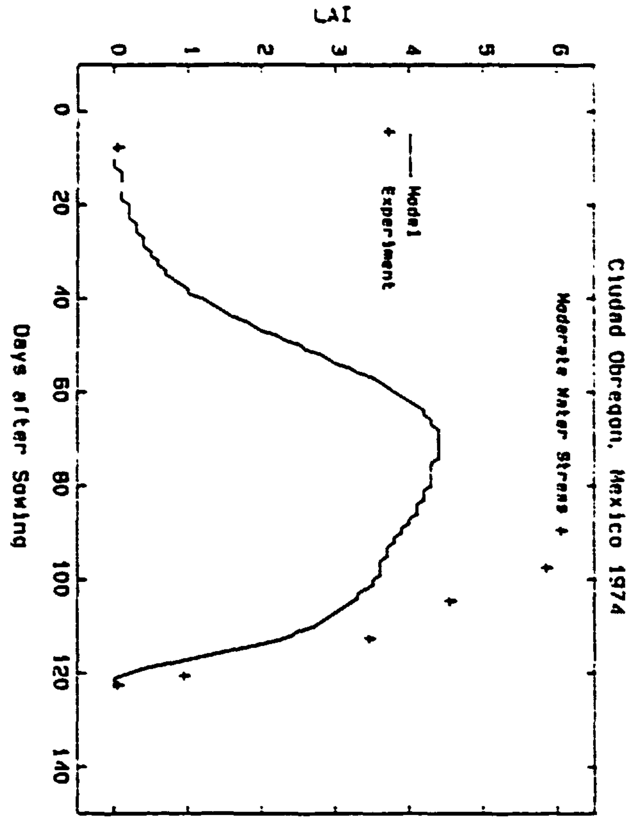

Roodeplaat, South Africa 1978
Irrigation 3
Model
Experiment
LAI

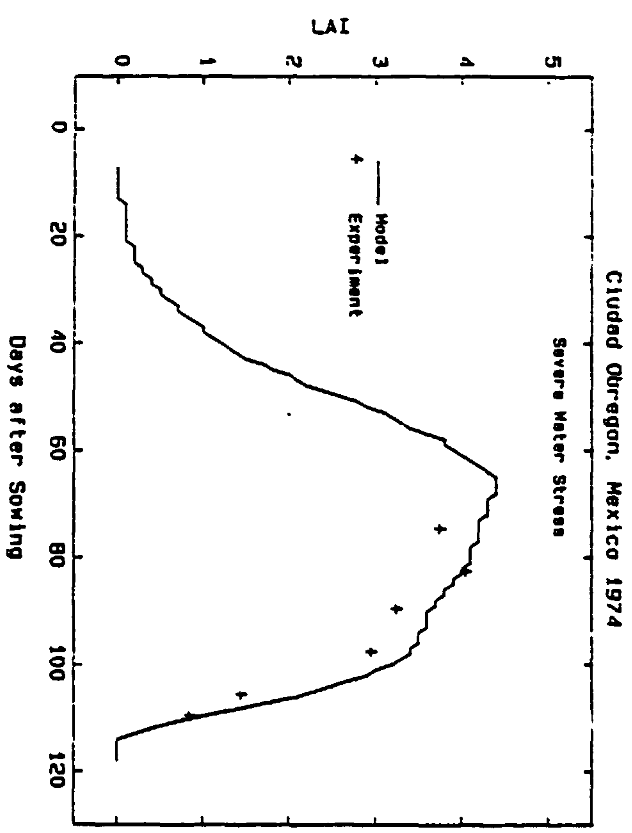

Irrigation 4
Model
Experiment
LAI
Days after Sowing

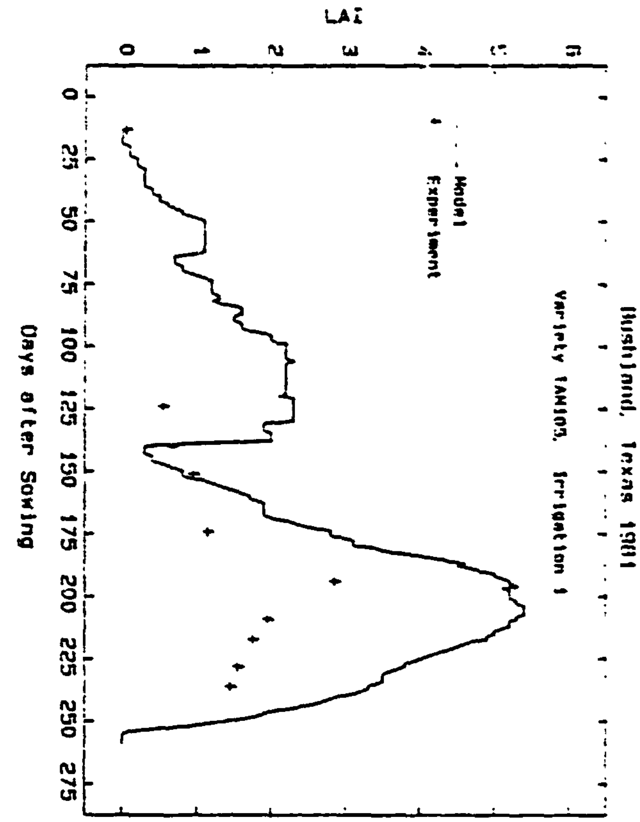

LAI
0
1
2
3
4
5
6
7
Model
Experiment
0
20
40
60
80
100
120
140
160
Days after Sowing

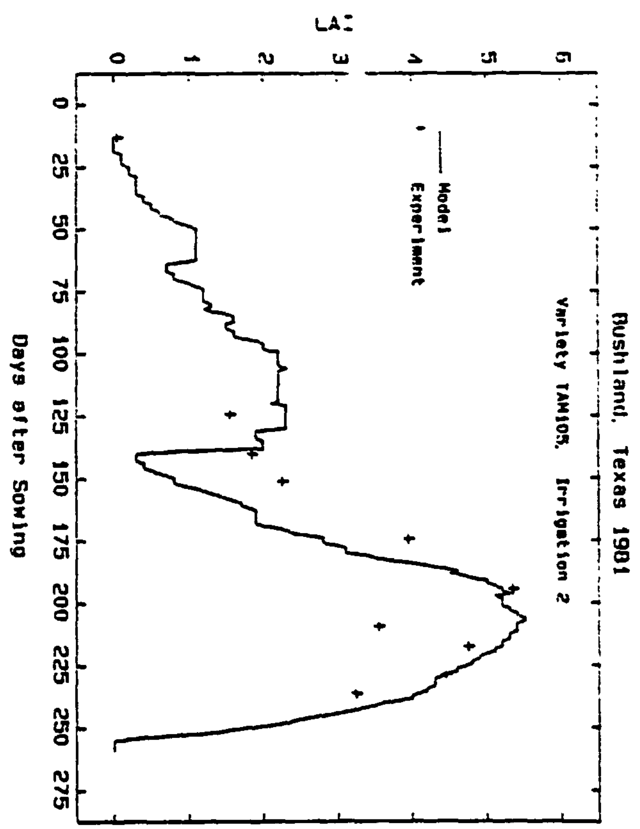

Ciudad Obregon, Mexico 1974
No Water Stress
Model
Experiment
LAI
Days after Sowing

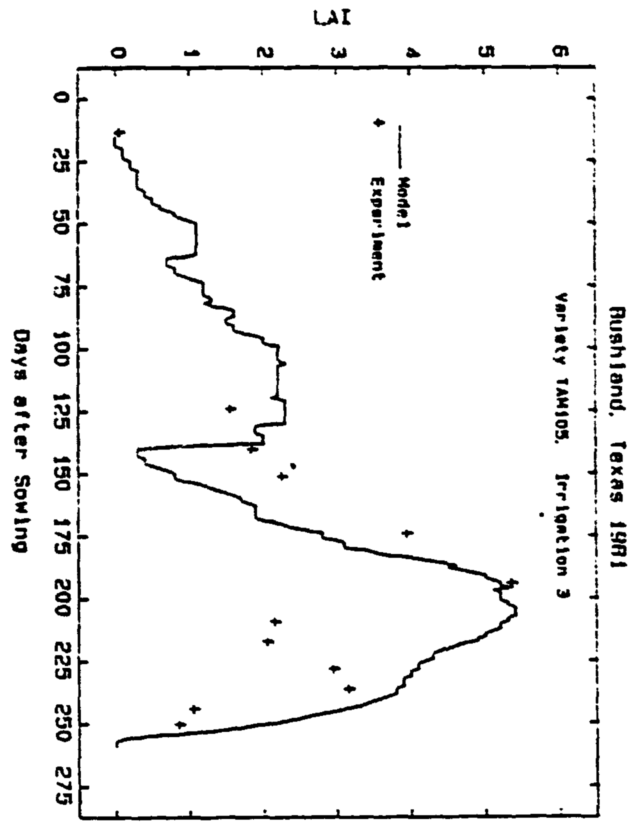

Ciudad Obregon, Mexico 1974
Light Water Stress
Model
Experiment
LAI
Days after Sowing

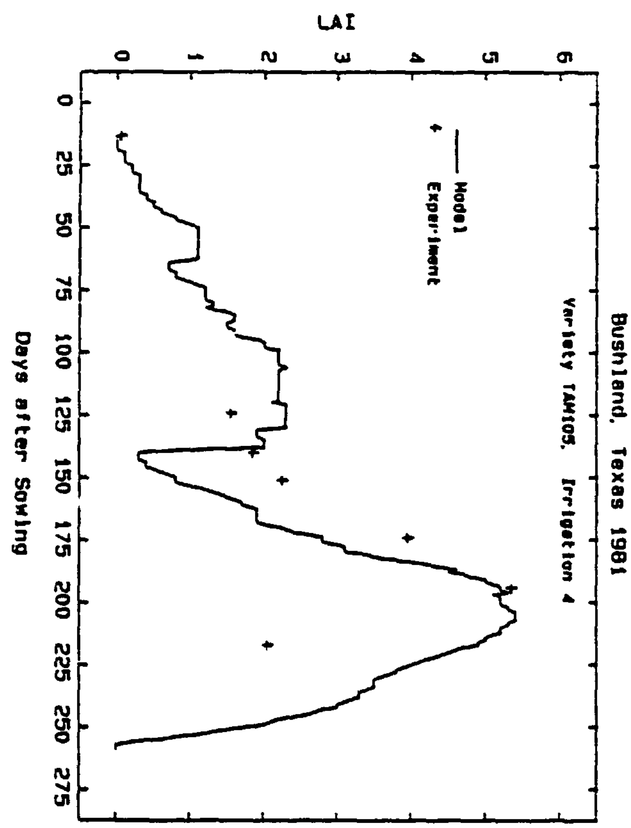

Ciudad Obregon, Mexico 1974
Moderate Water Stress
Model
Experiment
LAI
Days after Sowing

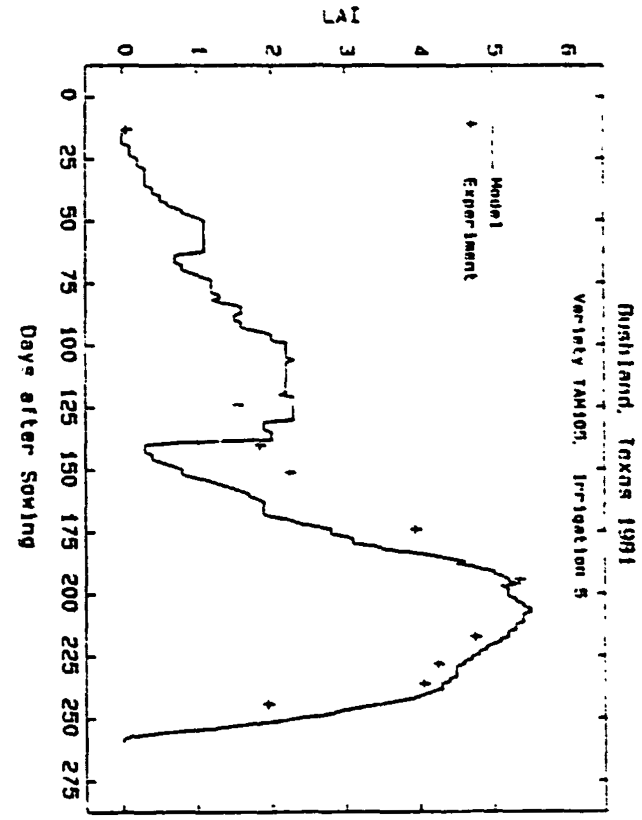

Ciudad Obregon, Mexico 1974
Severe Water Stress
Model
Experiment
LAI
Days after Sowing

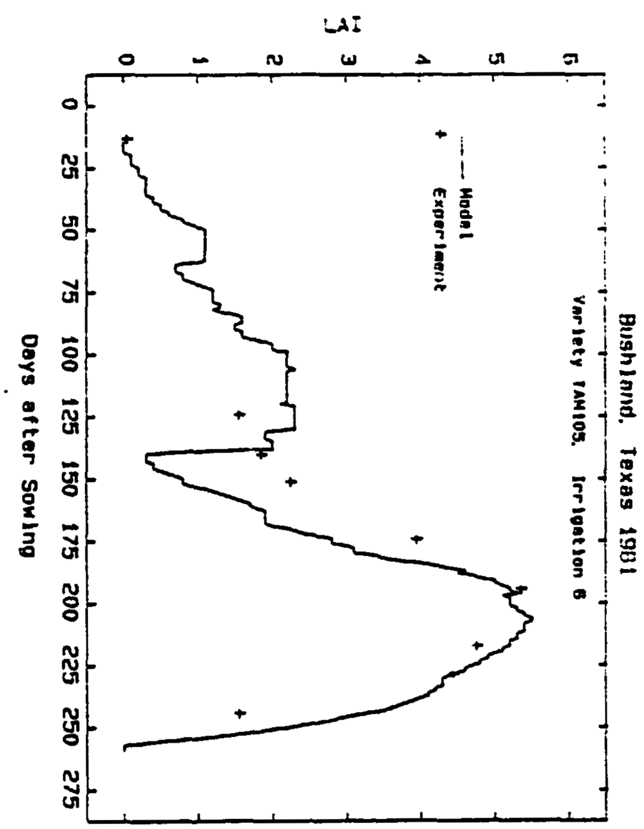

Bushland, Texas 1981
Variety TAM105, Irrigation 1
Model
Experiment
LAI
Days after Sowing

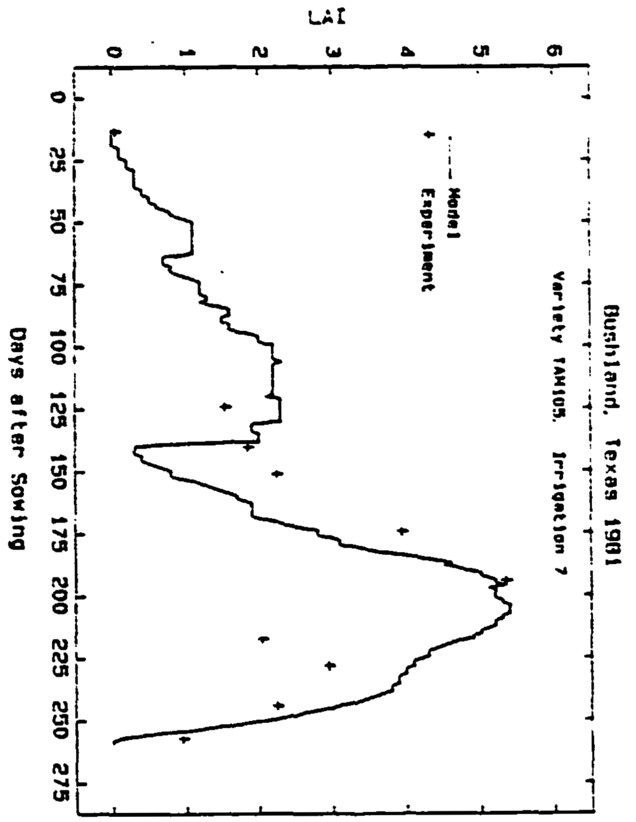

Bushland, Texas 1981
Variety TAM105, Irrigation 2
Model
Experiment
LAI
Days after Sowing

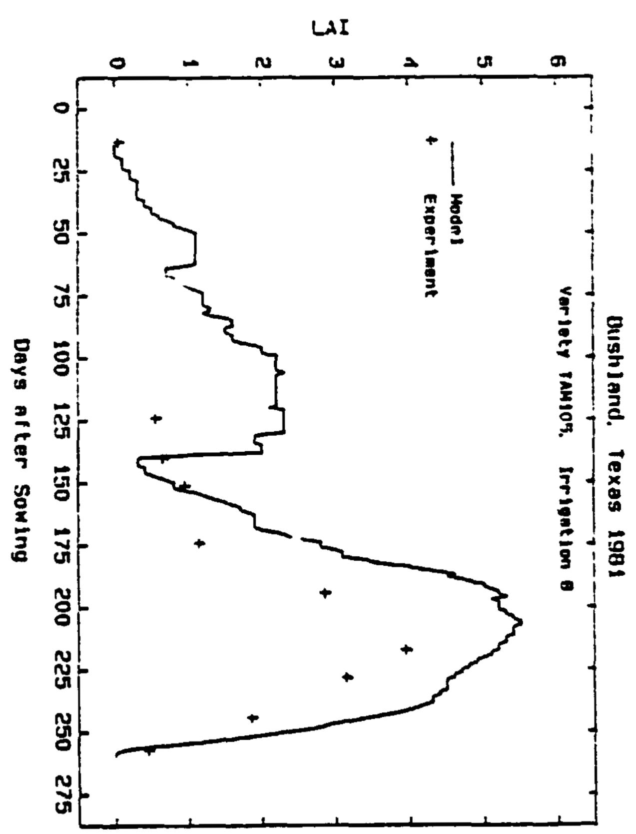

Bushland, Texas 1981
Variety TAM105, Irrigation 3
Model
Experiment
LAI
Days after Sowing

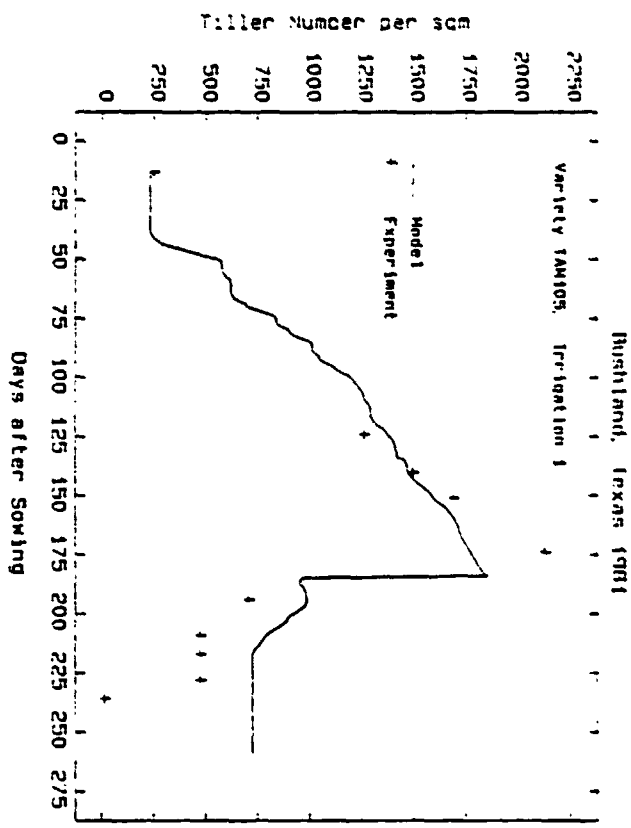

Bushland, Texas 1981
Variety TAM105, Irrigation 4
Model
Experiment
LAI
Days after Sowing

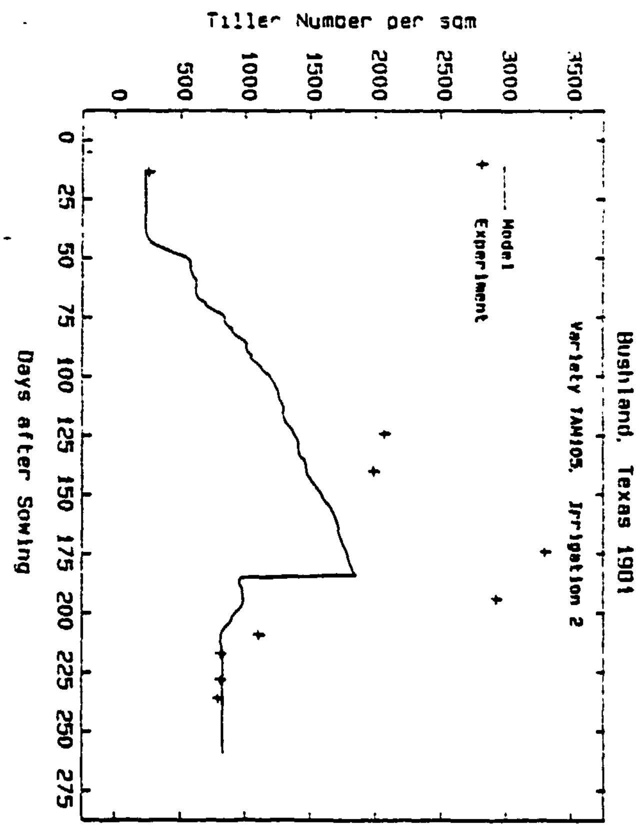

Bushland, Texas 1981
Variety TAM105, Irrigation 5
Model
Experiment
LAI
Days after Sowing

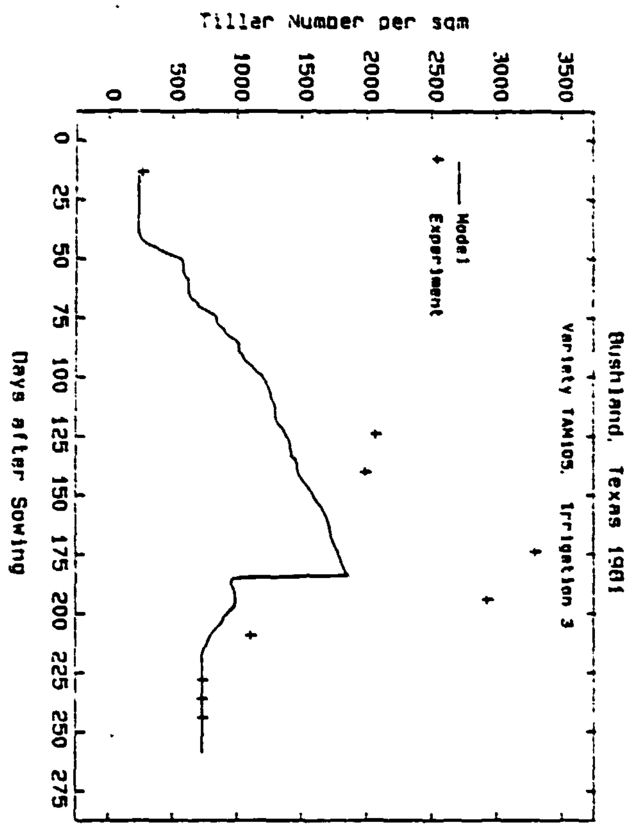

Bushland, Texas 1981
Variety TAM105, Irrigation 6
Model
Experiment
LAI
Days after Sowing

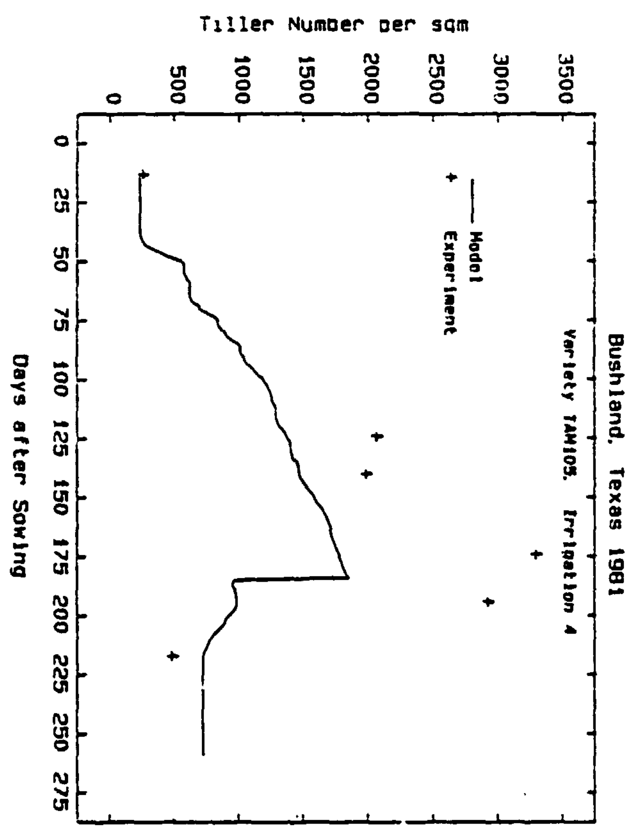

Bushland, Texas 1981
Variety TAM105, Irrigation 7
Model
Experiment
LAI
Days after Sowing

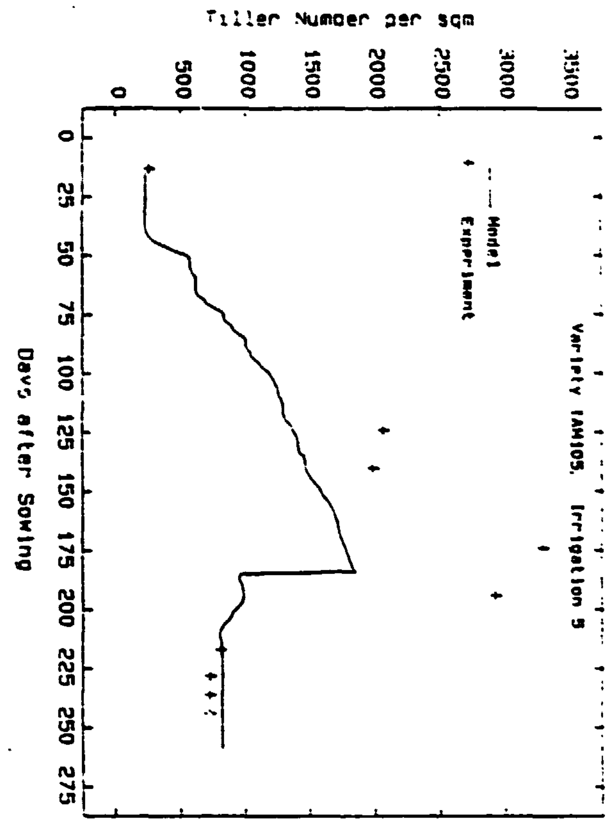

Bushland, Texas 1981
Variety TAM105, Irrigation 8
Model
Experiment
LAI
Days after Sowing

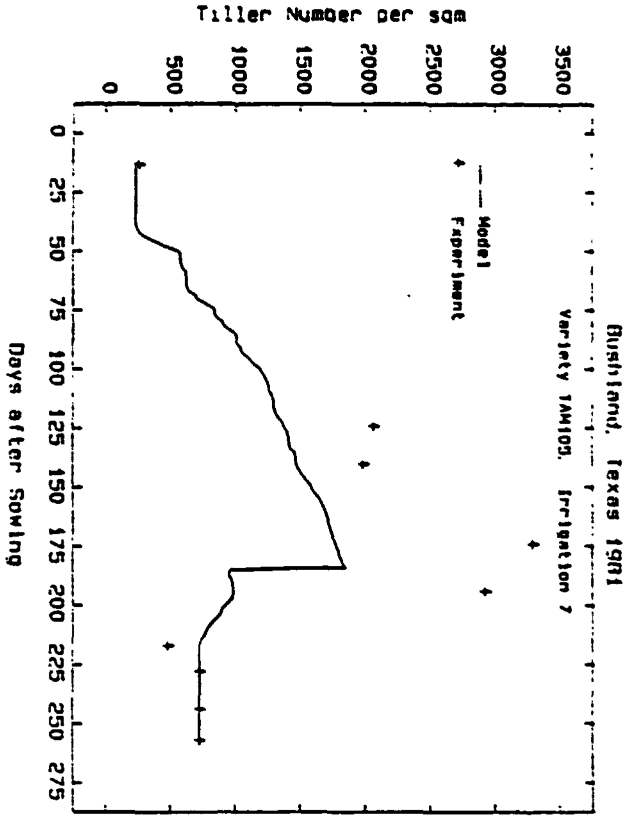

Bushland, Texas 1981
Variety TAM105, Irrigation 1
Model
Experiment
Tiller Number per sqm
0
250
500
750
1000
1250
1500
1750
2000
2250
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

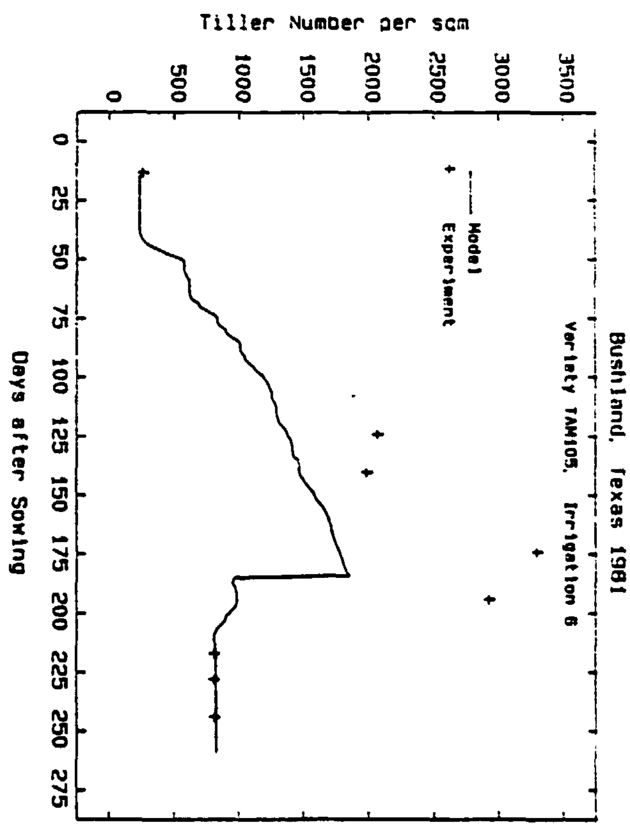

Bushland, Texas 1981
Variety TAM105, Irrigation 2
Model
Experiment
Tiller Number per sqm
0
500
1000
1500
2000
2500
3000
3500
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

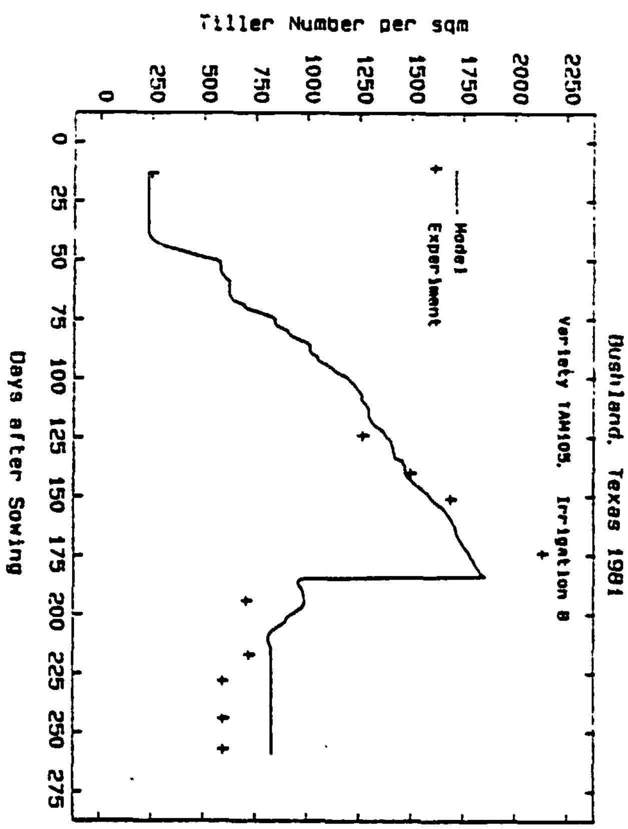

Bushland, Texas 1981
Variety TAM105, Irrigation 3
Model
Experiment
Tiller Number per sqm
0
500
1000
1500
2000
2500
3000
3500
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

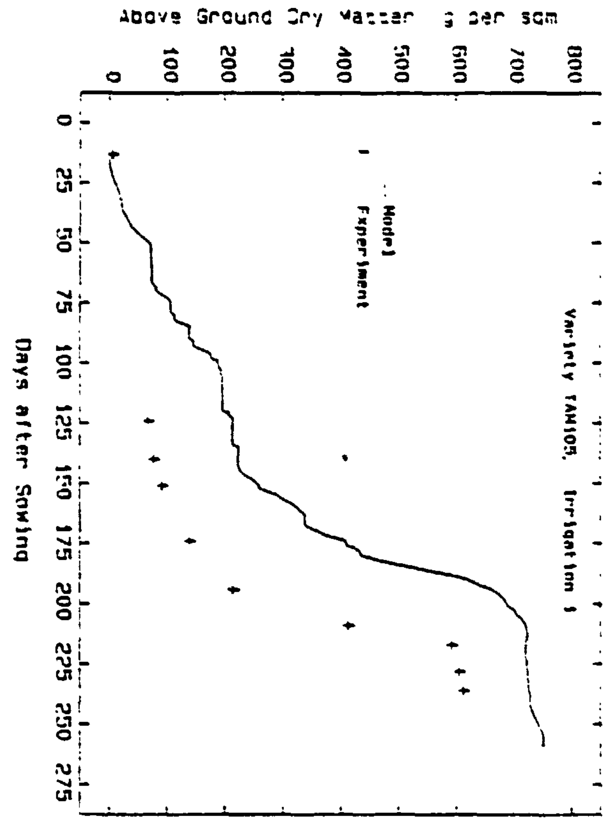

Bushland, Texas 1981
Variety TAM105, Irrigation 4
Model
Experiment
Tiller Number per sqm
0
500
1000
1500
2000
2500
3000
3500
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

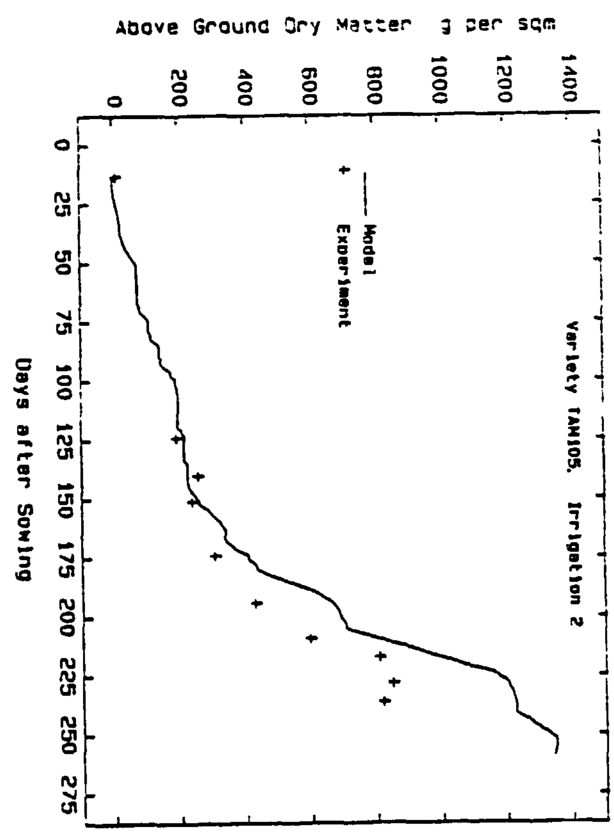

Bushland, Texas 1981
Variety TAM105, Irrigation 5
Model
Experiment
Tiller Number per sqm
Days after Sowing

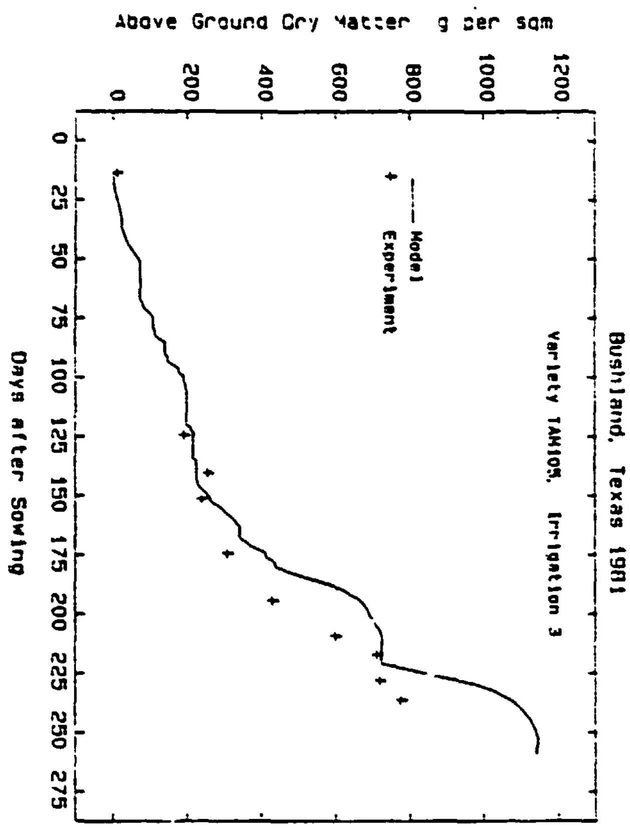

Bushland, Texas 1981
Variety TAM105, Irrigation 7
Model
Experiment
Tiller Number per sqm
Days after Sowing

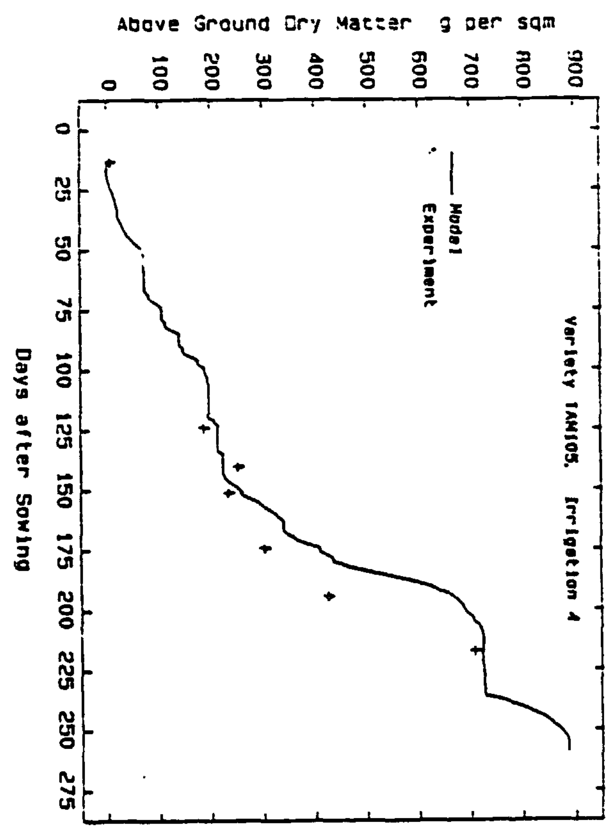

Bushland, Texas 1981
Variety TAM105, Irrigation 6
Model
Experiment
Tiller Number per scm
Days after Sowing

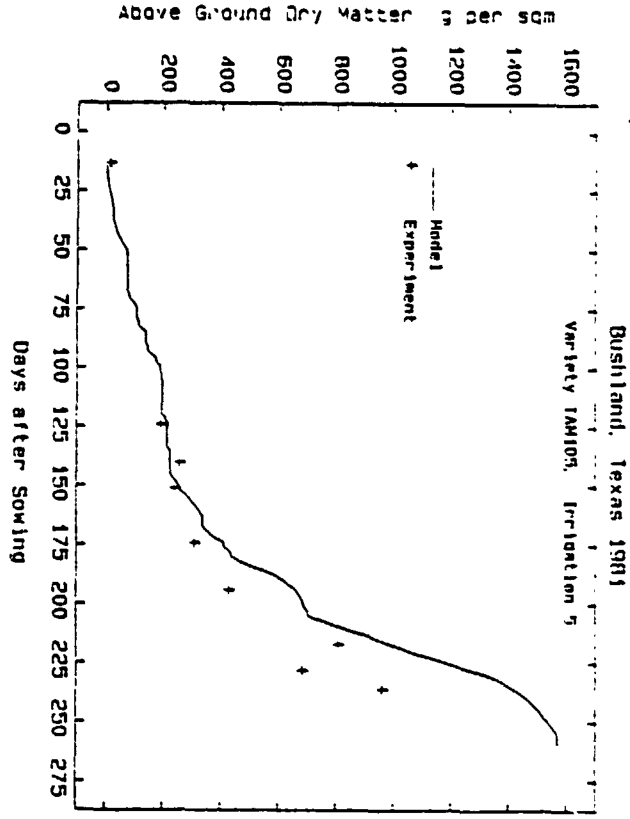

Bushland, Texas 1981
Variety TAM105, Irrigation 8
Model
Experiment
Tiller Number per sqm
Days after Sowing

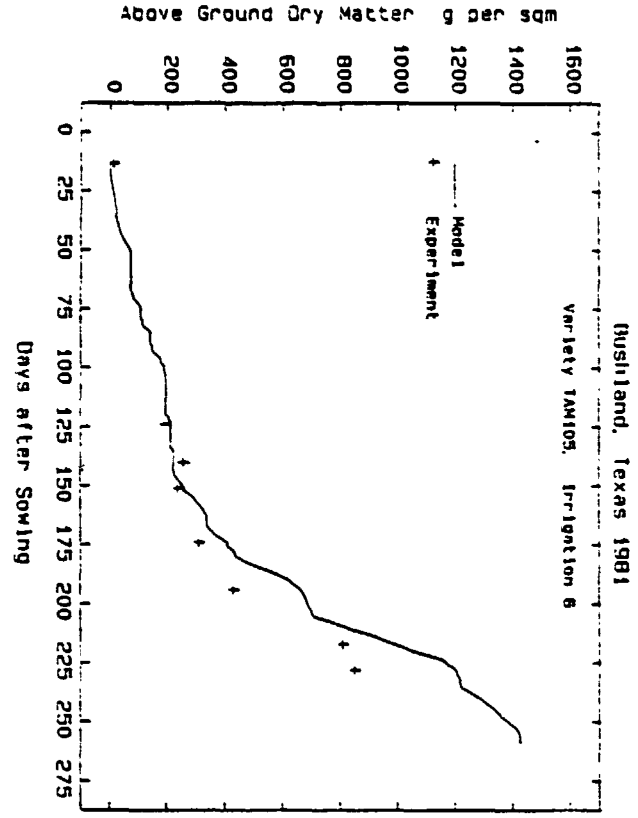

Bushland, Texas 1981
Variety TAM105, Irrigation 1
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

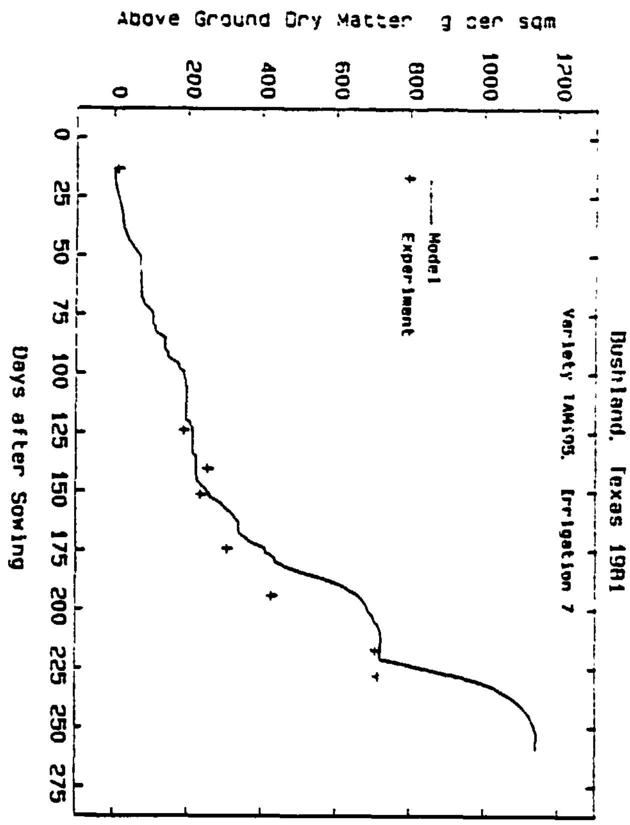

Bushland, Texas 1981
Variety TAM105, Irrigation 2
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

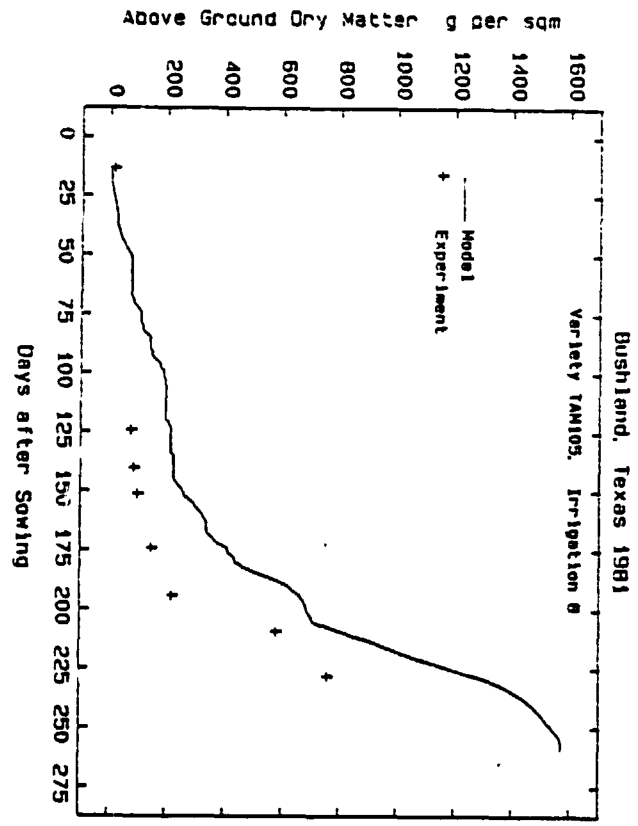

Bushland, Texas 1981
Variety TAM105, Irrigation 3
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

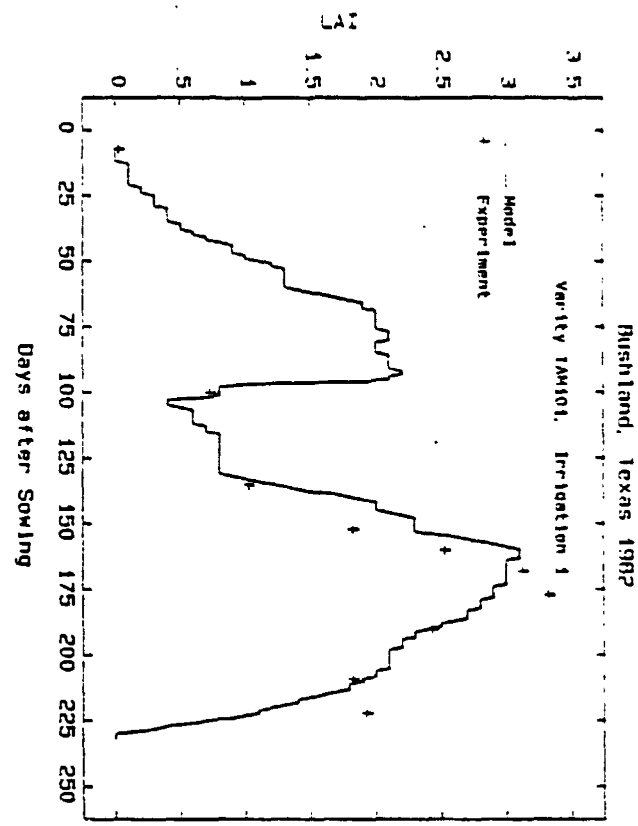

Bushland, Texas 1981
Variety TAM105, Irrigation 4
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

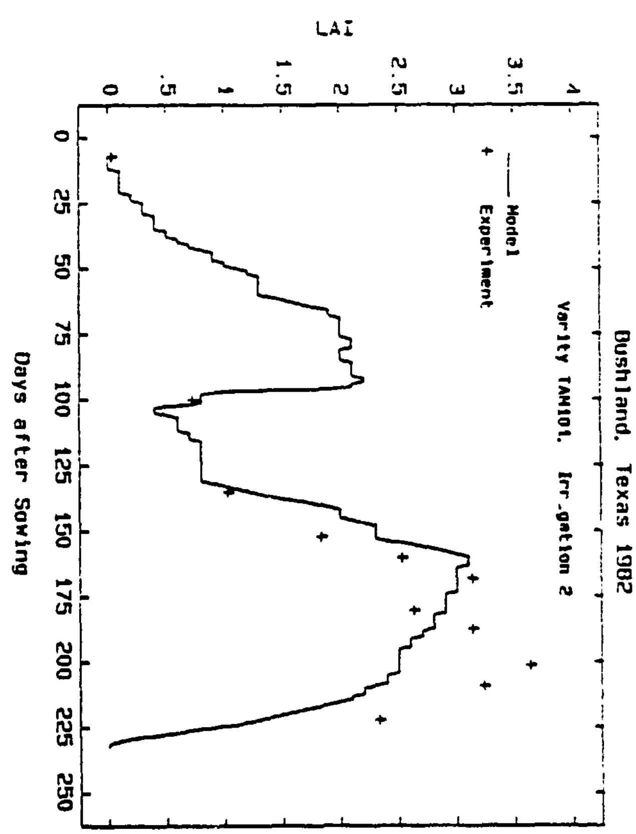

Bushland, Texas 1981
Variety TAM105, Irrigation 5
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

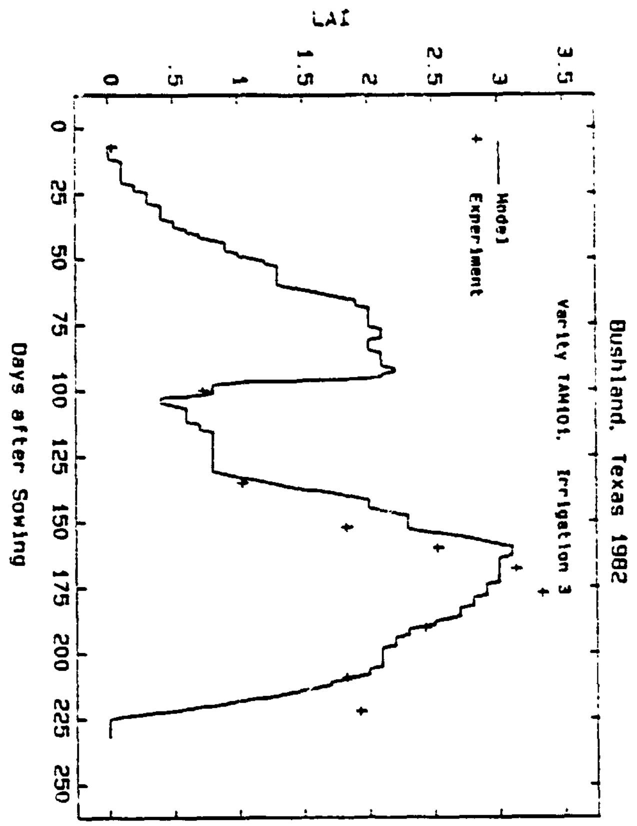

Bushland, Texas 1981
Variety TAM105, Irrigation 6
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

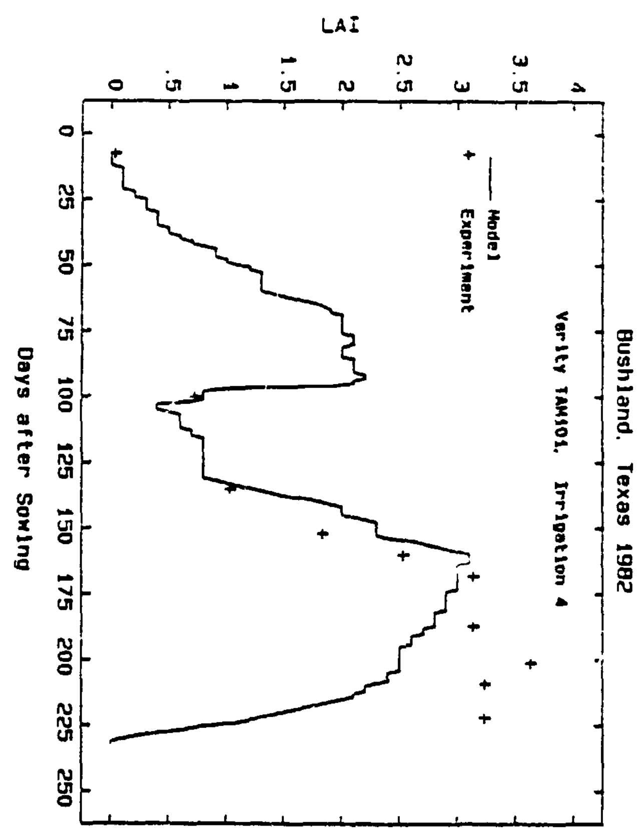

Bushland, Texas 1981
Variety TAM105, Irrigation 7
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

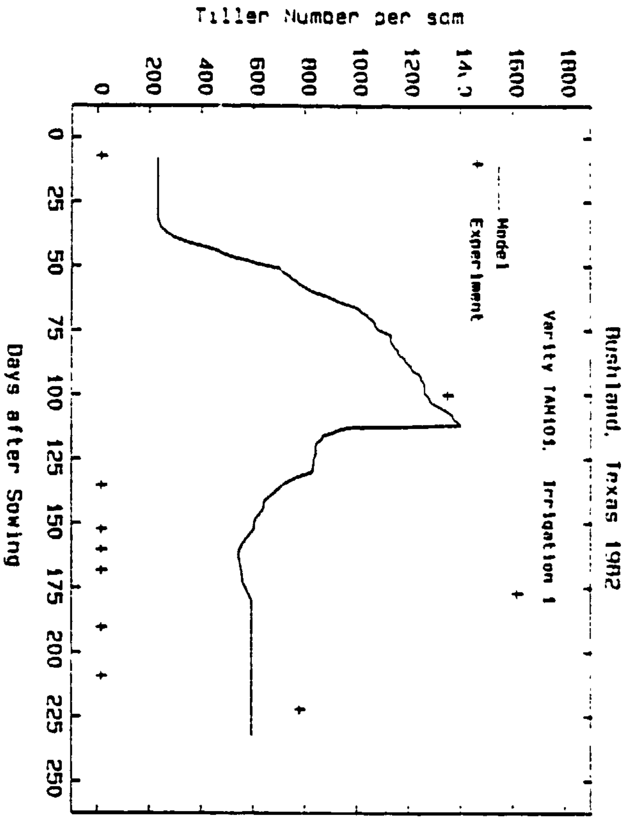

Bushland, Texas 1981
Variety TAM105, Irrigation 8
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

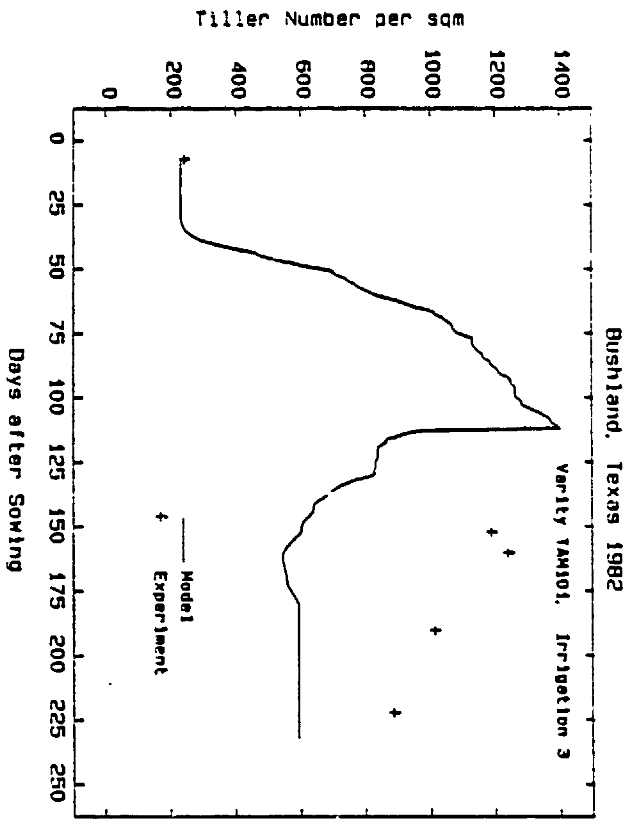

Bushland, Texas 1982
Varity TAM101, Irrigation 1
Model
Experiment
LAI
Days after Sowing

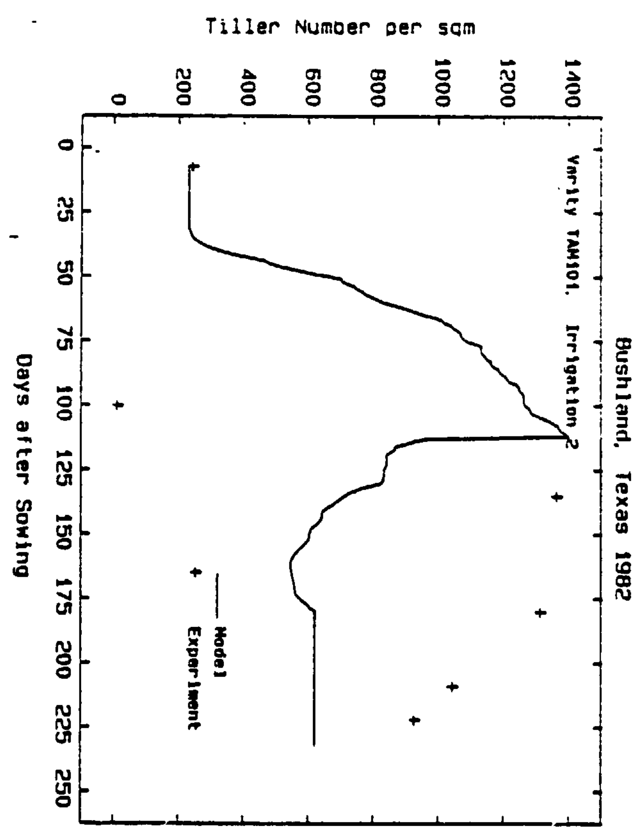

Bushland, Texas 1982
Varity TAM101, Irrigation 2
Model
Experiment
LAI
Days after Sowing

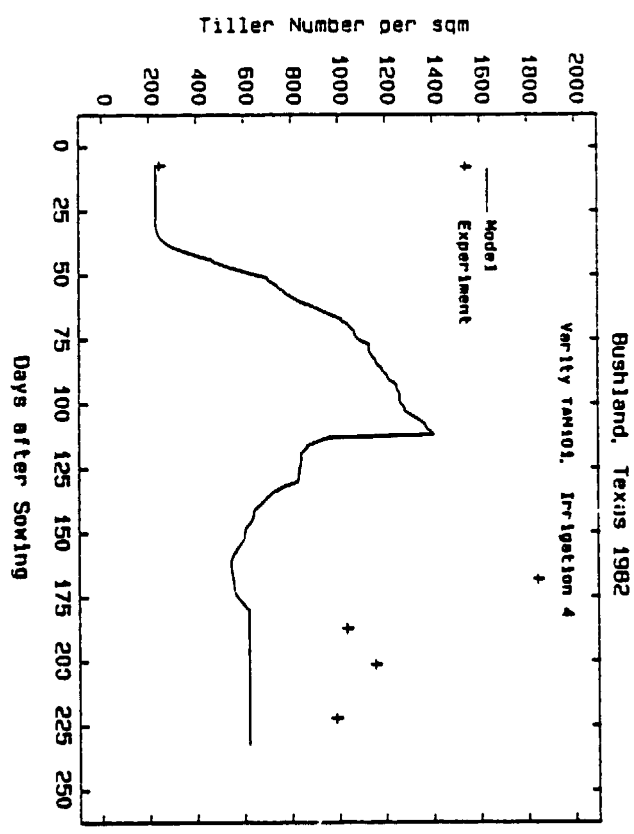

Bushland, Texas 1982
Varity TAM101, Irrigation 3
Model
Experiment
LAI
Days after Sowing


Bushland, Texas 1982
Varity TAM101, Irrigation 4
Model
Experiment
LAI
Days after Sowing

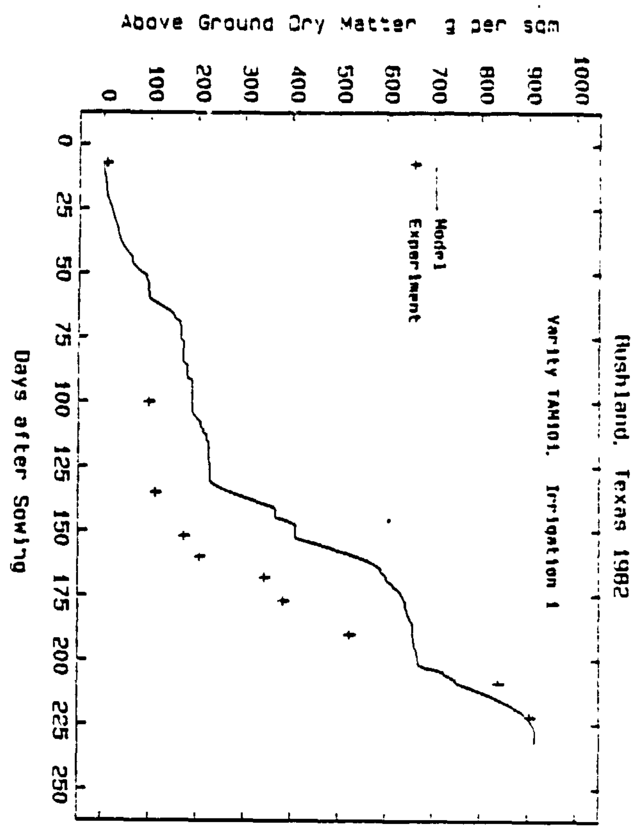

Bushland, Texas 1982
Varity TAM101, Irrigation 1
Model
Experiment
Tiller Number per sqm
Days after Sowing

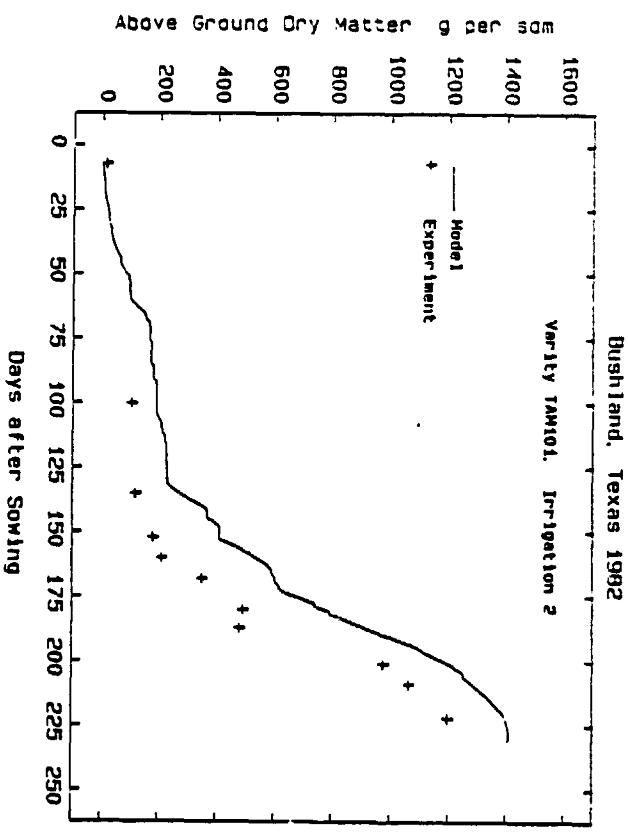

Bushland, Texas 1982
Varity TAM101, Irrigation 2
Model
Experiment
Tiller Number per sqm
Days after Sowing

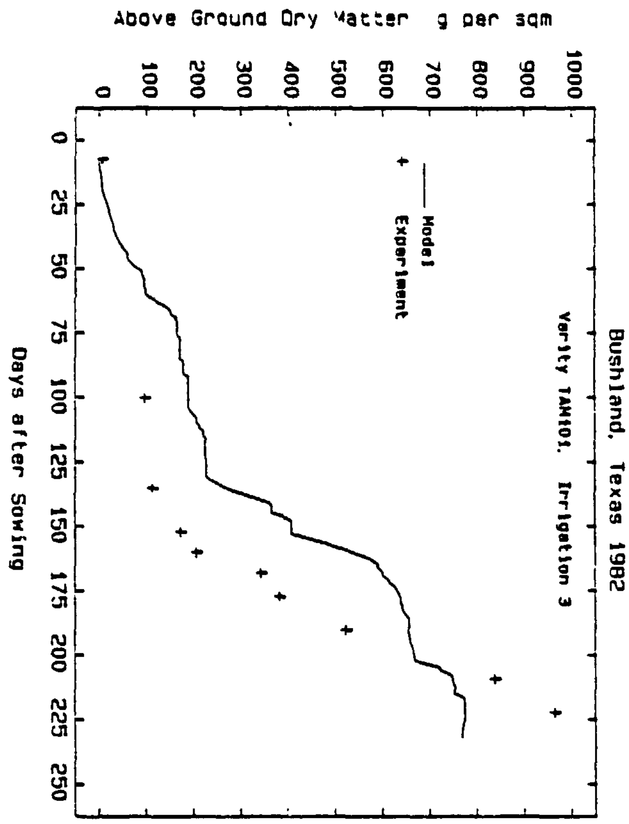

Bushland, Texas 1982
Varity TAM101, Irrigation 3
Model
Experiment
Tiller Number per sqm
Days after Sowing

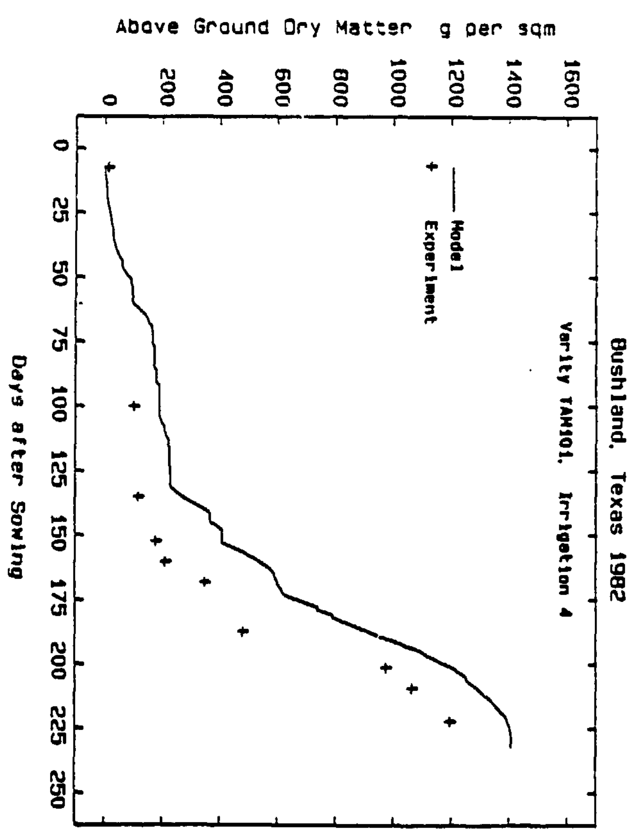

Bushland, Texas 1982
Varity TAM101, Irrigation 4
Model
Experiment
Tiller Number per sqm
Days after Sowing

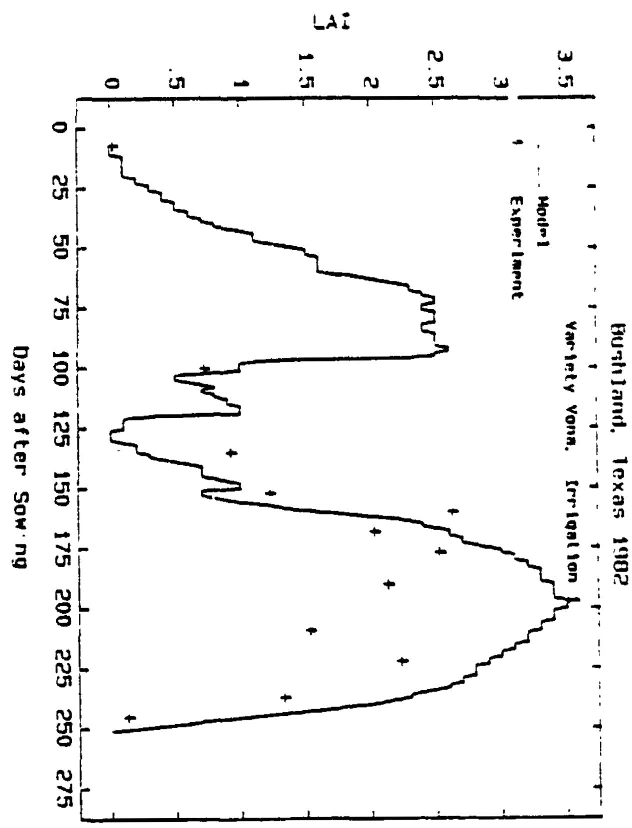
Bushland, Texas

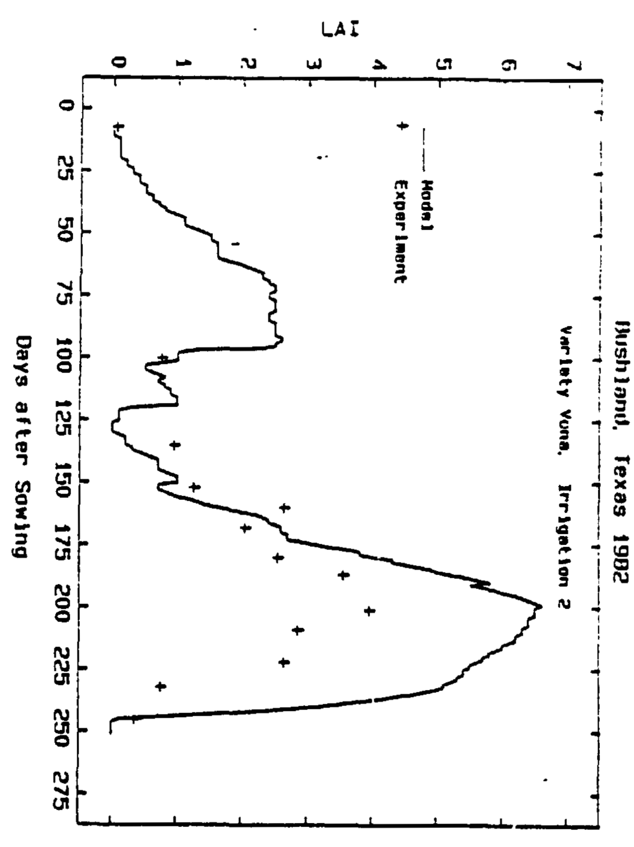


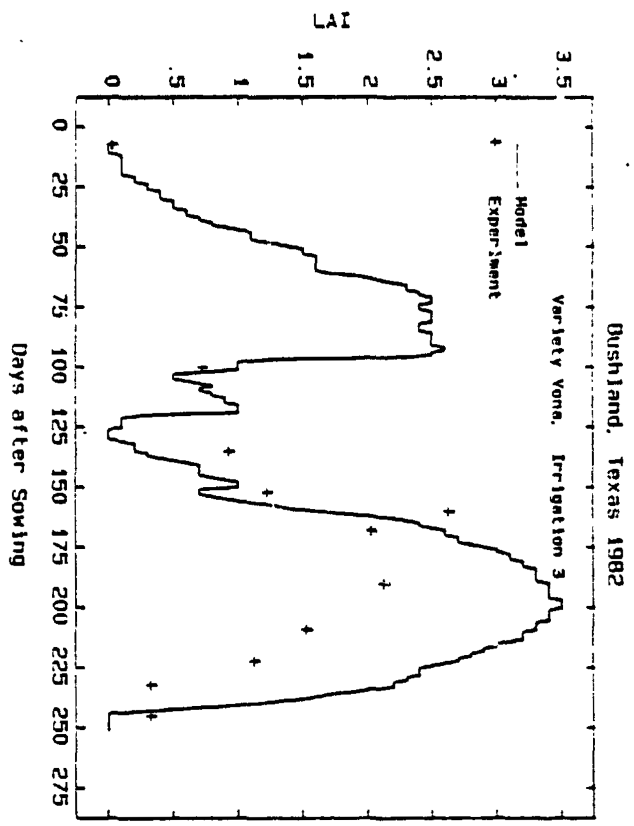


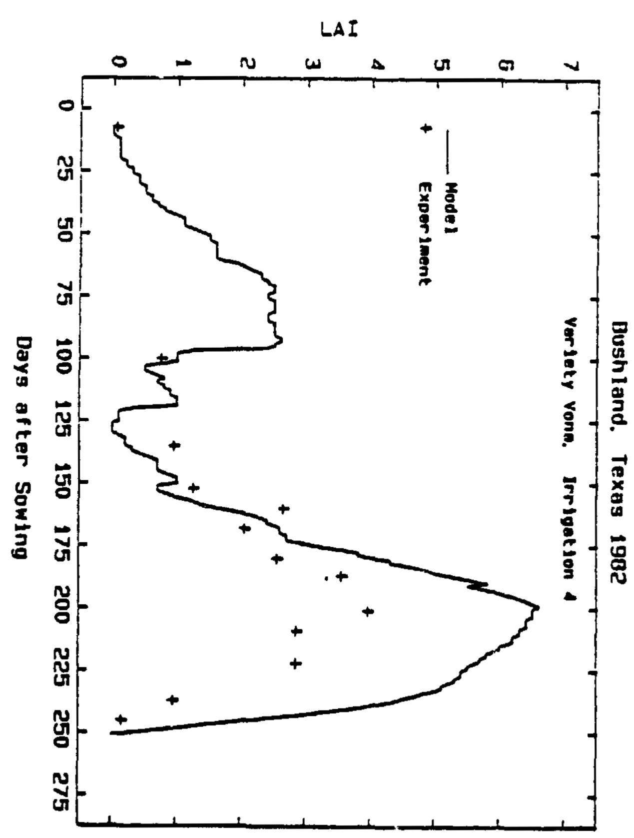


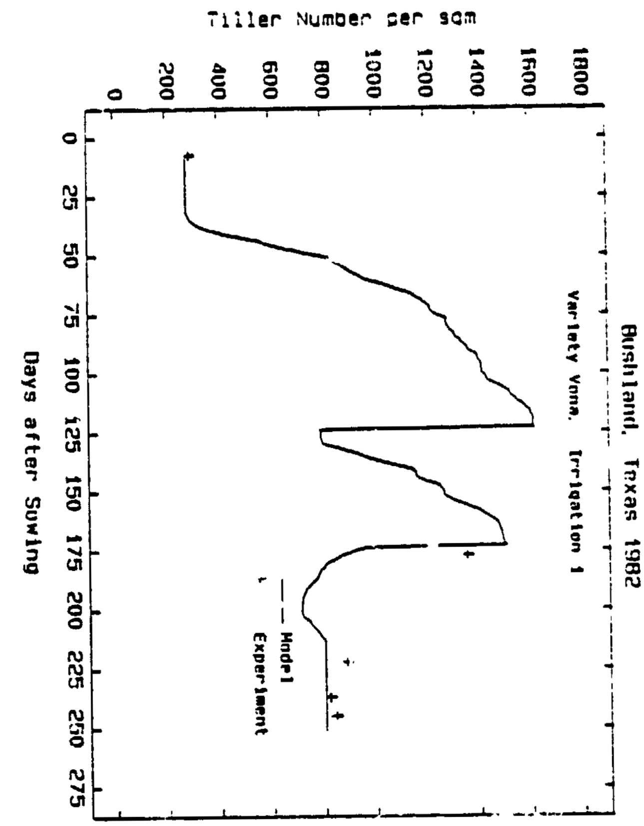


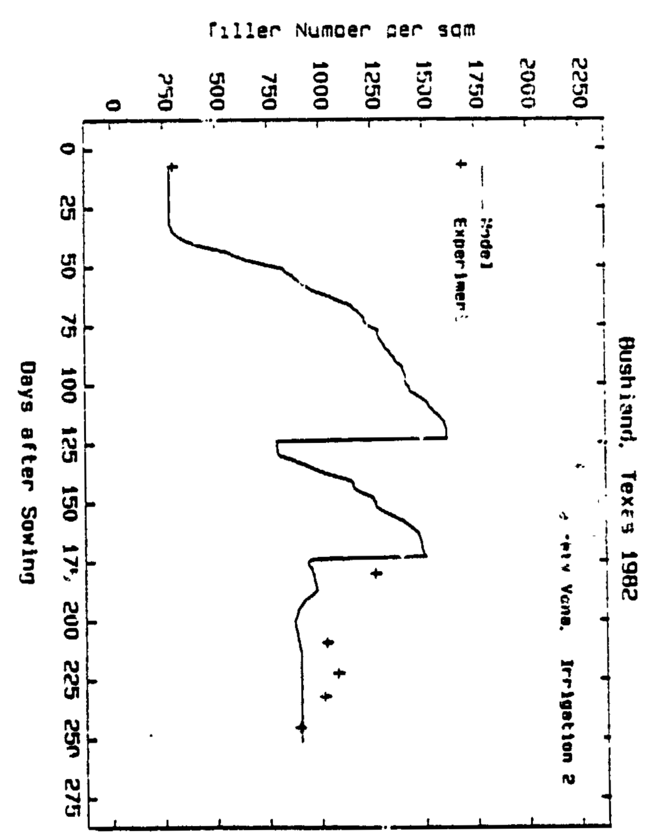

Bushland, Texas 1982
Variety Vona. Irrigation
Model
Experiment
LAI
Days after Sowing

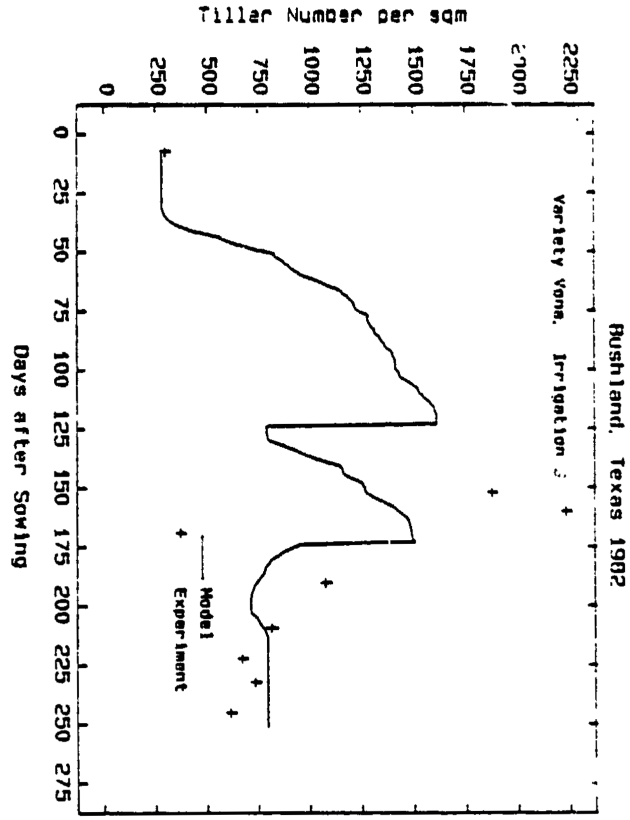

Bushland, Texas 1982
Variety Vona. Irrigation 2
Model
Experiment
LAI
Days after Sowing

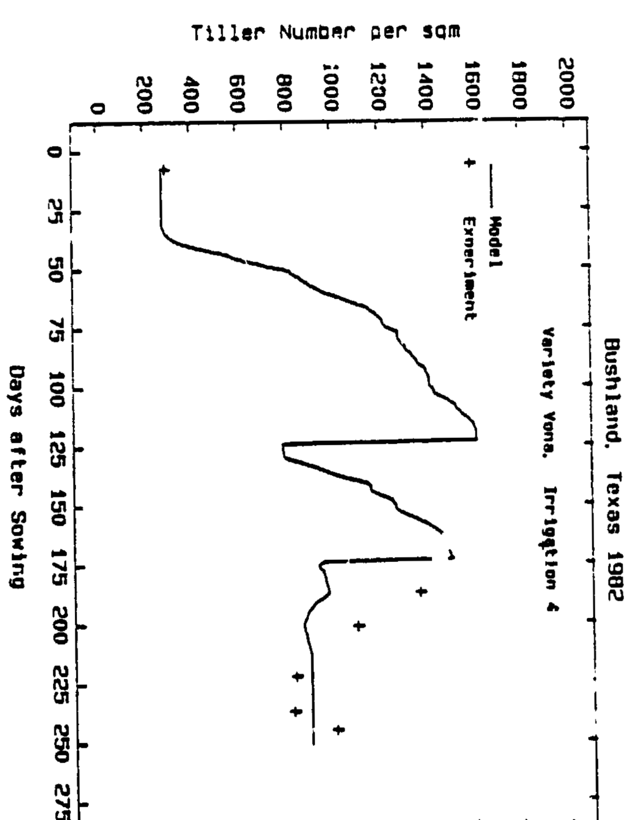

Bushland, Texas 1982
Variety Vona. Irrigation 3
Model
Experiment
LAI
Days after Sowing

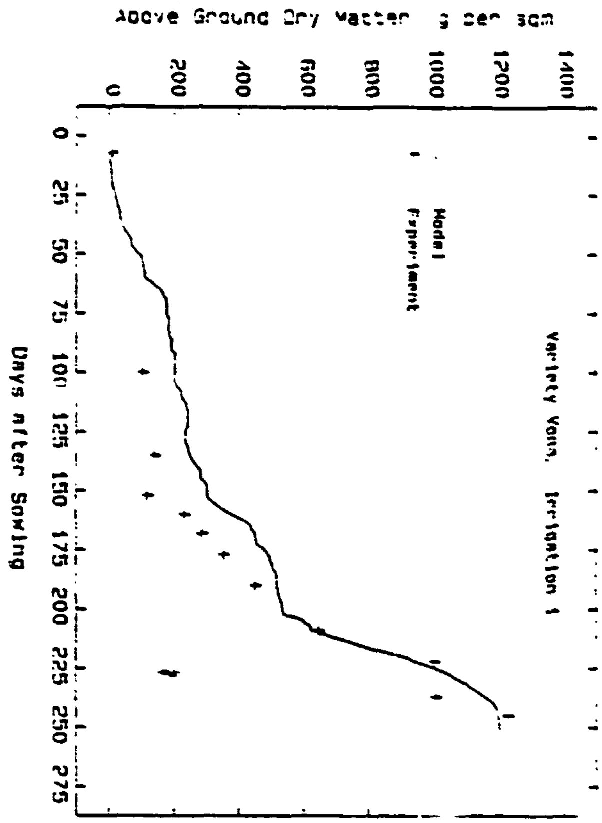

Bushland, Texas 1982
Variety Vona. Irrigation 4
Model
Experiment
LAI
Days after Sowing

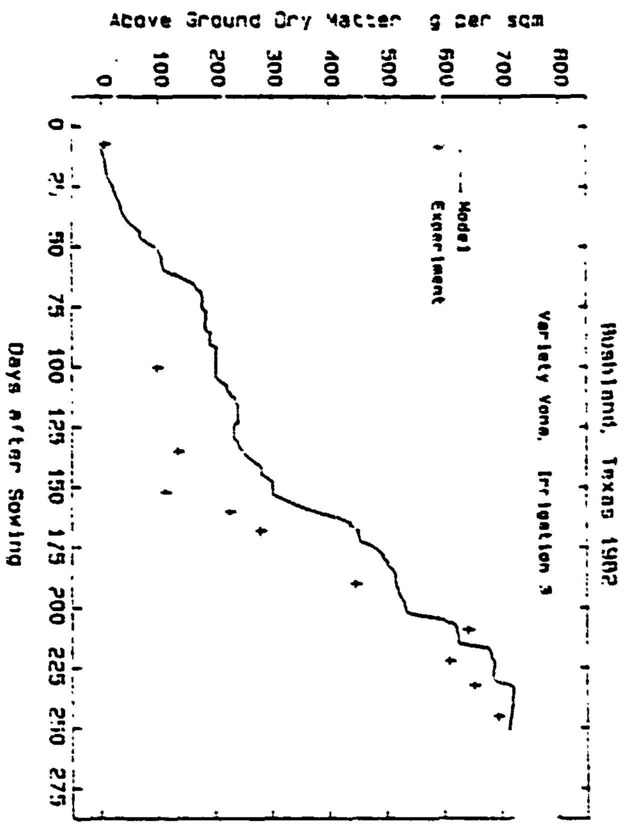

Bushland, Texas 1982
Variety Vona. Irrigation 1
Model
Experiment
Tiller Number per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

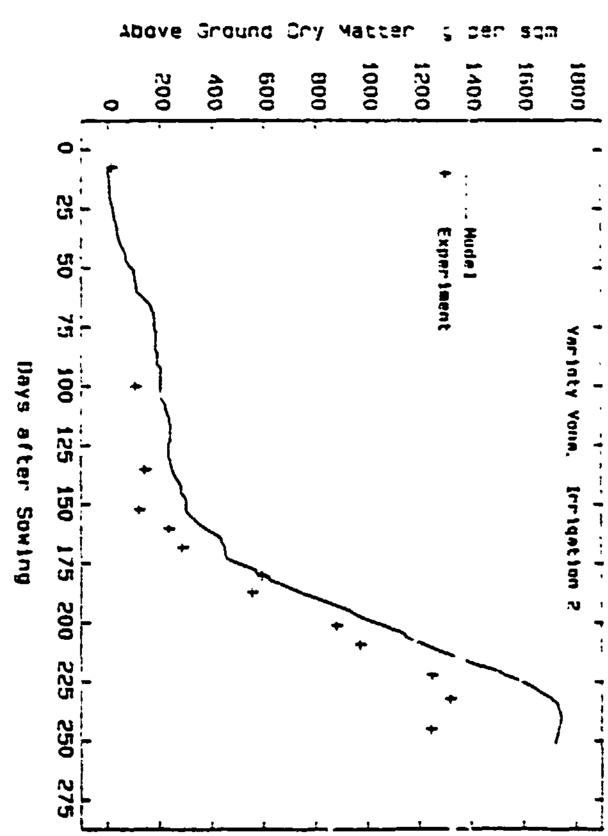

Bushland, Texas 1982
Irrigation 2
Model
Tiller Number per sqm
0
500
750
1000
1250
1750
2000
2250
0 25 50 75 100 125 150 200 275
Days after Sowing

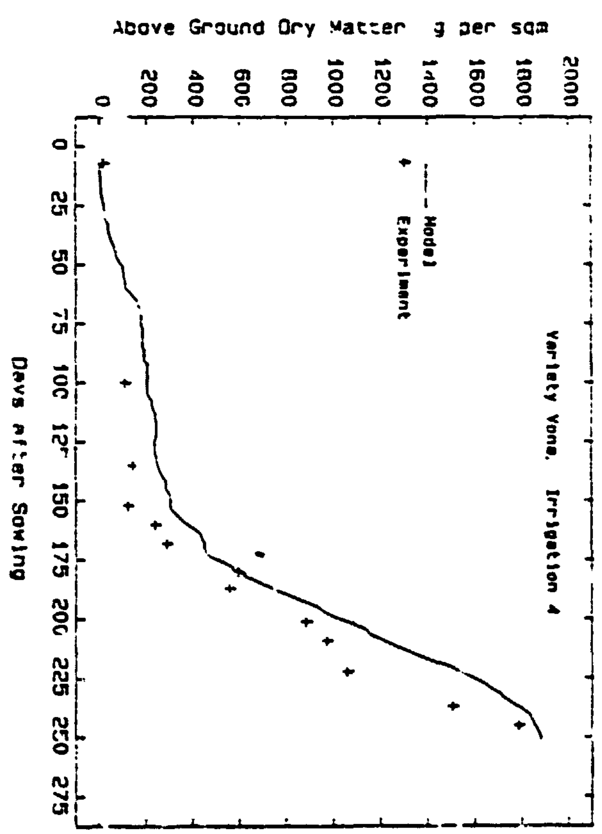

Bushland, Texas 1982
Variety Vona. Irrigation
Model
Experiment
Tiller Number per sqm
0
250
500
750
1000
1250
1500
1750
2250
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

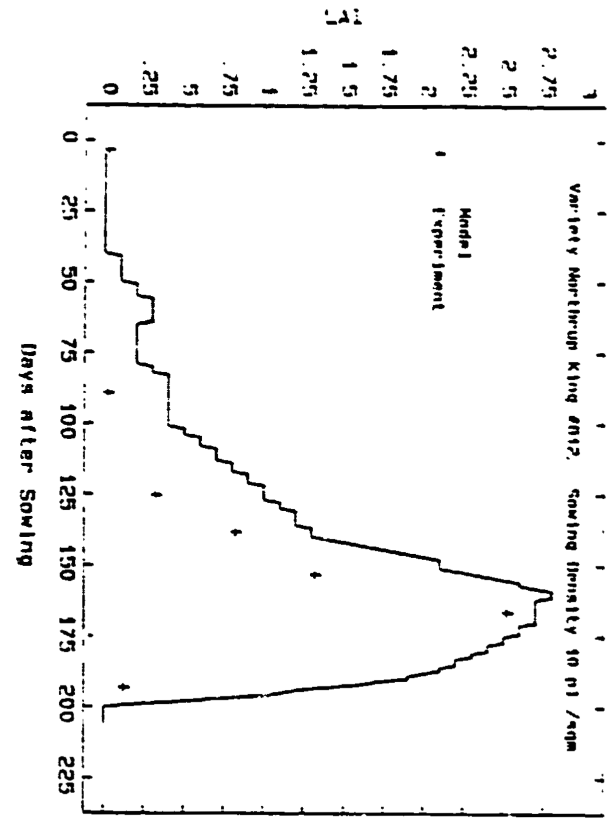

Bushland, Texas 1982
Variety Vona. Irrigation 4
Model
Experiment
Tiller Number per sqm
0
200
400
600
800
1200
1400
1600
1800
2000
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

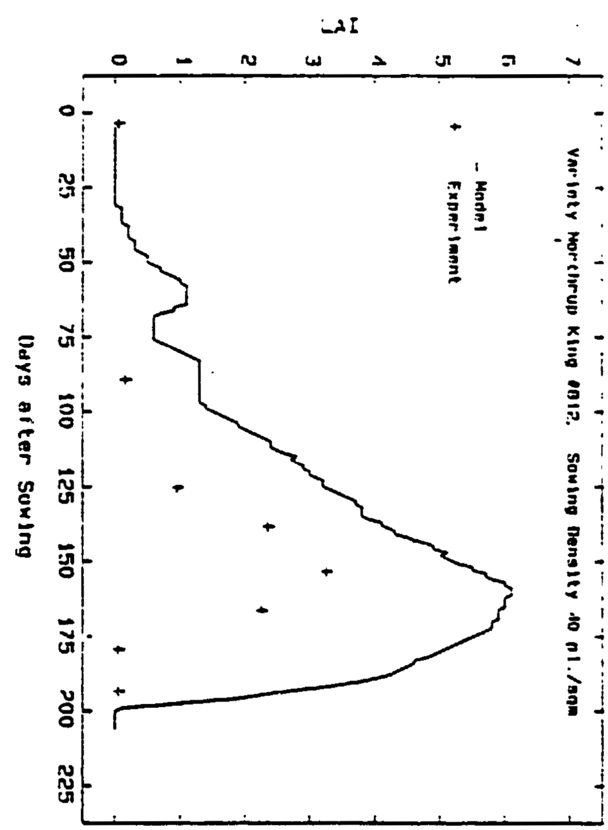

Bushland, Texas 1982
Variety Vona, Irrigation 1
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

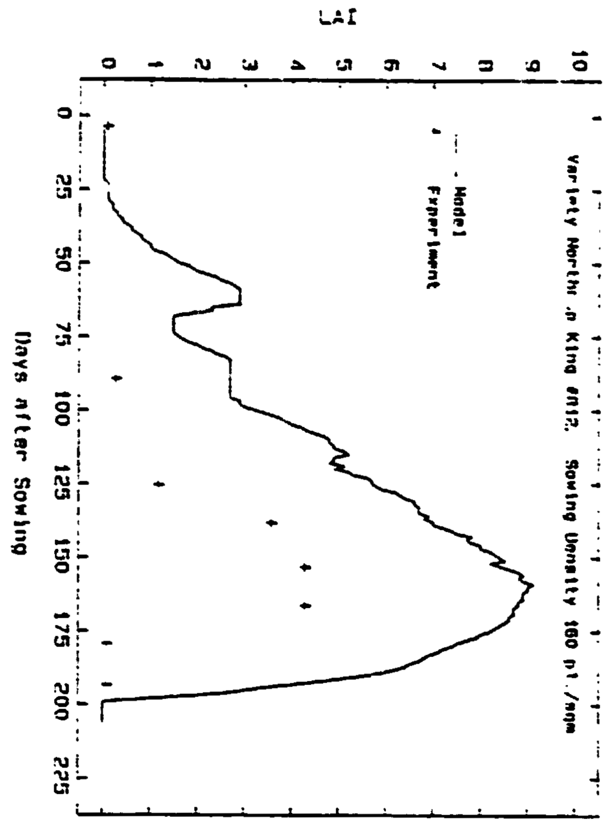

Bushland, Texas 1982
Variety Vona, Irrigation 3
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

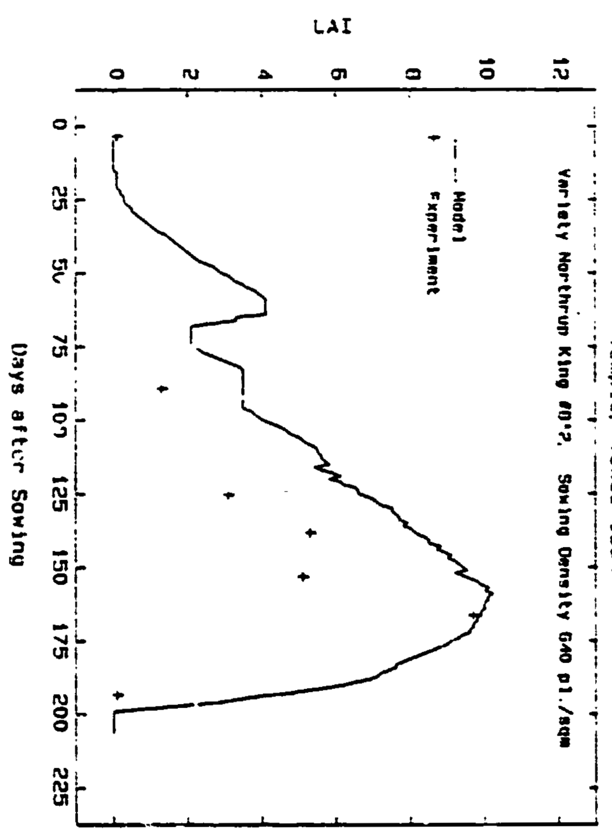

Bushland, Texas 1982
Variety Vona, Irrigation 2
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

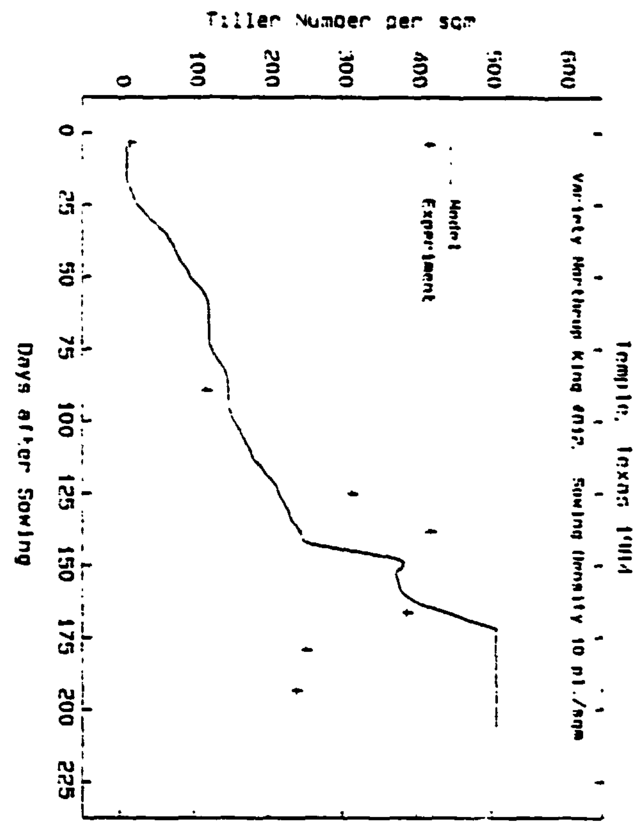

Bushland, Texas 1982
Variety Vona, Irrigation 4
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

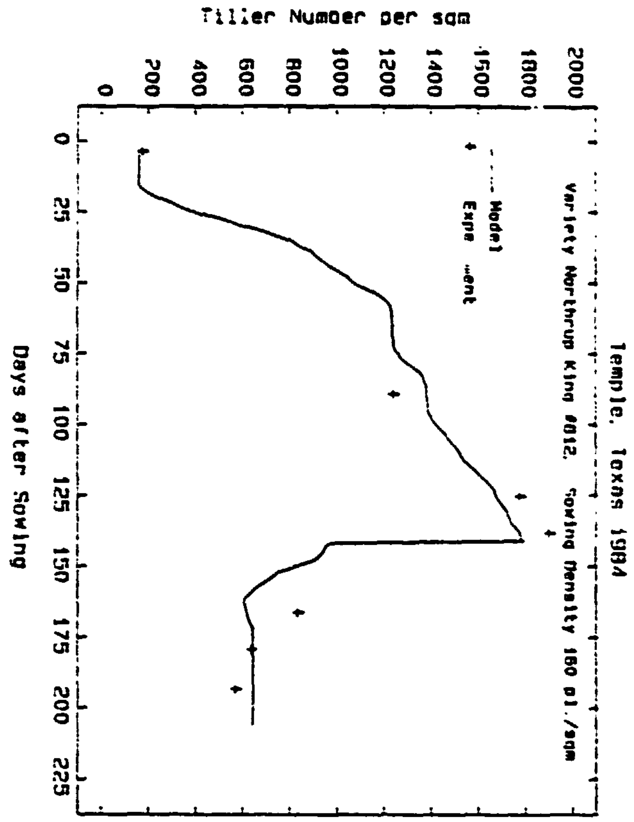

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 10 pl./sqm
Model
Experiment
LAI
Days after Sowing

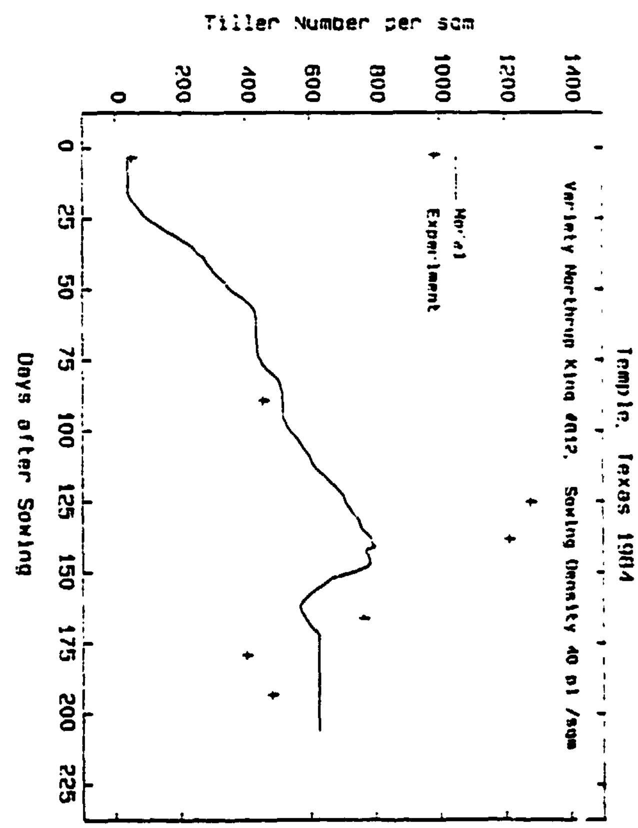

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 40 pl./sqm
Model
Experiment
LAI
Days after Sowing

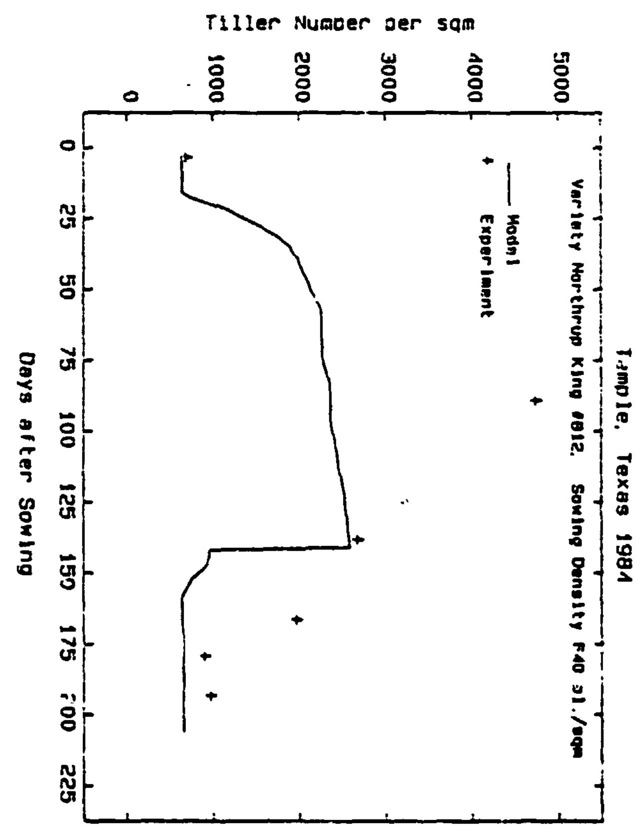

Temple, Texas 1984
Model
Experiment
LAI
Days after Sowing

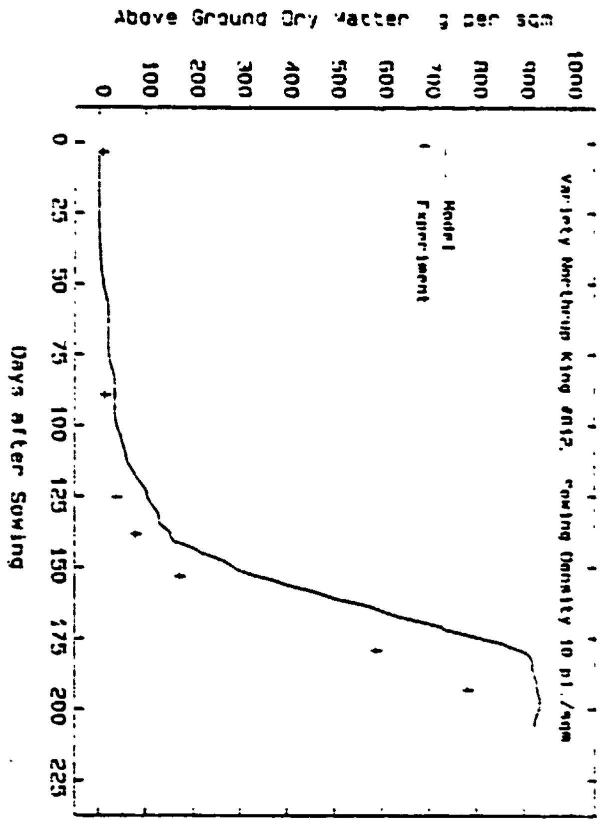

Temple, Texas 1984
Sowing Density 640 pl./sqm
Model
Experiment
LAI
Days after Sowing

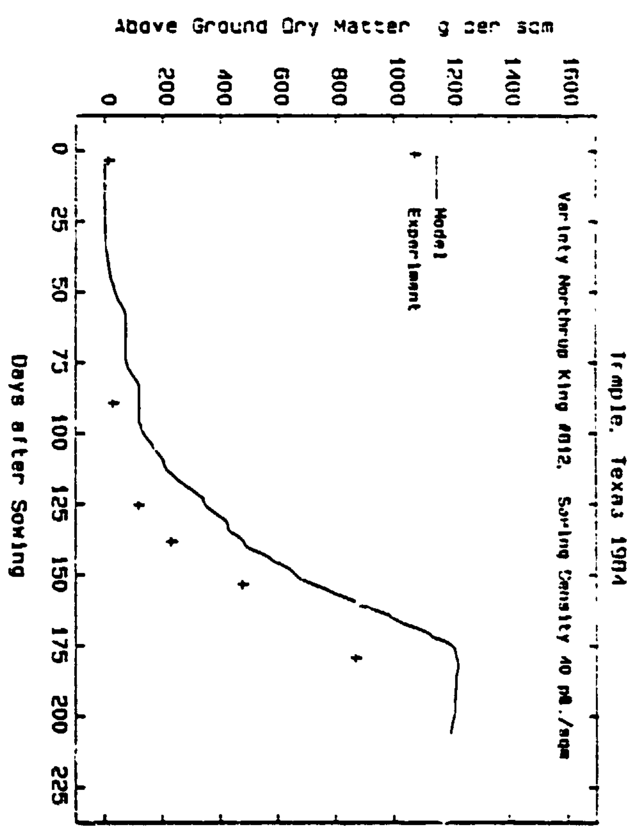

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 10 pl./sqm
Model
Experiment
Tiller Number per sqm
Days after Sowing

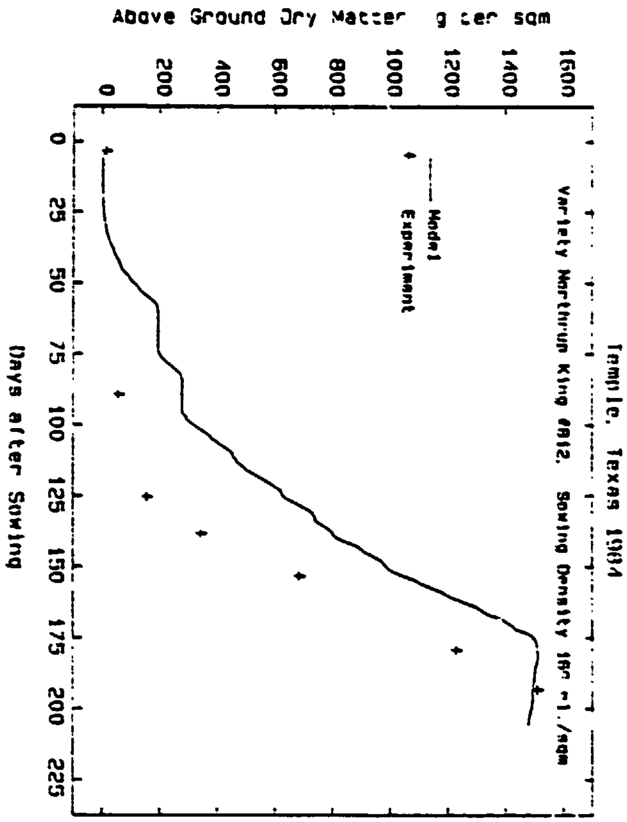

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 160 pl./sqm
Model
Tiller Number per sqm
Days after Sowing

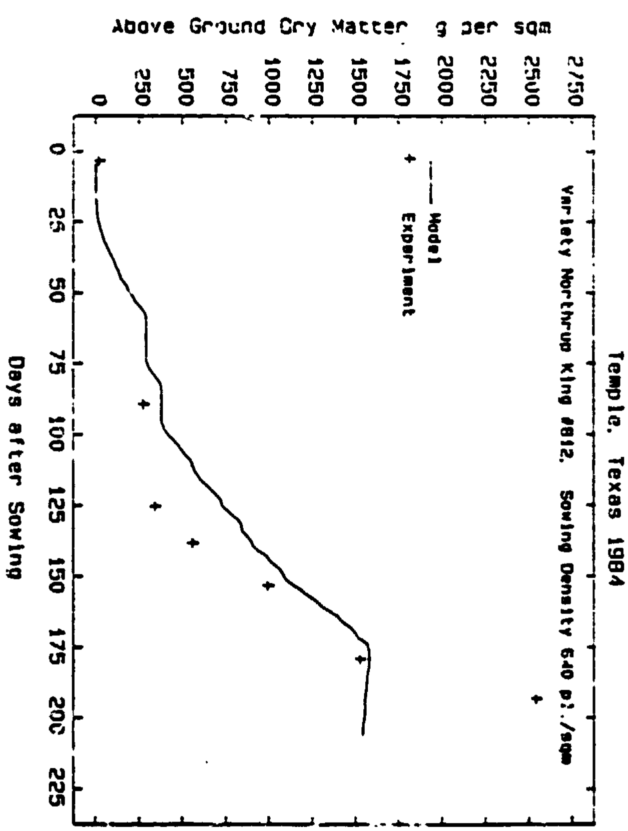

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 40 pl./sqm
Experiment
Tiller Number per sqm
Days after Sowing

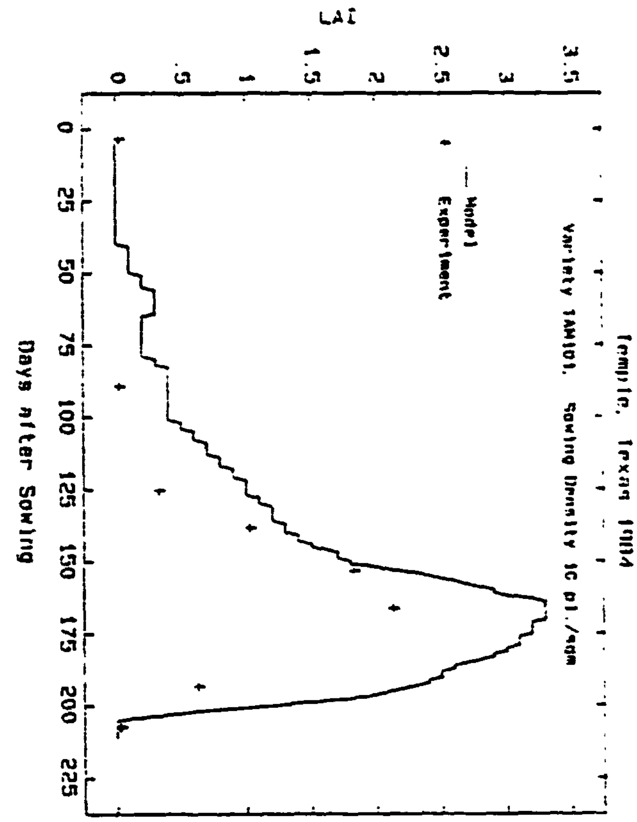

Variety Northrup King #812. Sowing Density
Model
Experiment
Tiller Number per sqm
Days after Sowing

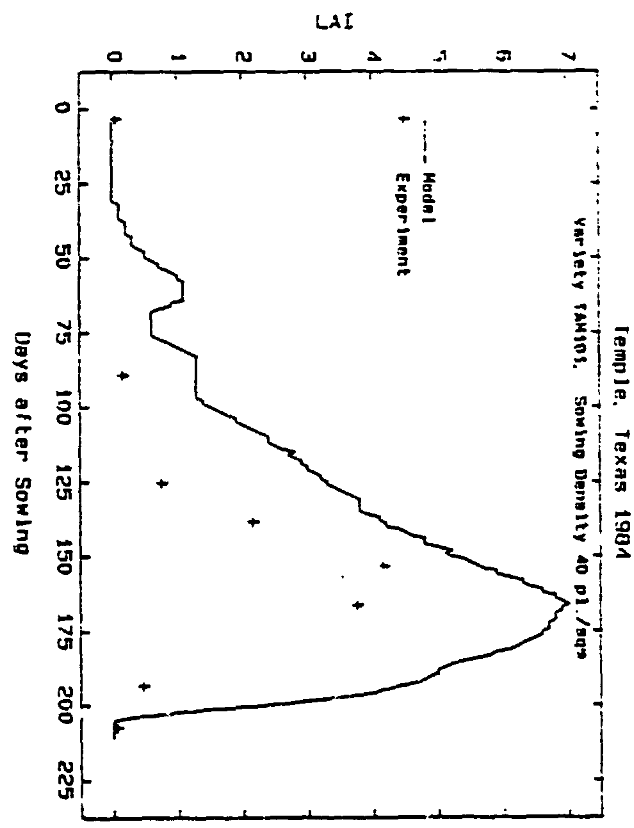

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 10 pl./sqm
Model
Experiment
Above Ground Dry Matter g per sqm
0
100
200
300
400
500
600
700
800
900
1000
Days after Sowing
0
25
50
75
100
125
150
175
200
225

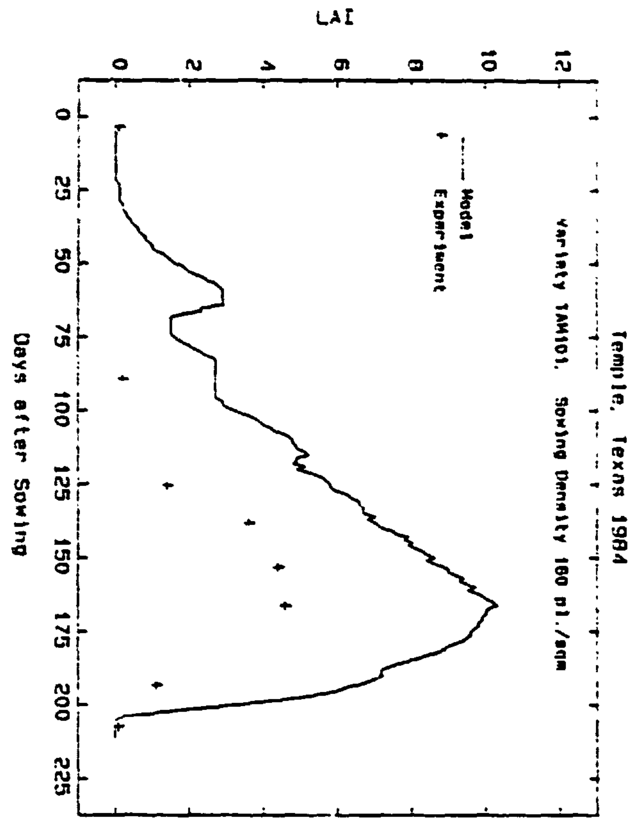

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 40 pl./sqm
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
25
50
75
100
125
150
175
200
225

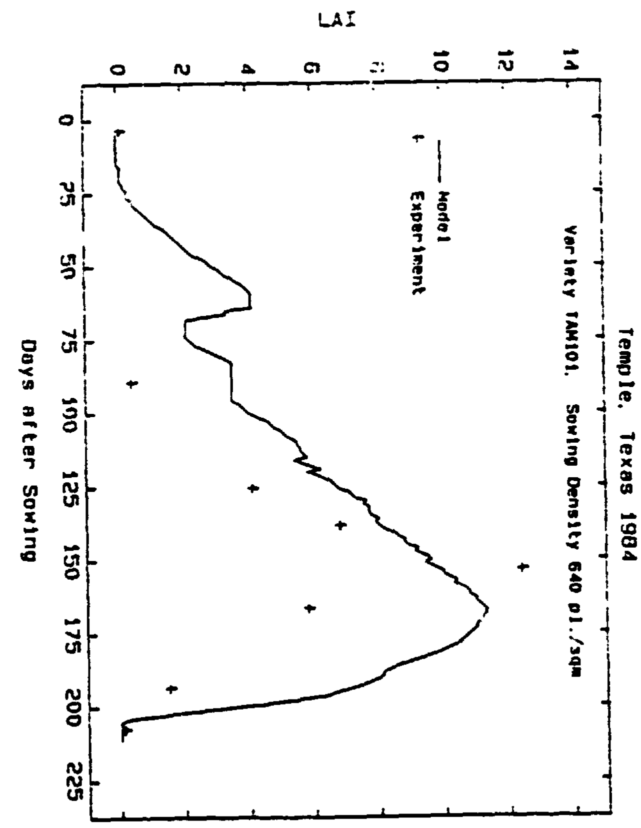

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 160 pl./sqm
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
25
50
75
100
125
150
175
200
225

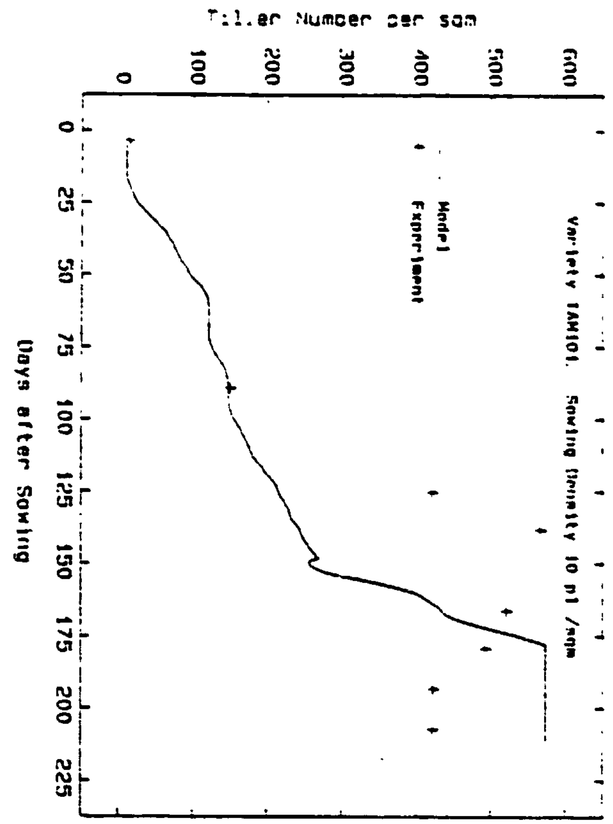

Temple, Texas 1984
Variety Northrup King #812. Sowing Density 640 pl./sqm
Model
Experiment
Above Ground Dry Matter g per sqm
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
Days after Sowing
0
25
50
75
100
125
150
175
200
225


Temple, Texas 1984
Variety TAM101. Sowing Density 10 pl./sqm
Model
Experiment
LAI
Days after Sowing

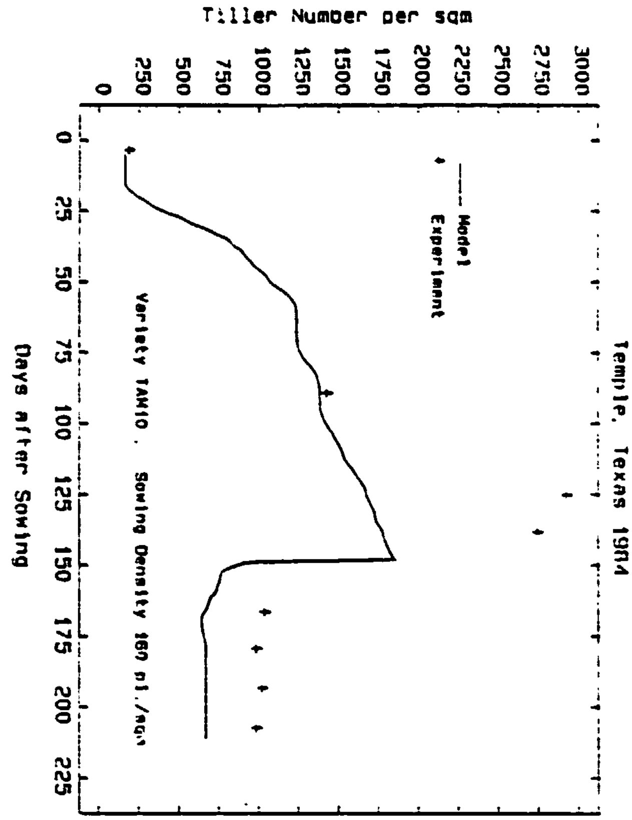

Temple, Texas 1984
Variety TAM101. Sowing Density 40 pl./sqm
Model
Experiment
LAI
Days after Sowing


Temple, Texas 1984
Variety TAM101. Sowing Density 160 pl./sqm
Model
Experiment
LAI
Days after Sowing

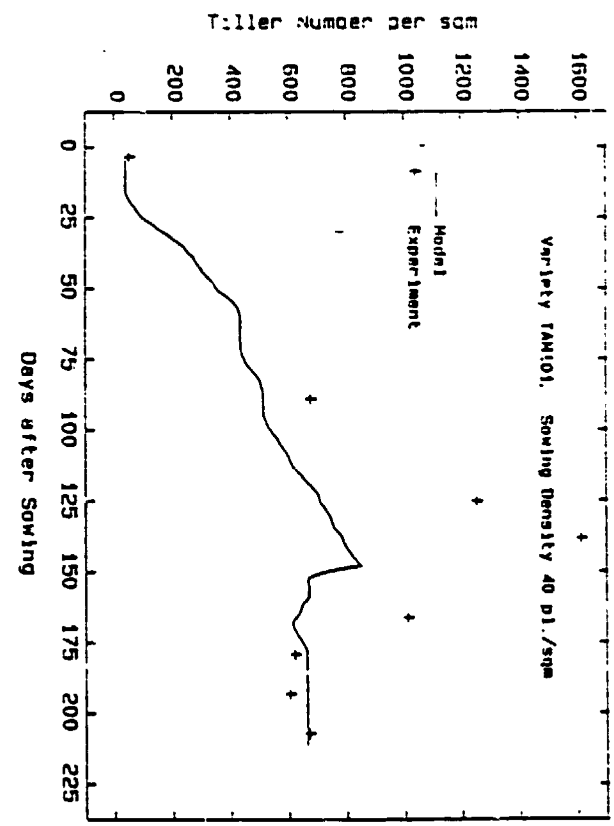

Temple, Texas 1984
Variety TAM101. Sowing Density 640 pl./sqm
Model
Experiment
LAI
Days after Sowing



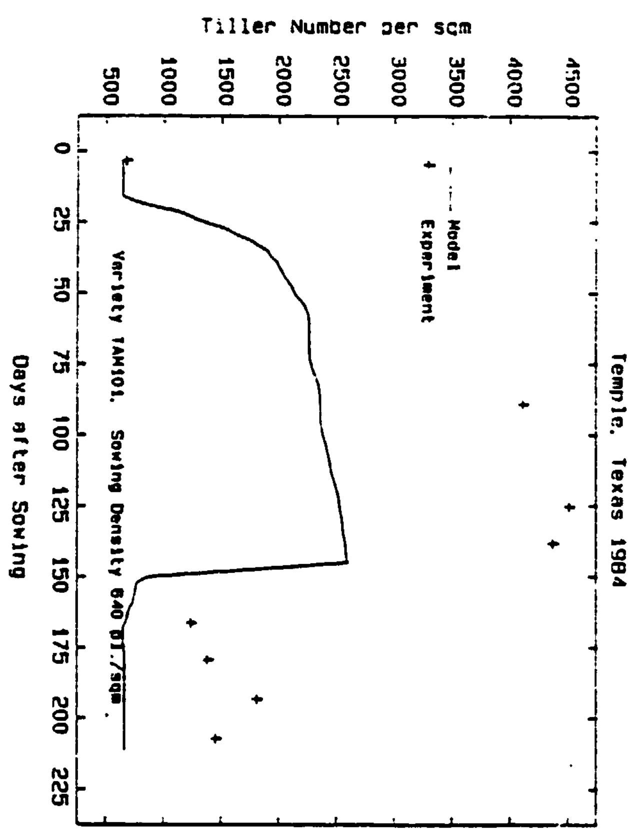
Temple, Texas 1984
Variety TAM101. Sowing Density 10 pl./sqm
Model
Experiment
Tiller Number per sqm
Days after Sowing



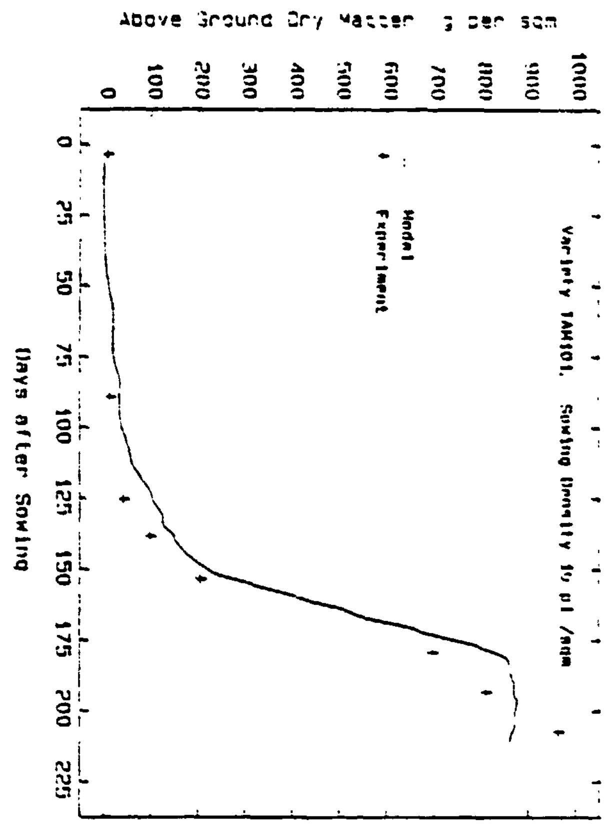
Temple, Texas 1984
Variety TAM10. Sowing Density 160 pl./sqm
Model
Experiment
Tiller Number per sqm
Days after Sowing

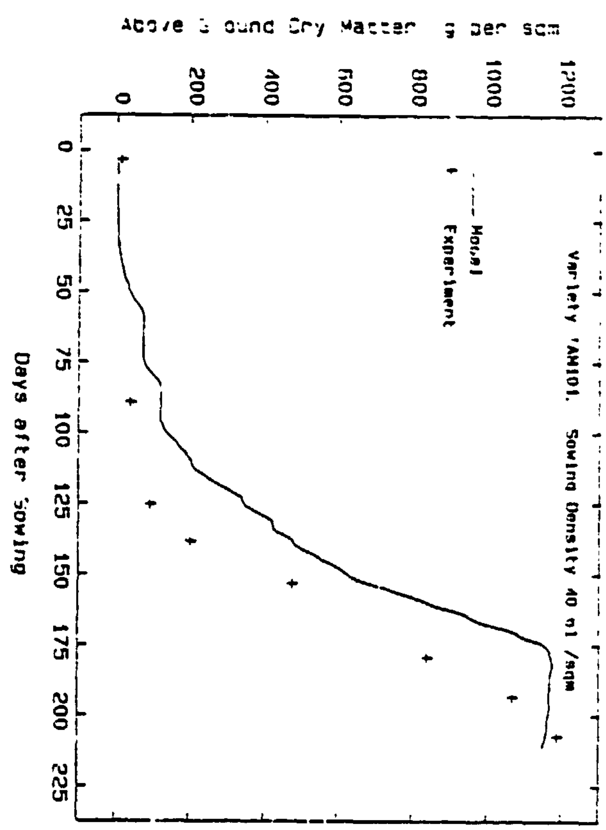


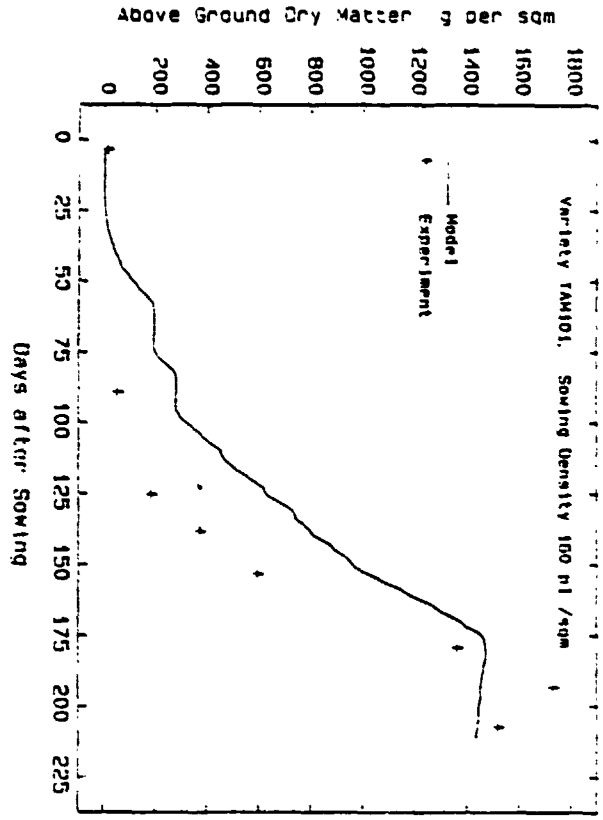
Temple, Texas 1984
Variety TAM101. Sowing Density 40 pl./sqm
Model
Experiment
Tiller Number per sqm
Days after Sowing

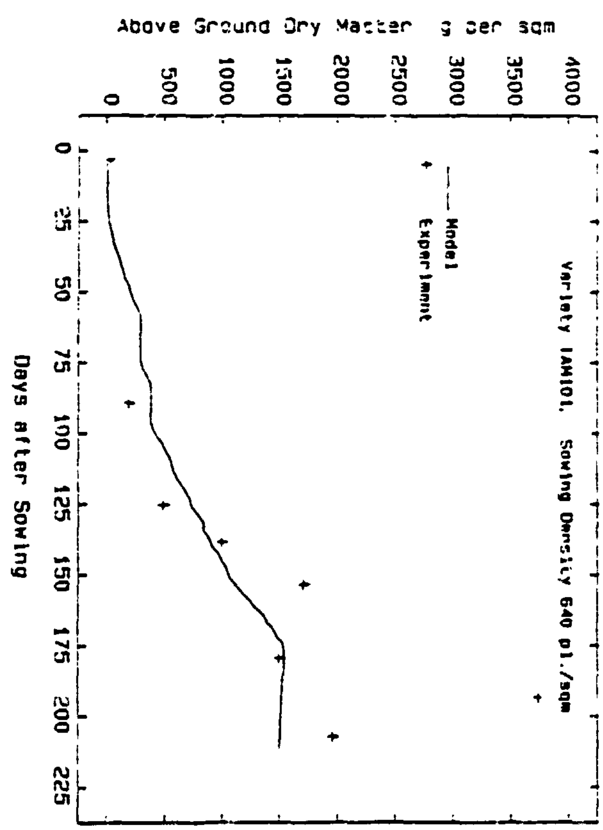


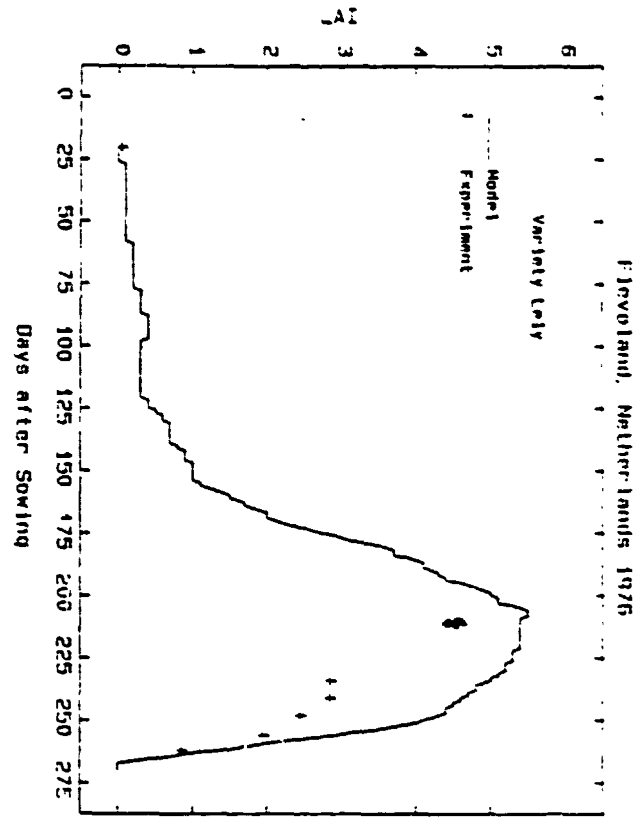
Temple, Texas 1984
Variety TAM101. Sowing Density 640 pl./sqm
Model
Experiment
Tiller Number per sqm
Days after Sowing

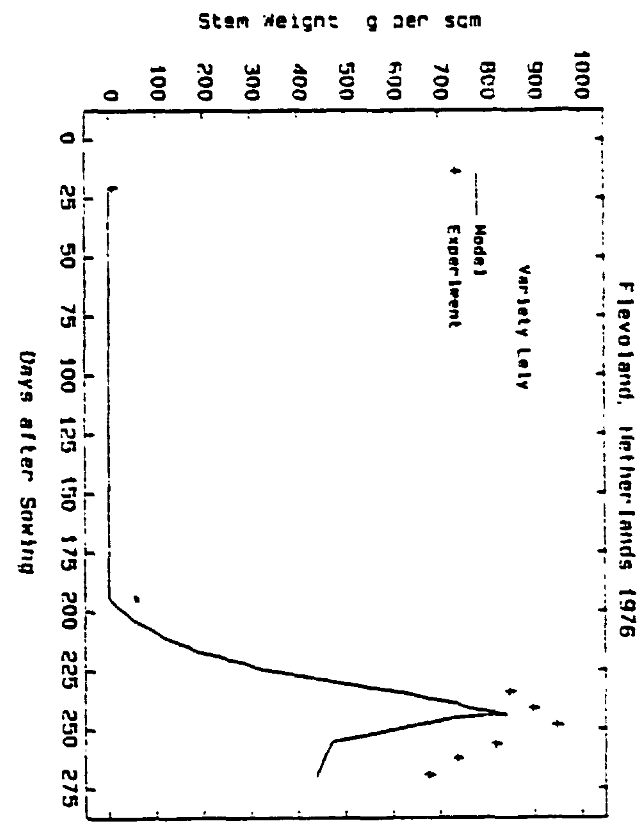

Temple, Texas 1984
Variety TAM101. Sowing Density 10 pl /sqm
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

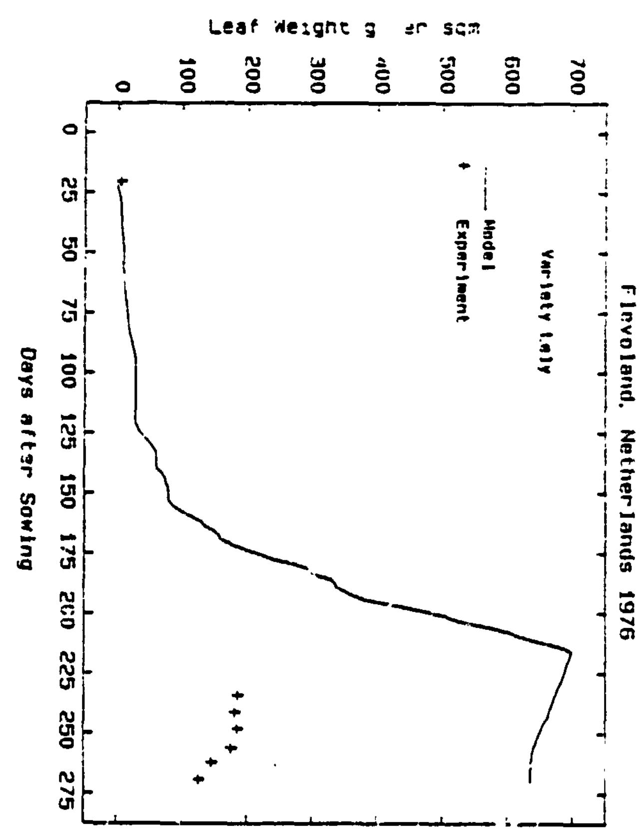

Temple, Texas 1984
Variety TAM101. Sowing Density 40 pl /sqm
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

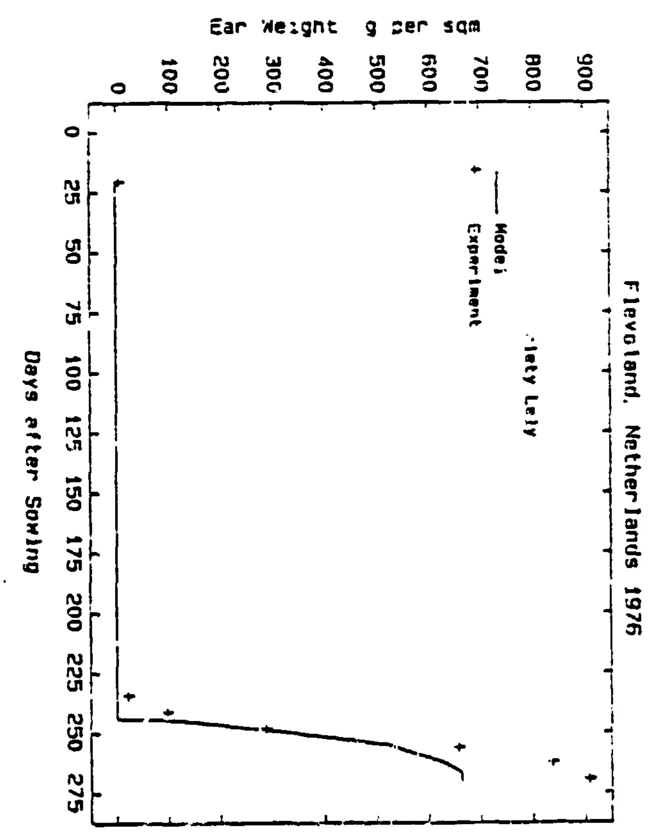

Temple, Texas 1984
Variety TAM101. Sowing Density 100 pl /sqm
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

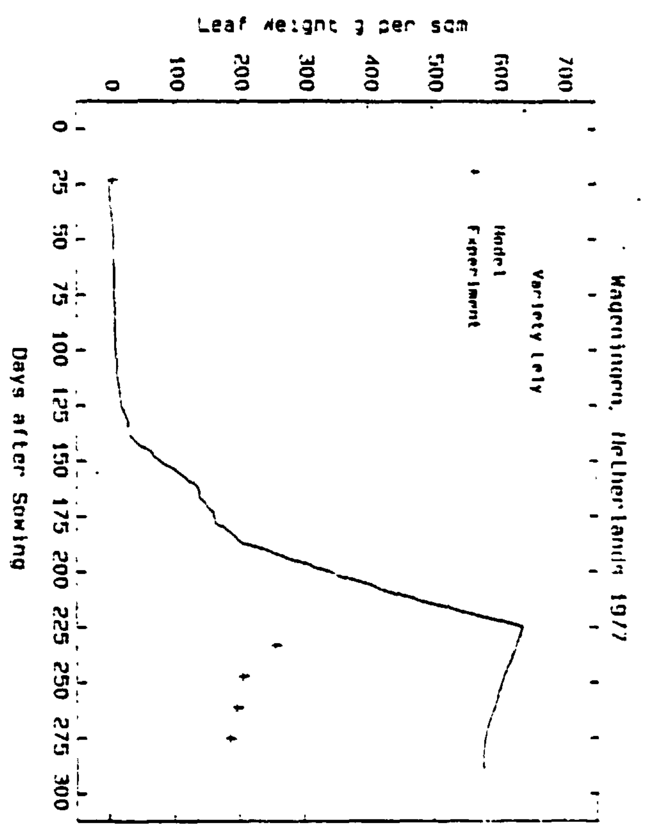

Temple, Texas 1984
Variety TAM101. Sowing Density 640 pl./sqm
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

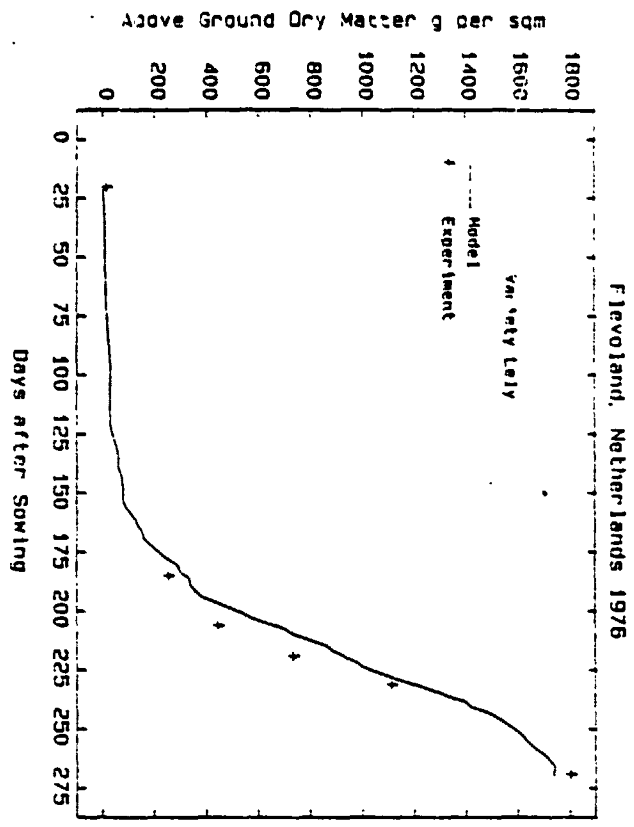

Flevoland, Netherlands 1976
Variety Lely
Model
Experiment
LAI
Days after Sowing

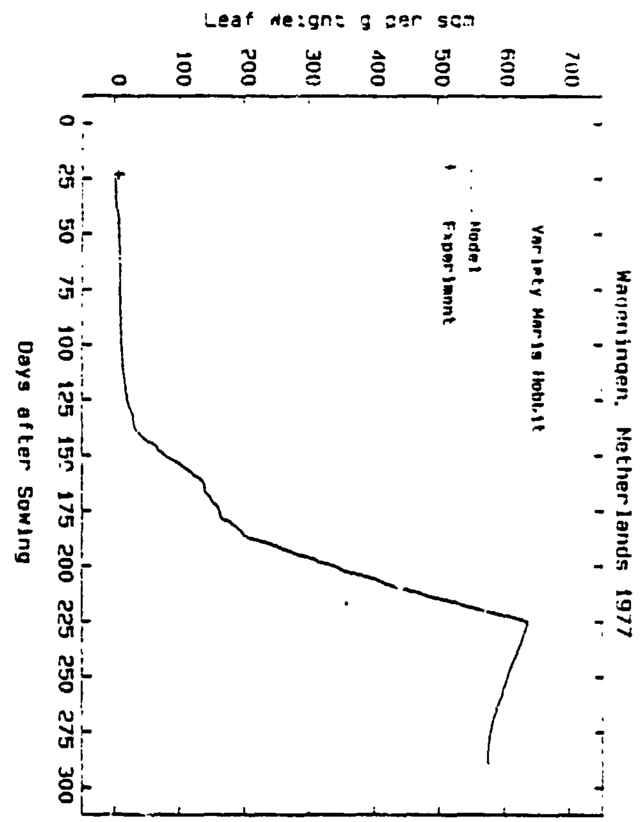

Flevoland, Netherlands 1976
Variety Lely
Model
Experiment
Stem Weight g per sqm
Days after Sowing

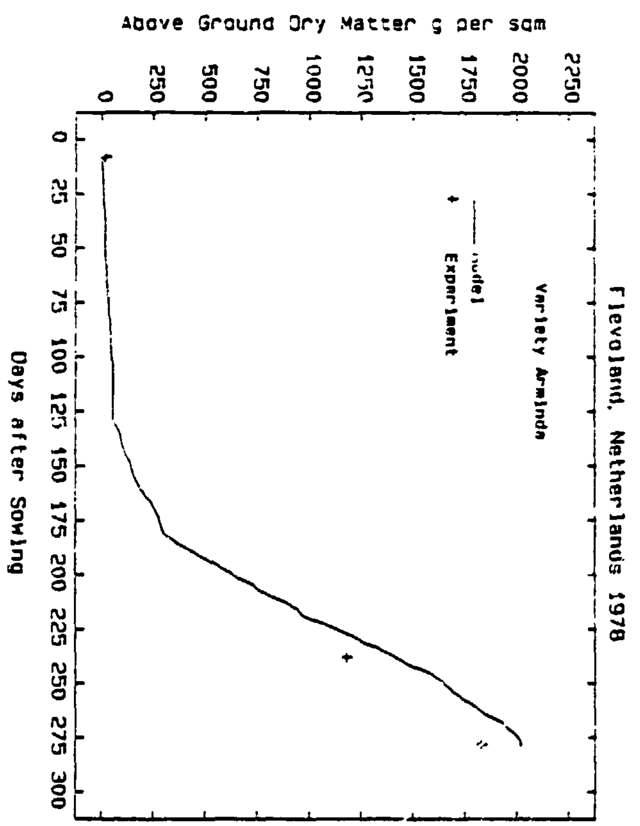

Flevoland, Netherlands 1976
Variety Lely
Model
Experiment
Days after Sowing

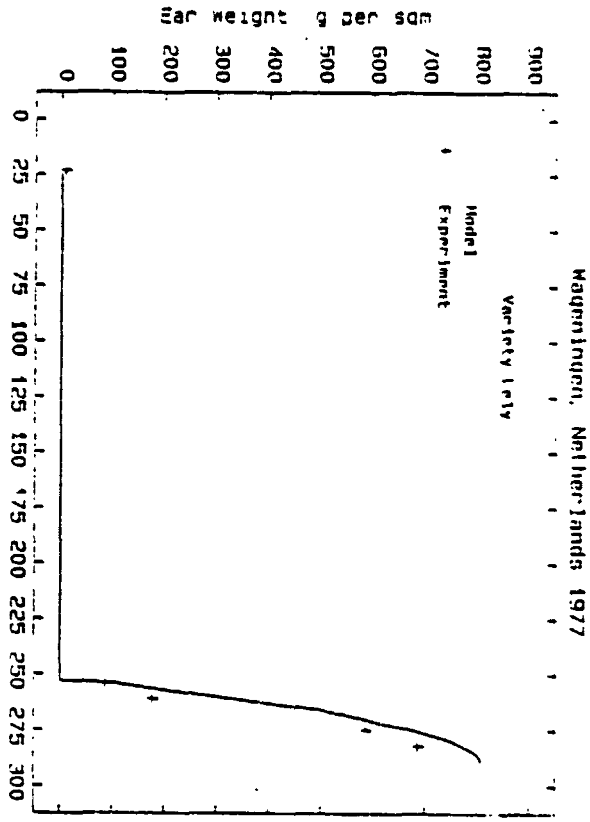

Flevoland, Netherlands 1976
Model
Experiment
Days after Sowing

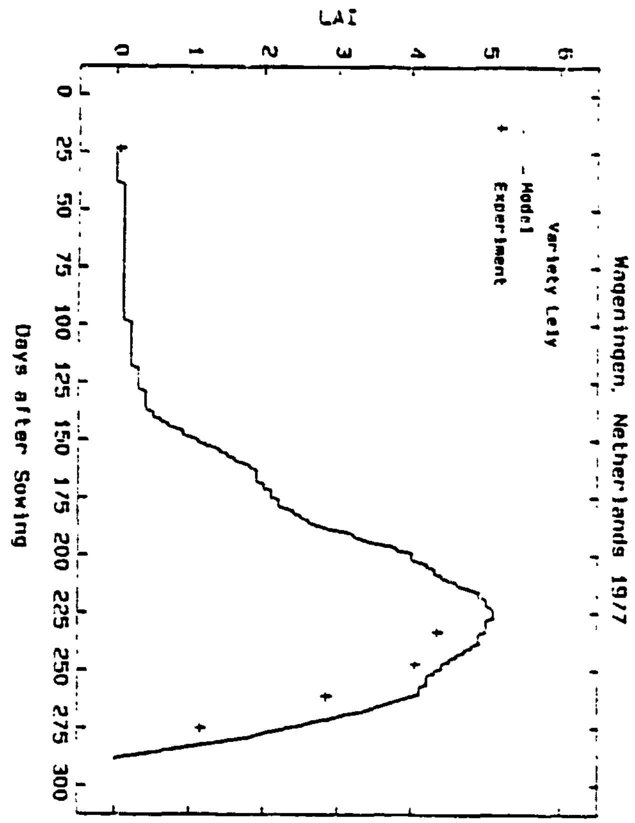

Wageningen, Netherlands 1977
Variety Lely
Model
Experiment
Leaf Weight g per sqm
0
100
200
300
400
500
600
700
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

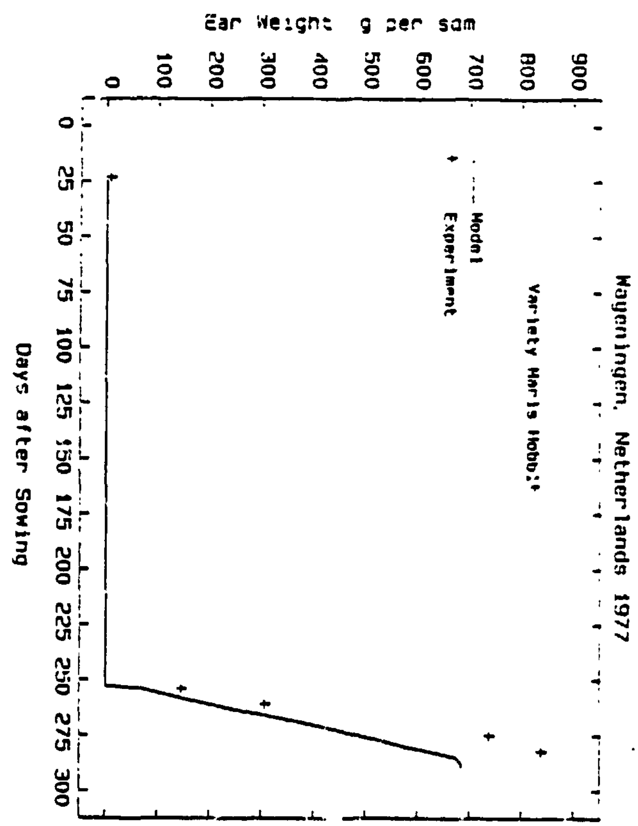

Flevoland, Netherlands 1976
Variety Lely
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

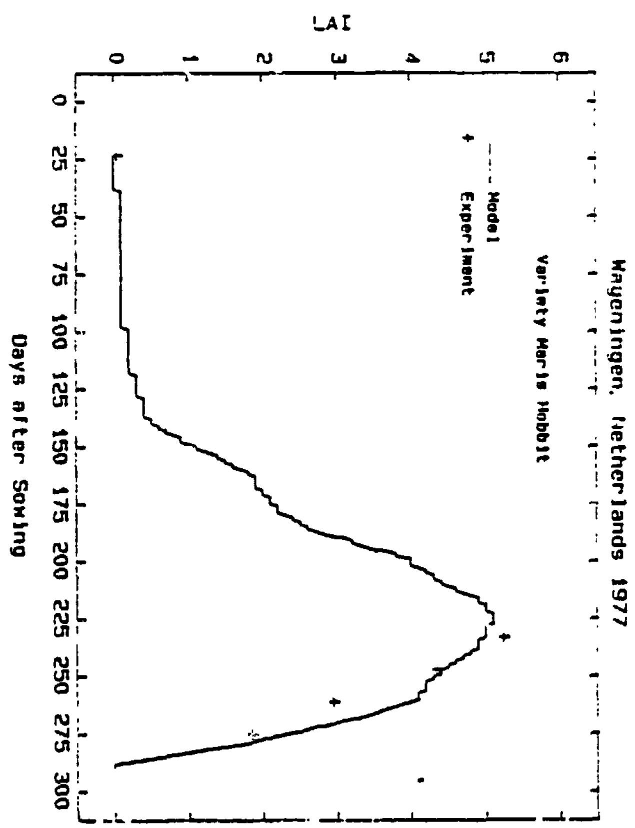

Wageningen, Netherlands 1977
Variety Maris Hobbit
Model
Experiment
Leaf Weight g per sqm
0
100
200
300
400
500
600
700
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

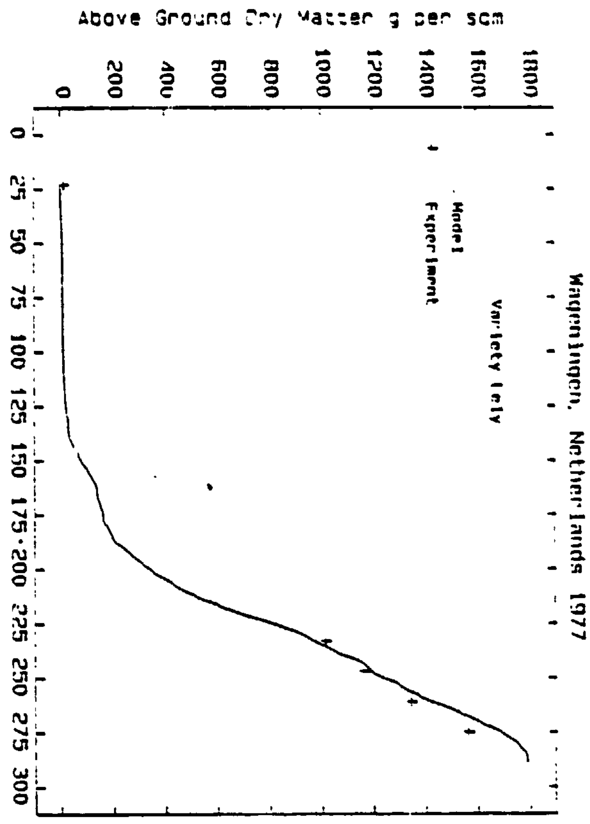

Flevoland, Netherlands 1978
Variety Arminda
Model
Experiment
Above Ground Dry Matter g per sqm
0
250
500
750
1000
1250
1500
1750
2000
2250
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

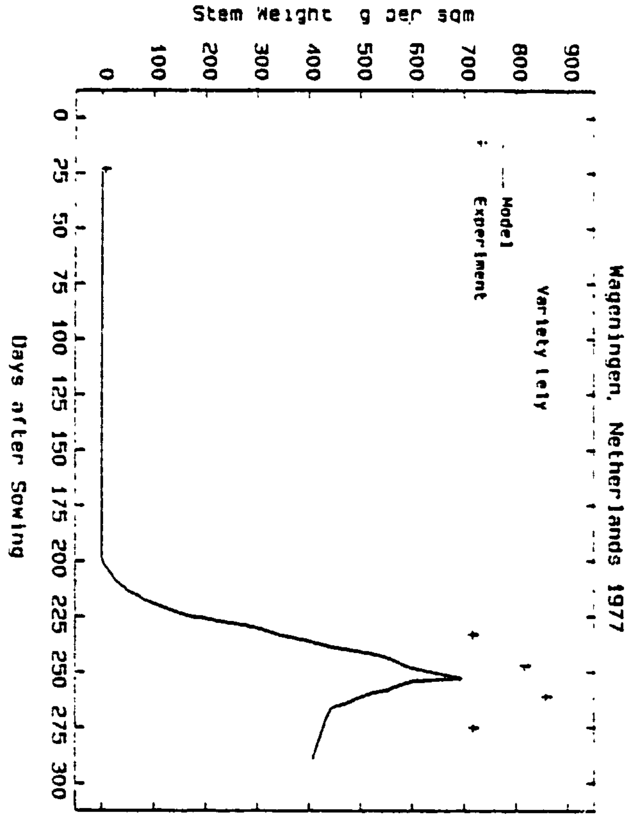

Wageningen, Netherlands 1977
Variety Lely
Model
Experiment
Ear weight g per sqm
0
100
200
300
400
500
600
700
800
900
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

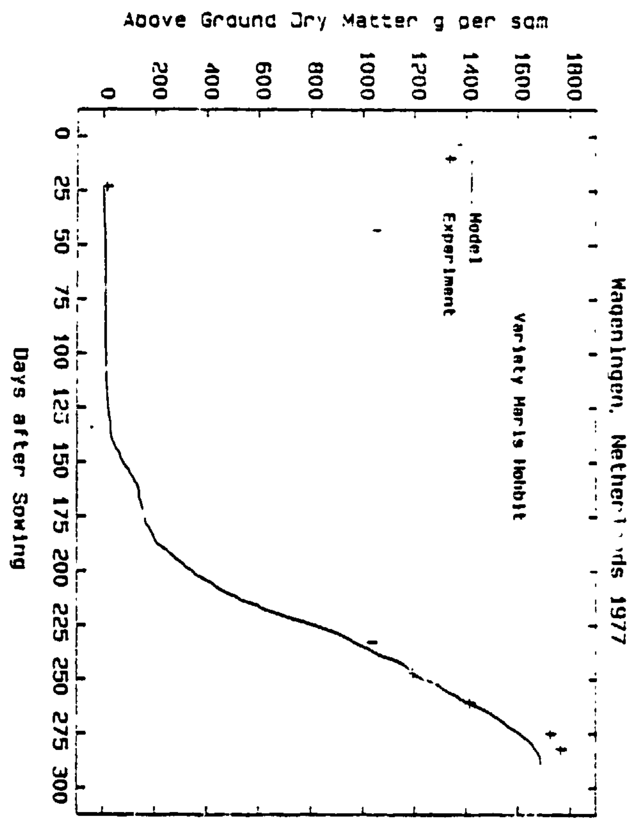

Wageningen, Netherlands 1977
Variety Lely
Model
Experiment
LAI
0
1
2
3
4
5
6
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

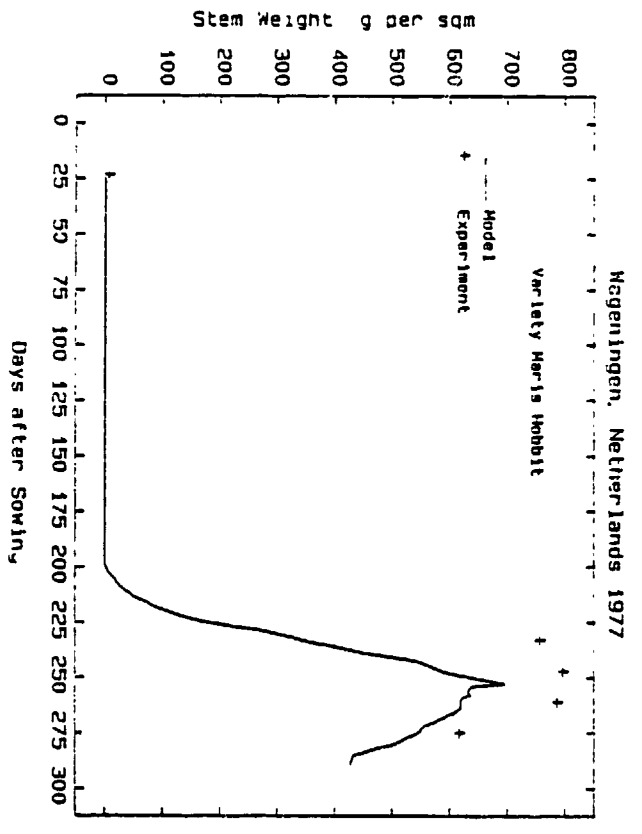

Wageningen, Netherlands 1977
Variety Maris Hobbit
Model
Experiment
Ear Weight g per sqm
0
100
200
300
400
500
600
700
800
900
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

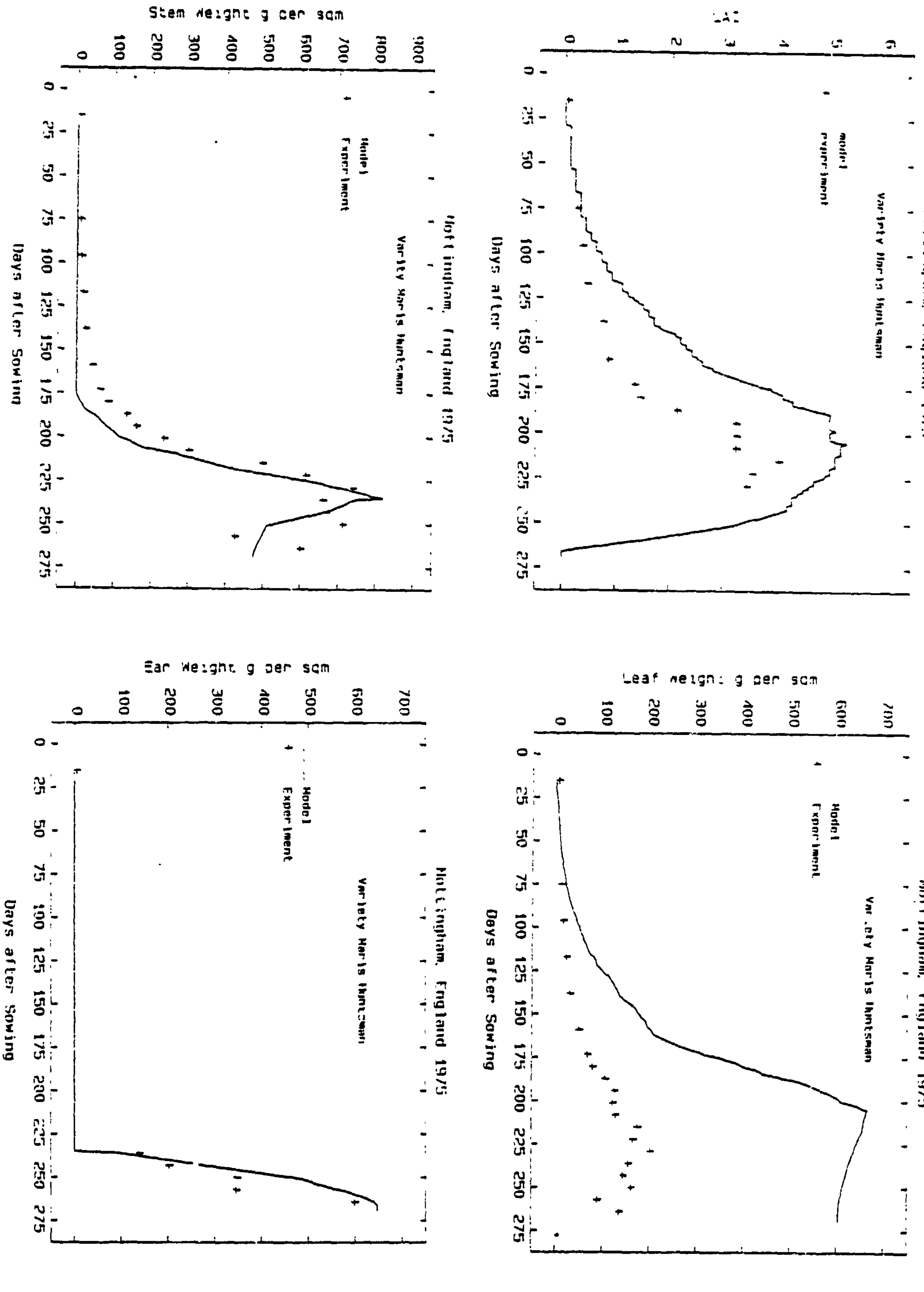

Wageningen, Netherlands 1977
Variety Maris Hobbit
Model
Experiment
LAI
0
1
2
3
4
5
6
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

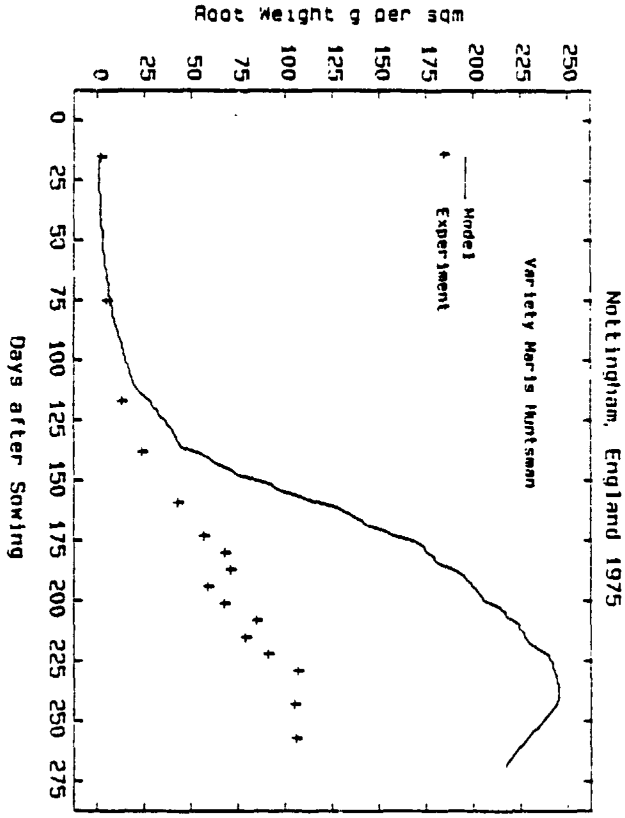

Wageningen, Netherlands 1977
Variety Lely
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

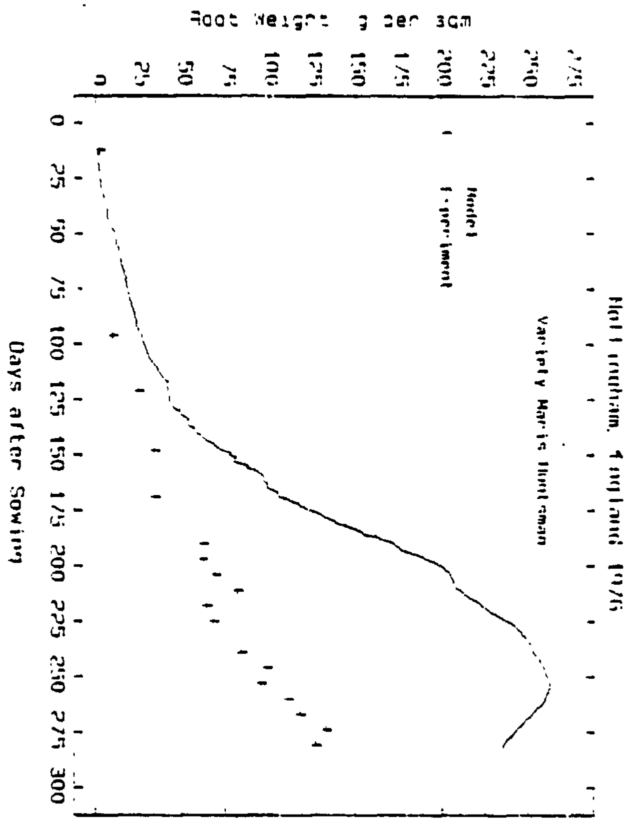

Wageningen, Netherlands 1977
Variety Lely
Model
Experiment
Stem Weight g per sqm
0
100
200
300
400
500
600
700
800
900
0 25 50 75 100 125 150 175 200 225 250 275 300
Days after Sowing

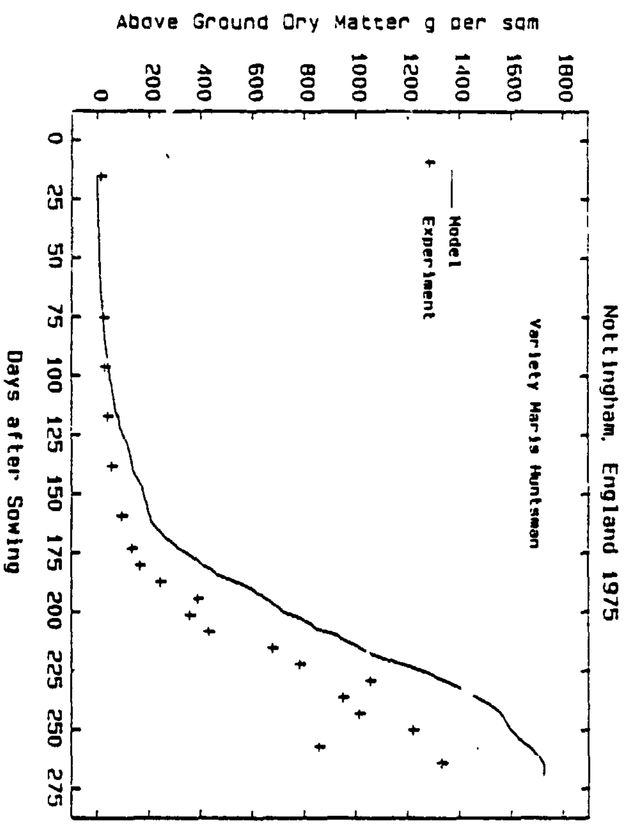

Variety Maris Hobbit
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
0 25 50 75 100 150 175 200 225 250 275 300
Days after Sowing

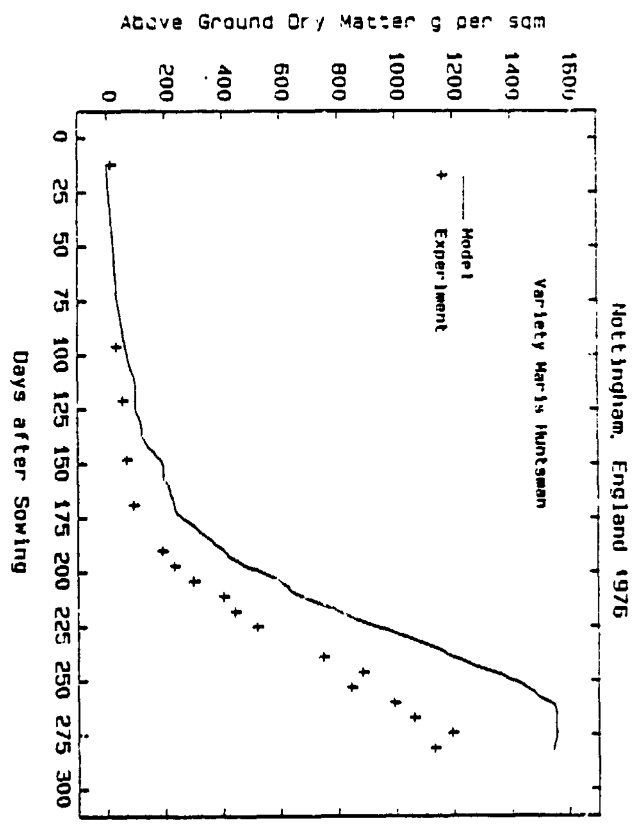

Wageningen, Netherlands 1977
Variety Maris Hobbit
Model
Experiment
Stem Weight g per sqm
0
100
200
300
400
500
600
700
800
0 25 75 100 125 150 175 200 225 250 275 300
Days after Sowing


Nottingham, England 1975
Variety Maris Huntsman
Model
Experiment
LAI
Days after Sowing
Leaf weight g per sqm
Stem Weight g per sqm
Ear Weight g per sqm

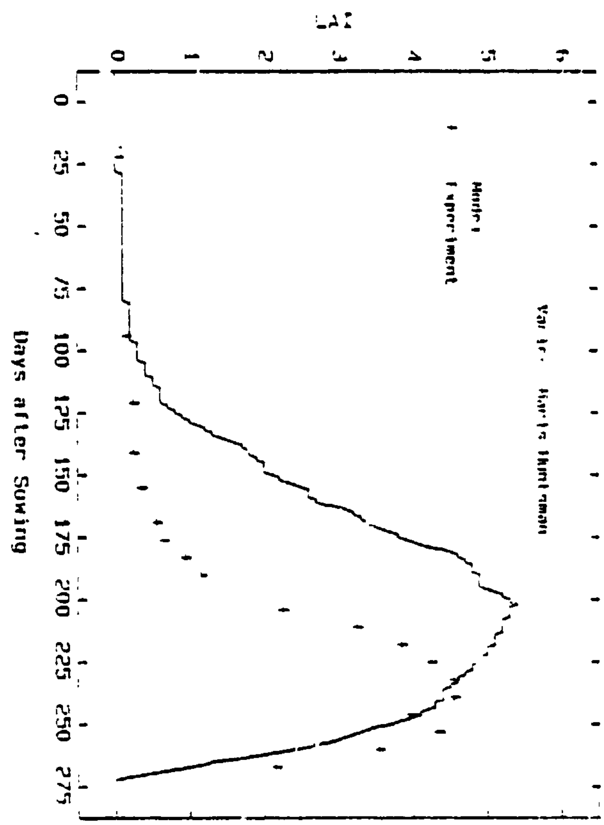

Nottingham, England 1975
Variety Maris Huntsman
Model
Experiment
Root Weight g per sqm
Days after Sowing

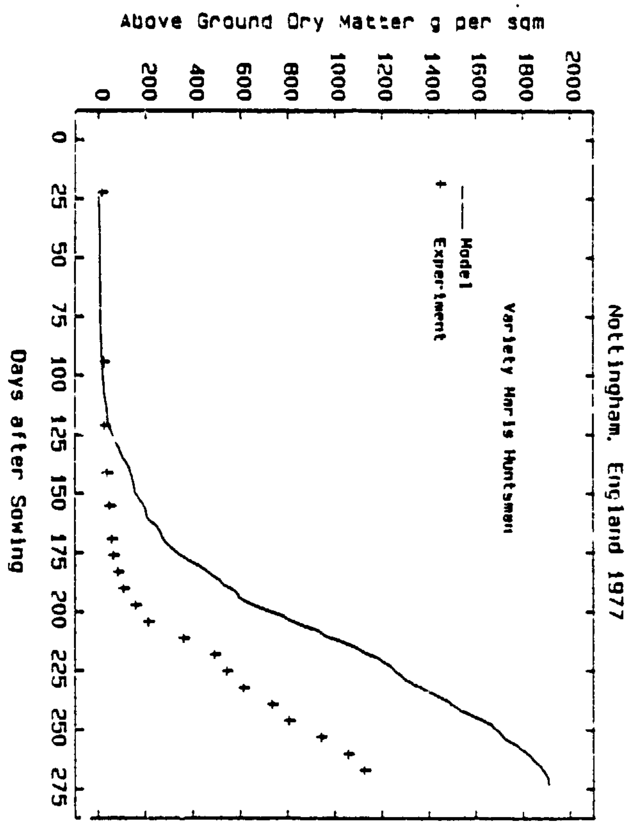

Root Weight g per sqm
Days after Sowing

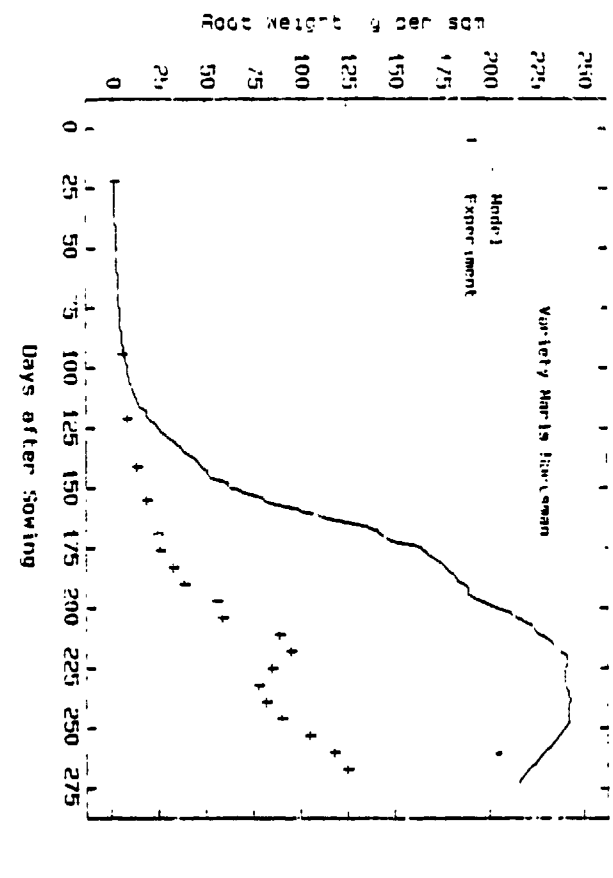

Nottingham, England 1975
Variety Maris Huntsman
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

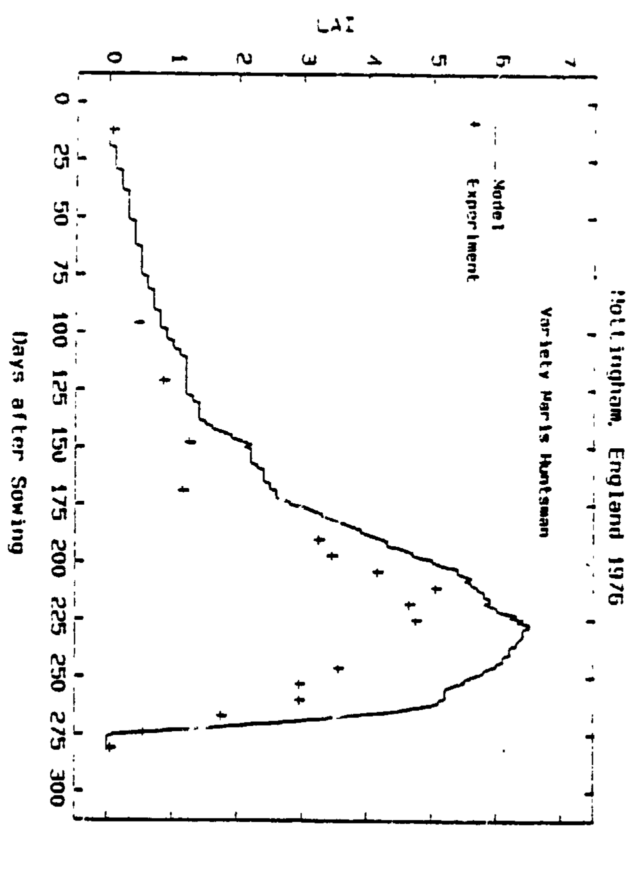

Nottingham, England 1976
Variety Maris Huntsman
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

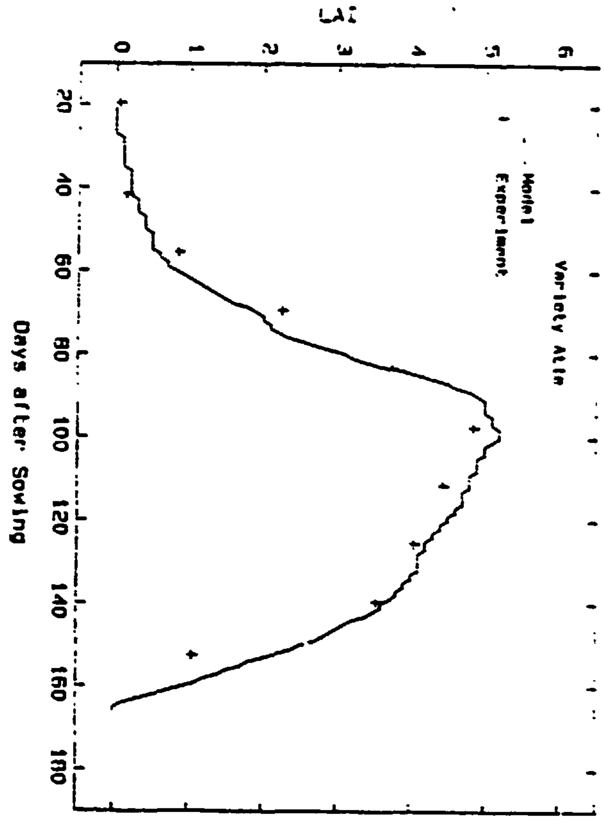
Nottingham, England

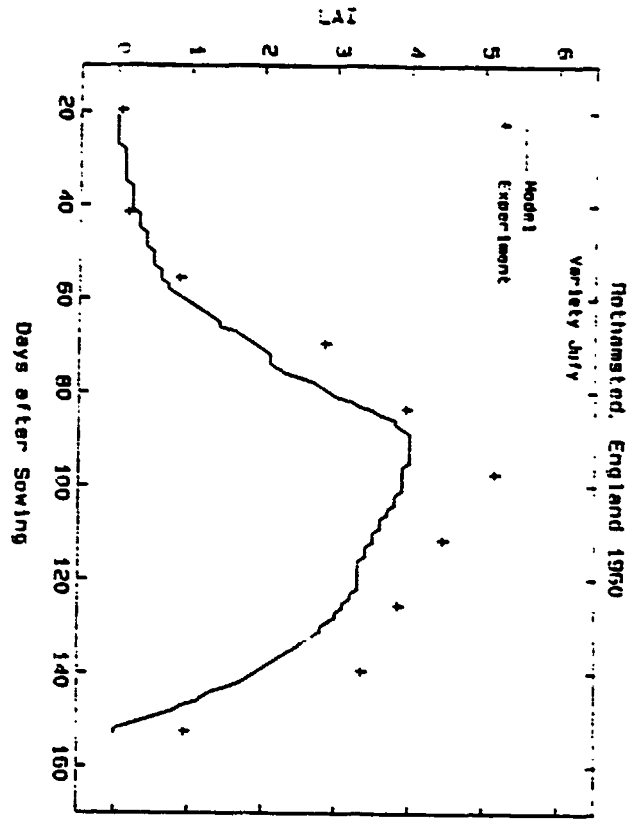


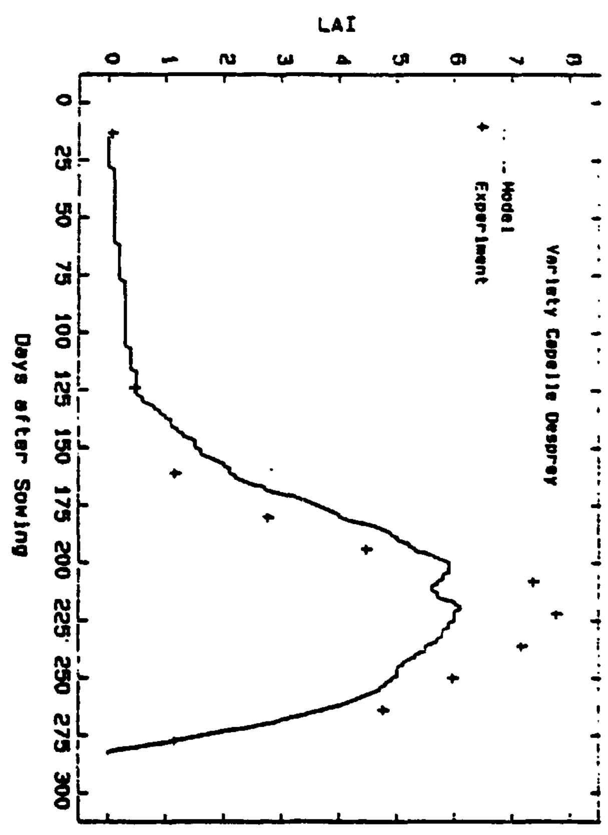


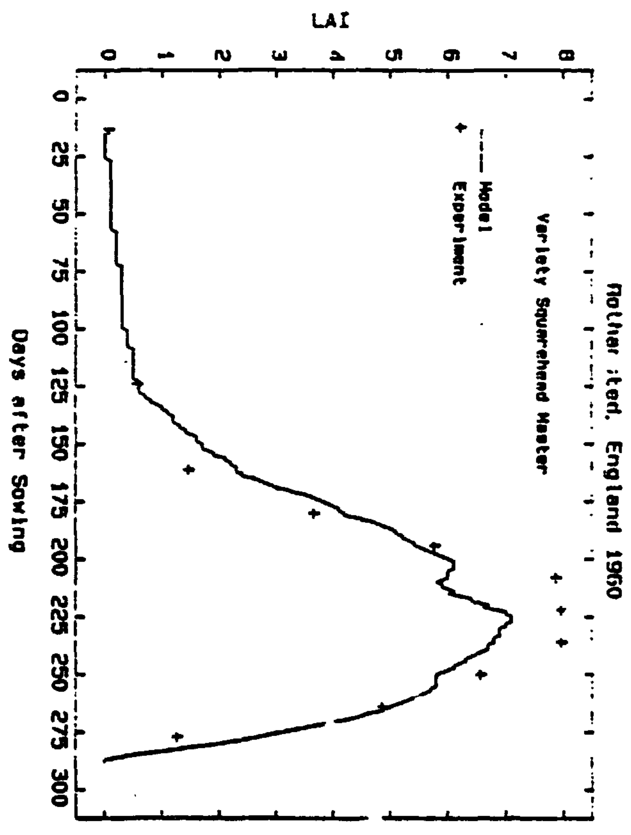


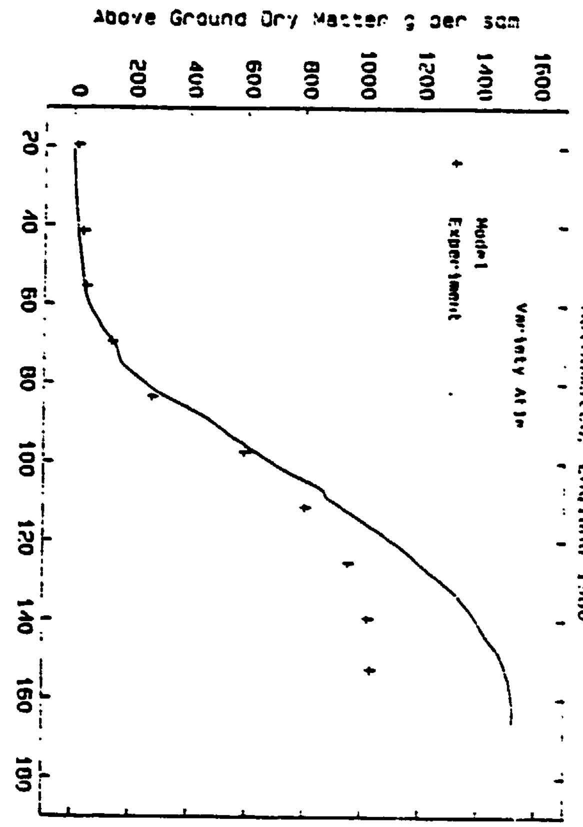


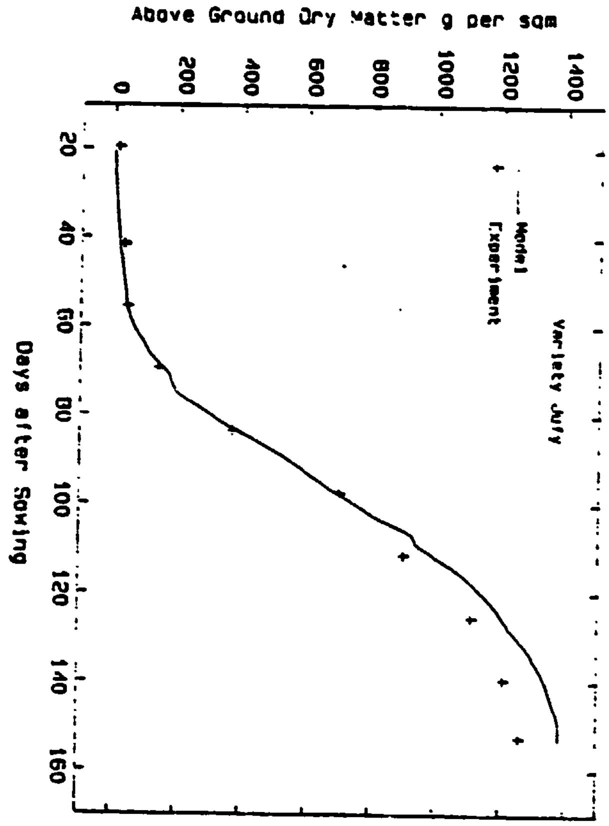

Rothamsted, England 1960
Variety Atle
Model
Experiment
LAI
Days after Sowing

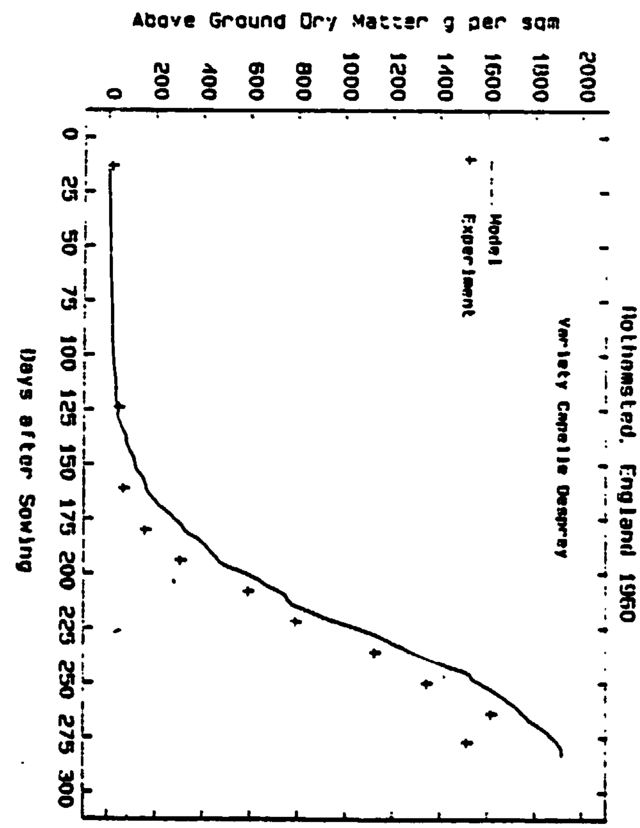

Rothamsted, England 1960
Variety Jufy
Model
Experiment
LAI
Days after Sowing

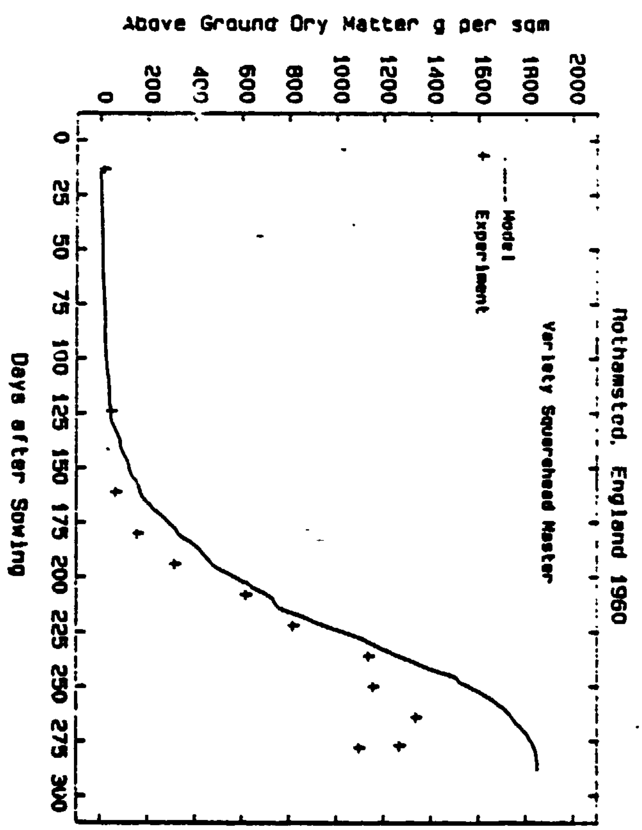

Rothamsted, England 1960
Variety Capelle Desprey
Model
Experiment
LAI
Days after Sowing

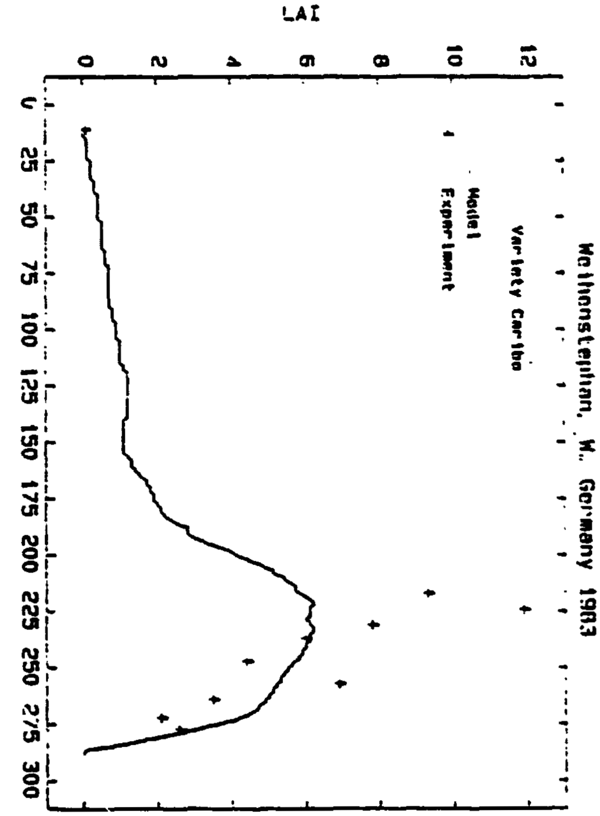

Variety Squarehead Master
Model
Experiment
LAI
Days after Sowing

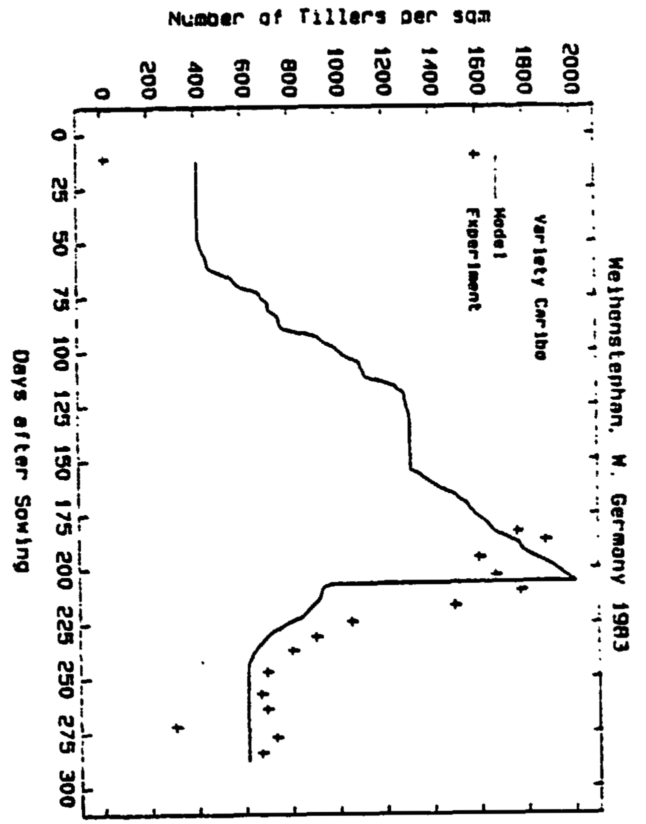

Rothamsted, England 1960
Variety Atle
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

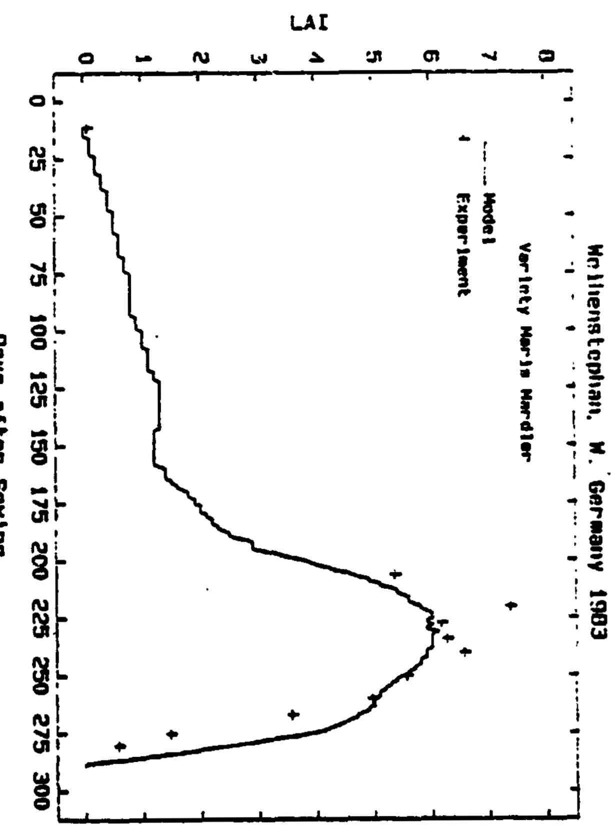

Rothamsted, England 1960
Variety July
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

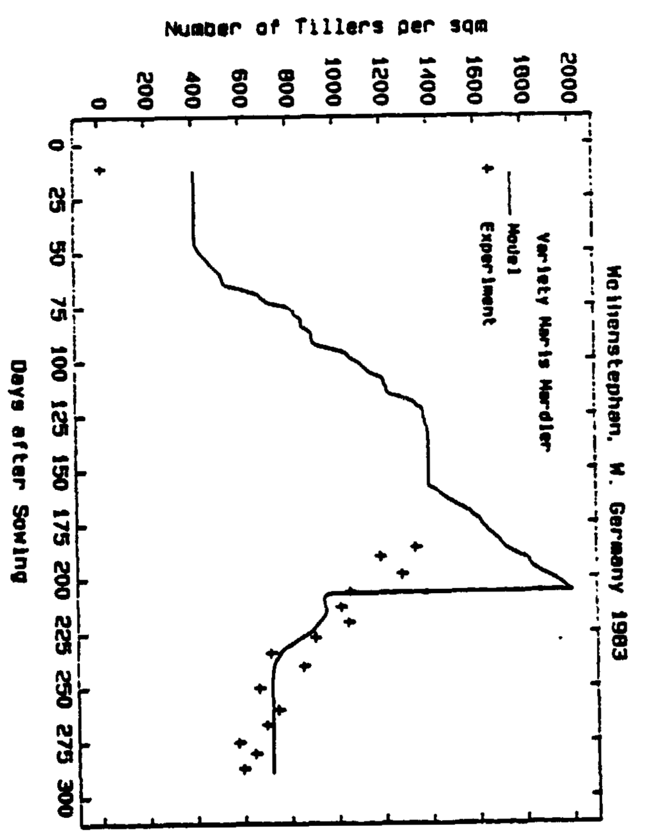

Rothamsted, England 1960
Variety Capelle Desprez
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

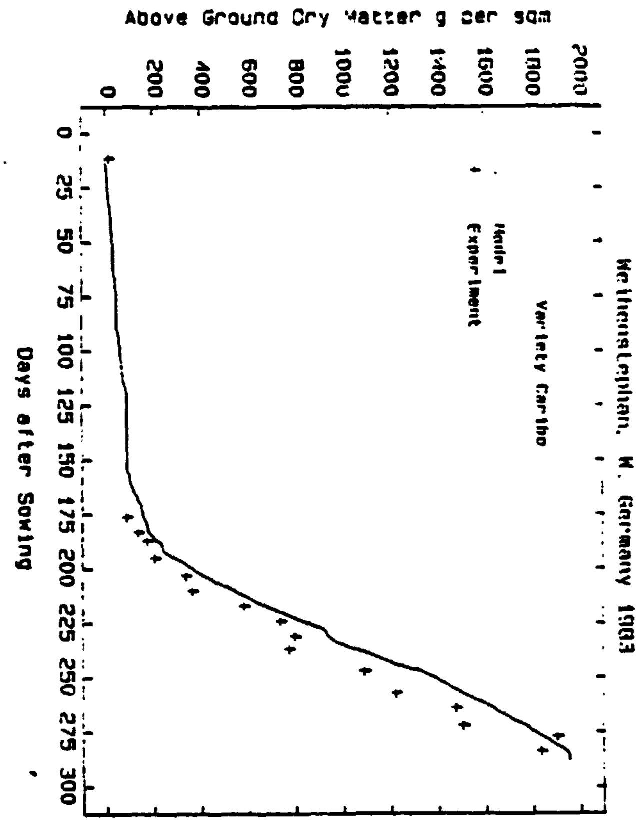

Rothamsted, England 1960
Variety Squarehead Master
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

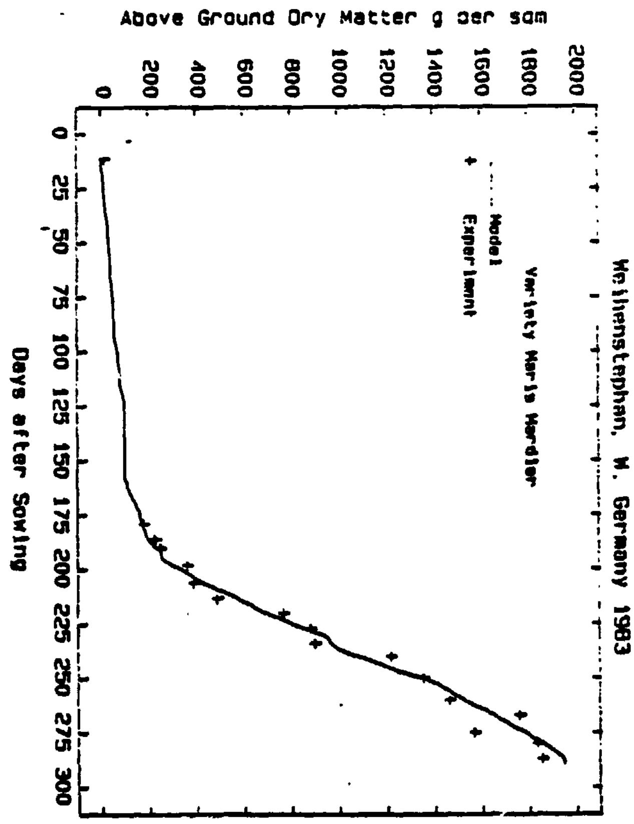

Weihenstephan, W. Germany 1983
Variety Caribo
Model
Experiment
LAI
Days after Sowing

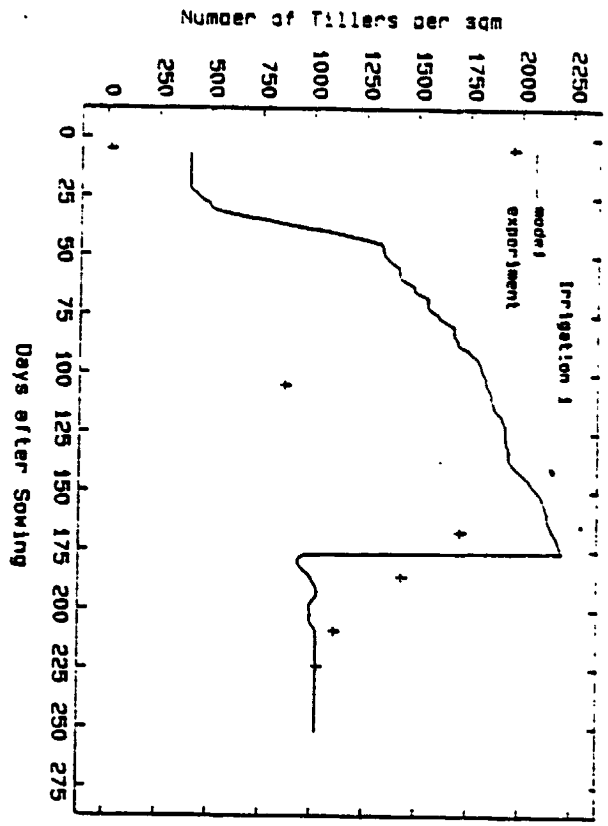

Weihenstephan, W. Germany 1983
Variety Caribo
Model
Experiment
Number of Tillers per sqm
Days after Sowing

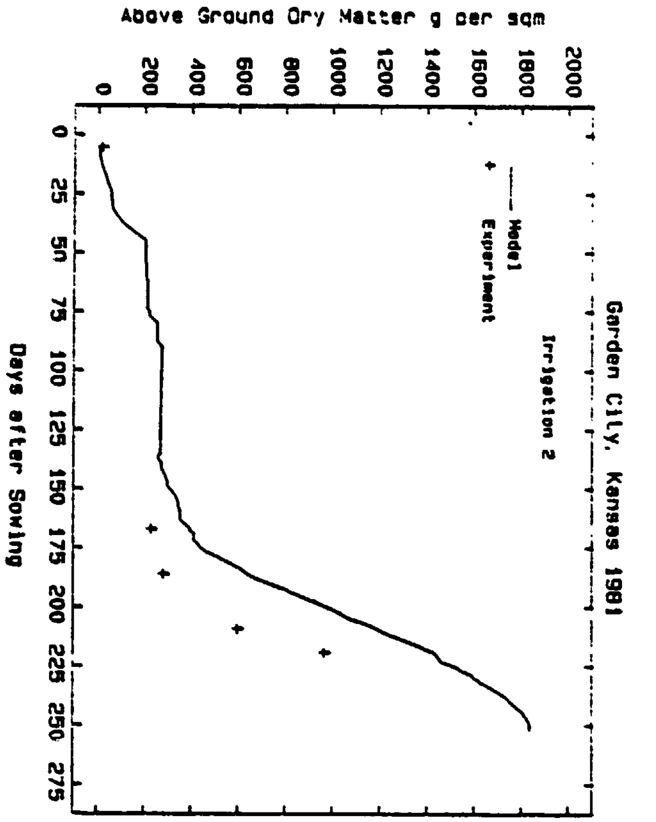

Weihenstephan, W. Germany 1983
Variety Maris Hardier
Model
Experiment
LAI
Days after Sowing

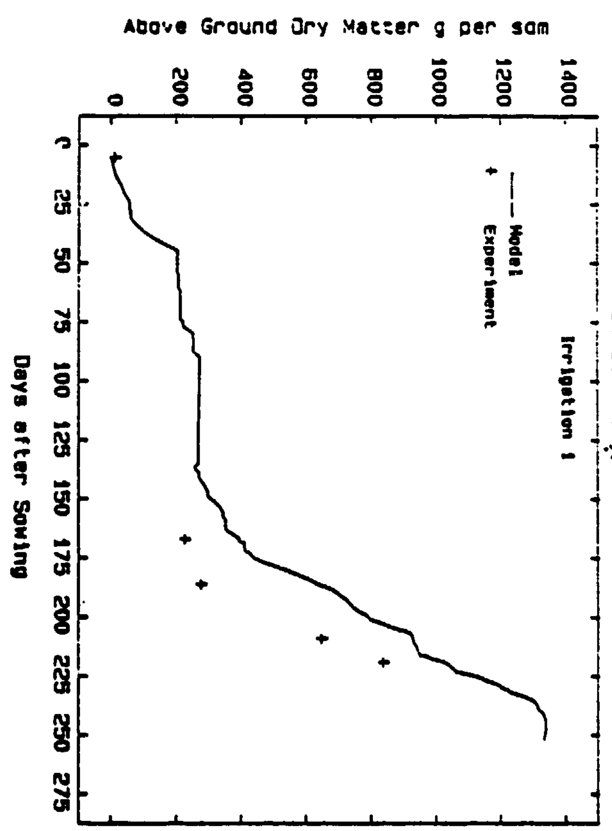

Weihenstephan, W. Germany 1983
Variety Maris Hardier
Model
Experiment
Number of Tillers per sqm
Days after Sowing

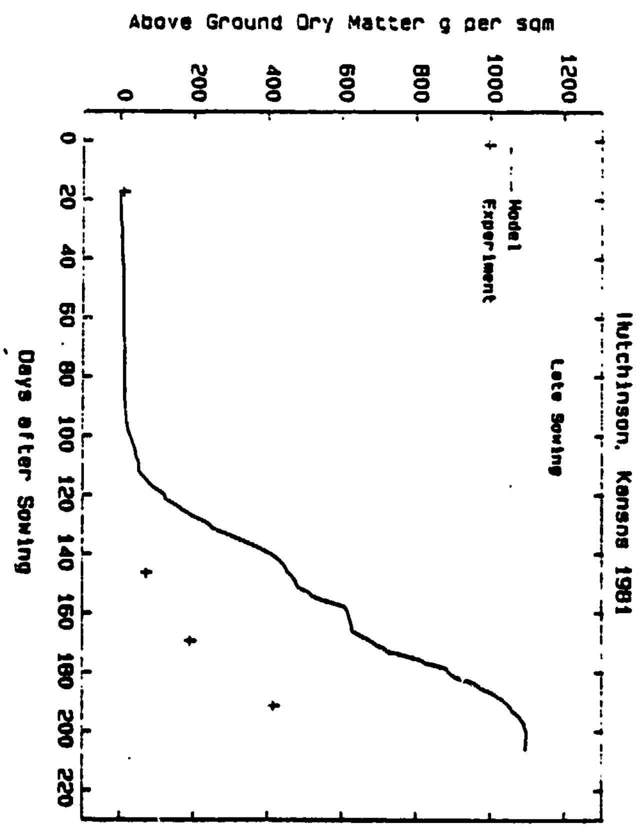

Weihenstephan, W. Germany 1983
Variety Caribo
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

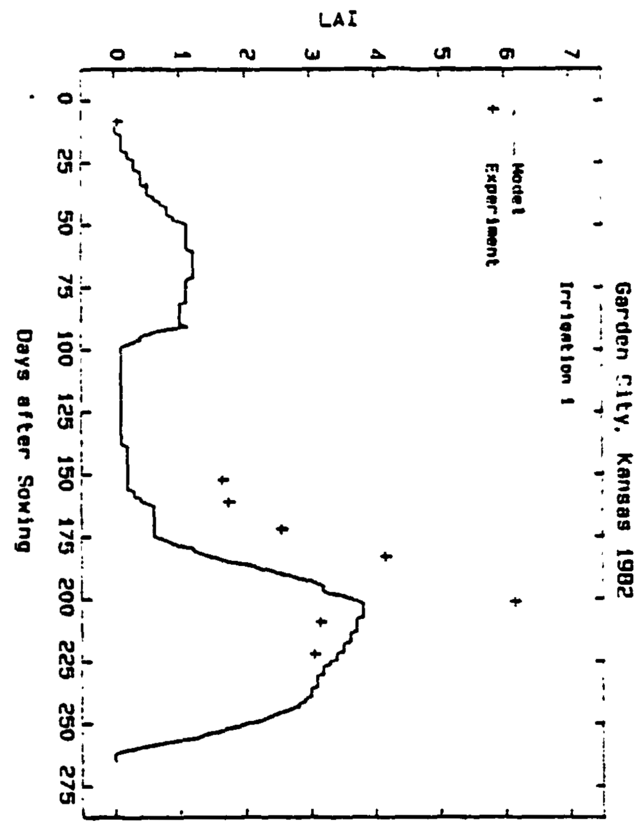

Weihenstephan, W. Germany 1983
Variety Maris Hordler
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

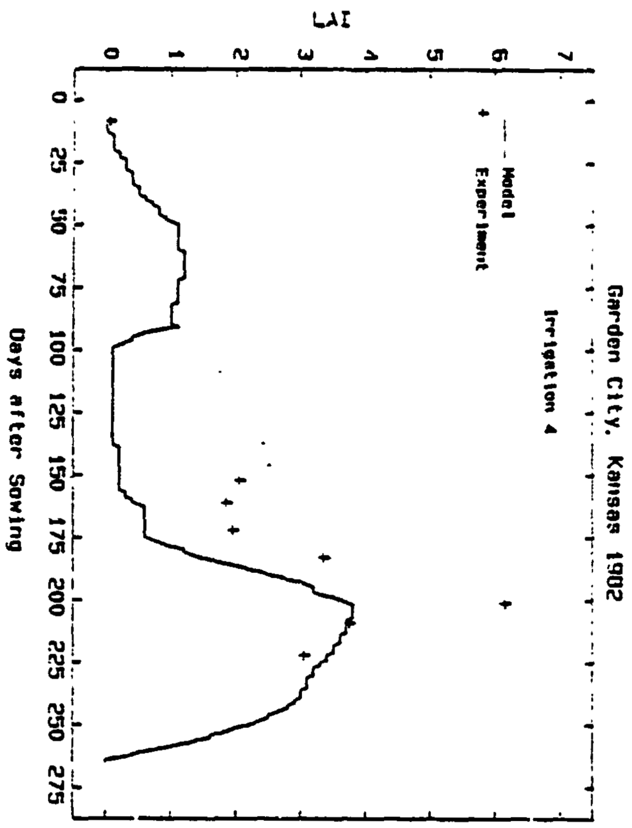

Garden City, Kansas 1981
Irrigation 1
model
experiment
Number of Tillers per sqm
0
250
500
750
1000
1250
1500
1750
2000
2250
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

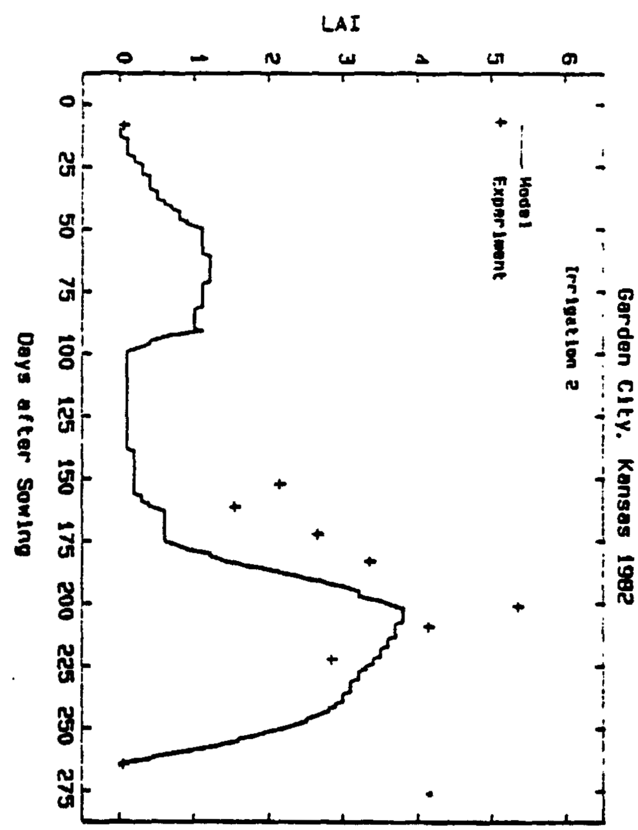

Garden City, Kansas 1981
Irrigation 2
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

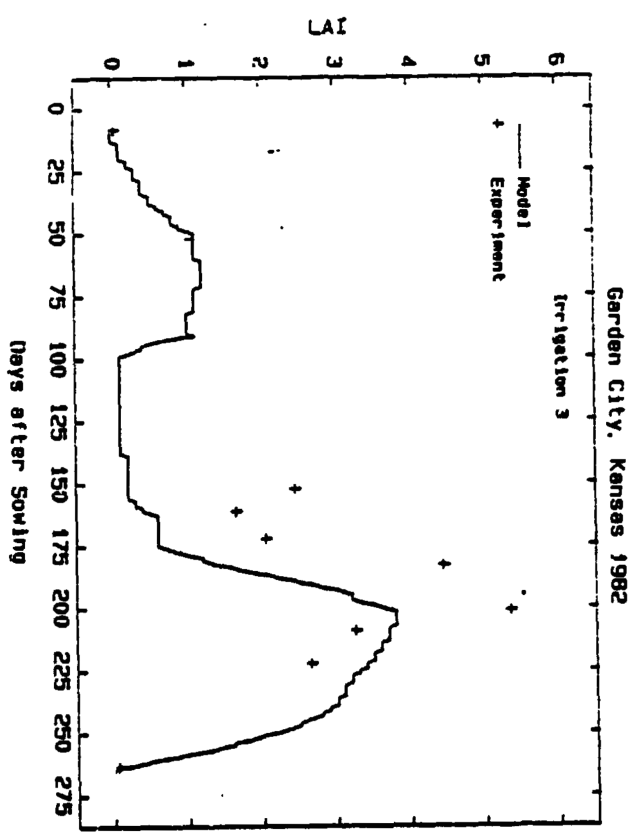

Garden City, Kansas 1981
Irrigation 1
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
0 25 50 75 100 125 150 175 200 225 250 275
Days after Sowing

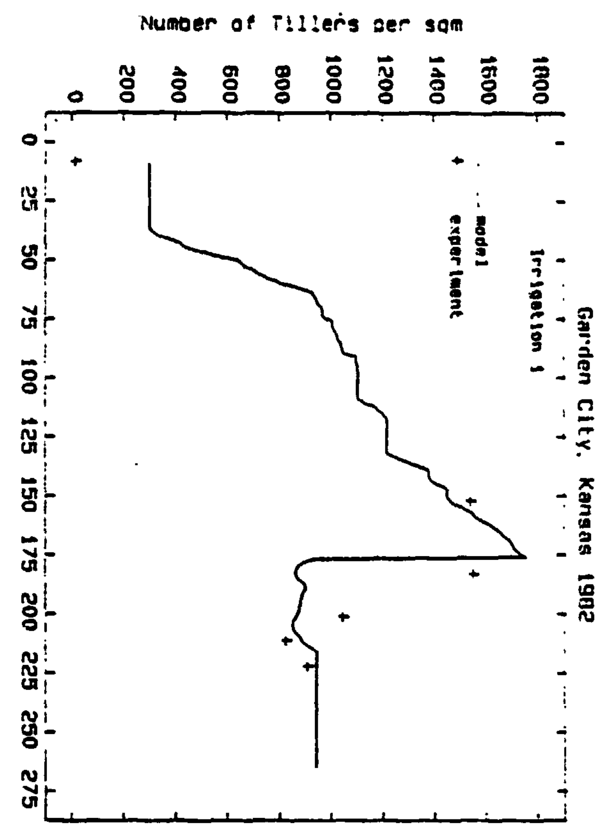

Hutchinson, Kansas 1981
Late Sowing
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
0 20 40 60 80 100 120 140 160 180 200 220
Days after Sowing

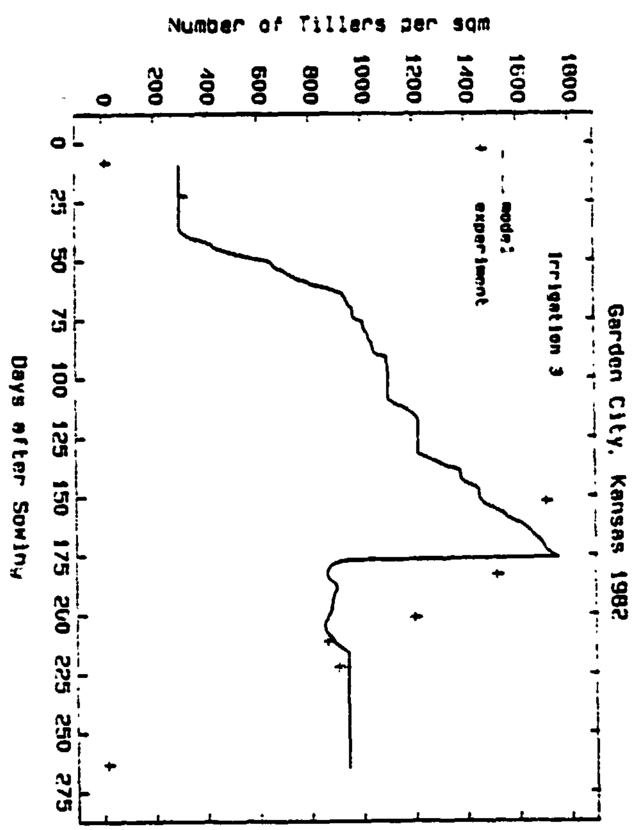

Garden City, Kansas 1982
Irrigation 1
Model
Experiment
LAI
Days after Sowing

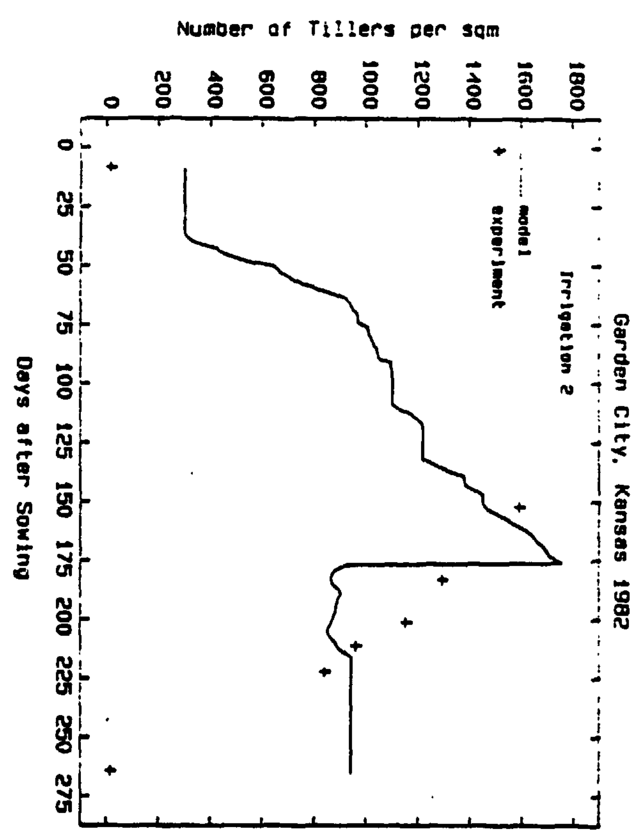

Garden City, Kansas 1982
Irrigation 2
Model
Experiment
LAI
Days after Sowing

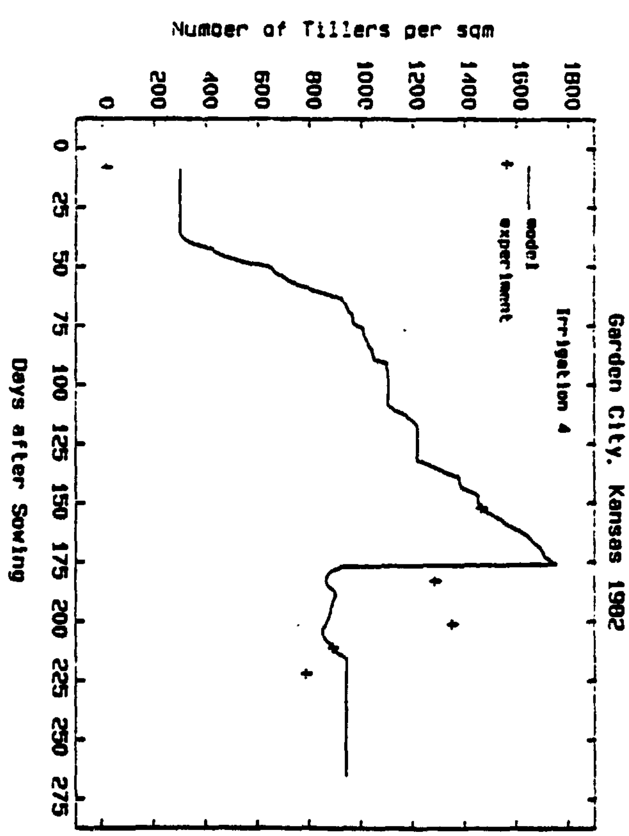

Garden City, Kansas 1982
Irrigation 3
Model
Experiment
LAI
Days after Sowing

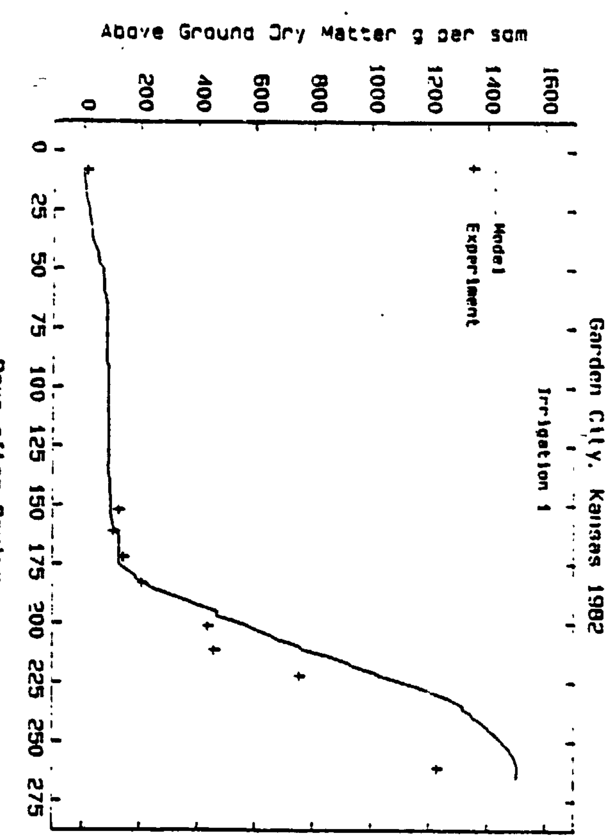

Garden City, Kansas 1982
Irrigation 4
Model
Experiment
LAI
Days after Sowing

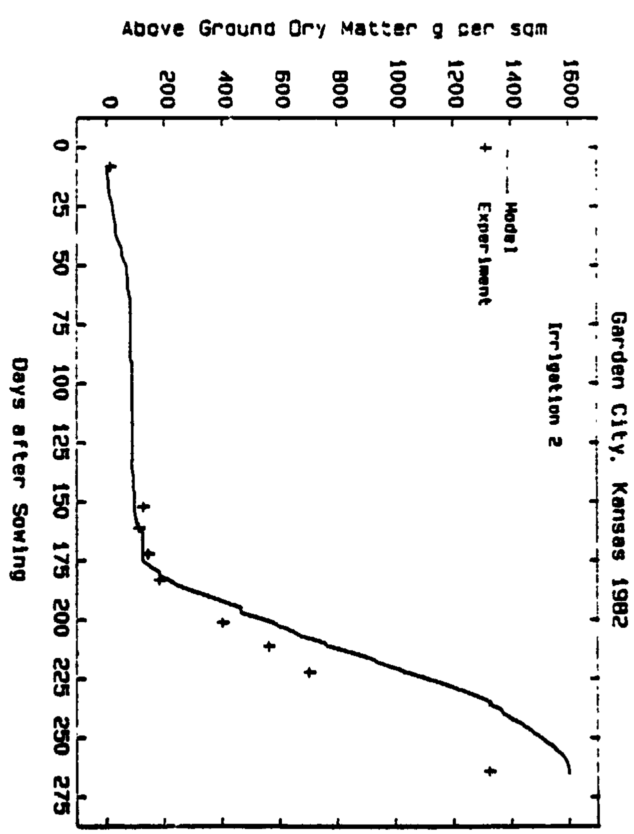

Garden City, Kansas 1982
Irrigation 1
model
experiment
Number of Tillers per sqm
0 200 400 600 800 1000 1200 1400 1600 1800
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

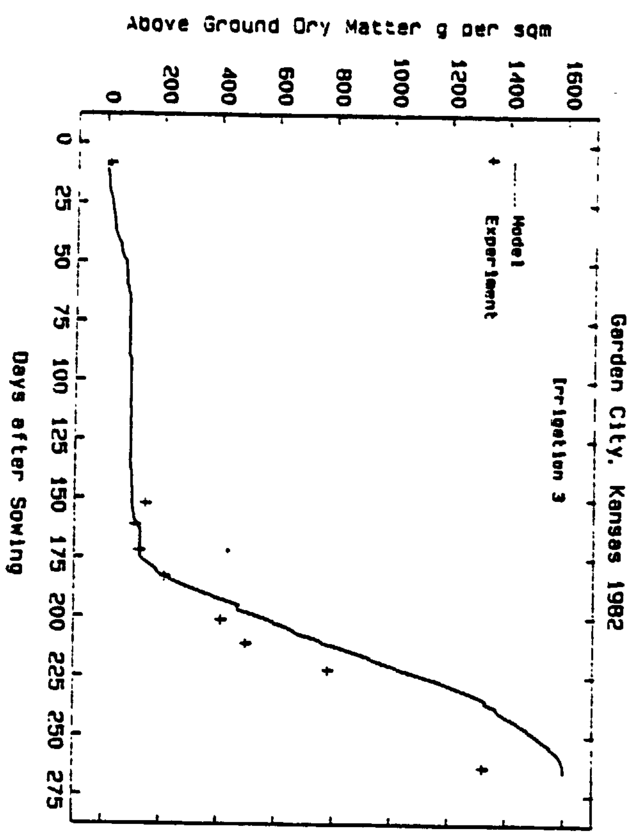

Garden City, Kansas 1982
Irrigation 3
model
experiment
Number of Tillers per sqm
0 200 400 600 800 1000 1200 1400 1600 1800
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

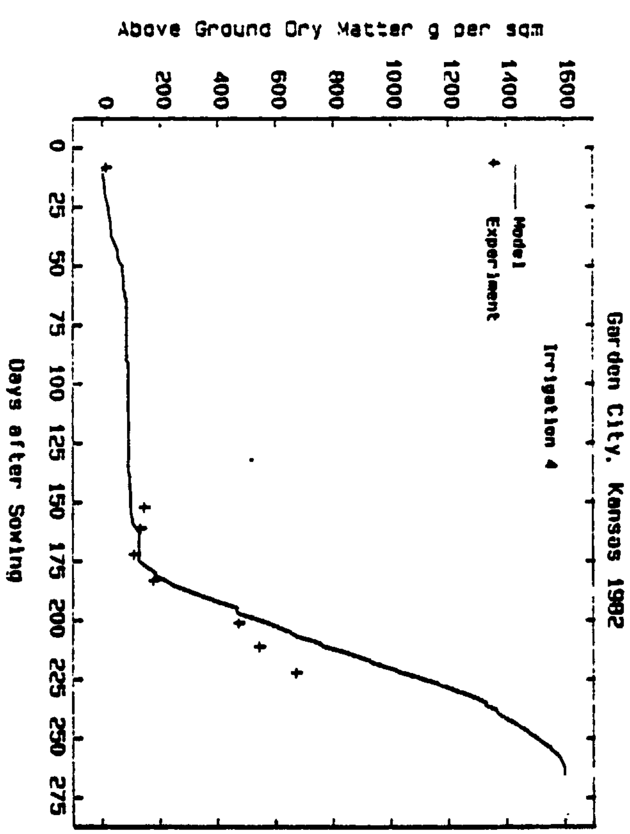

Garden City, Kansas 1982
Irrigation 2
model
experiment
Number of Tillers per sqm
0 200 400 600 800 1000 1200 1400 1600 1800
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

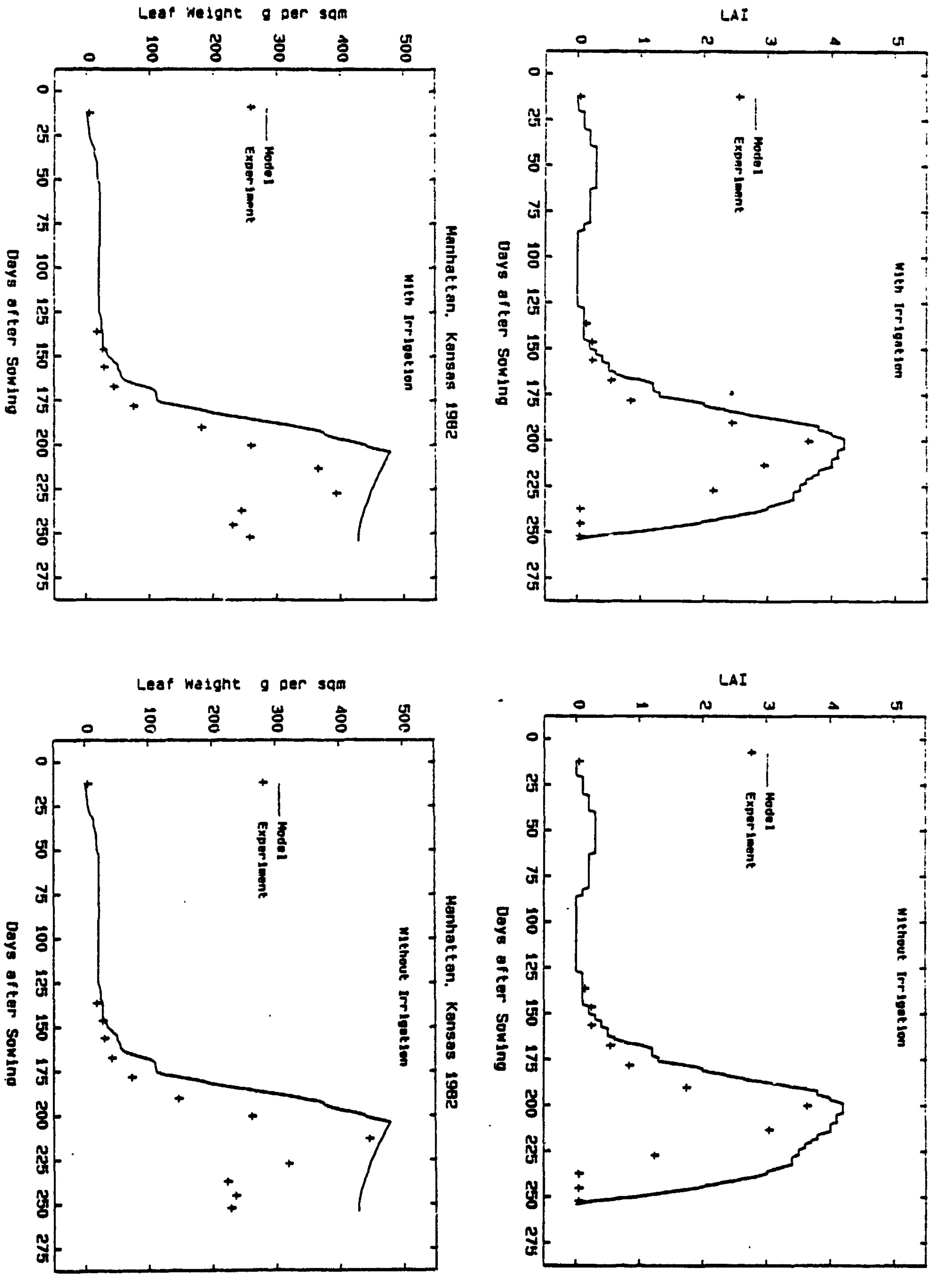

Garden City, Kansas 1982
Irrigation 4
model
experiment
Number of Tillers per sqm
0 200 400 600 800 1000 1200 1400 1600 1800
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275

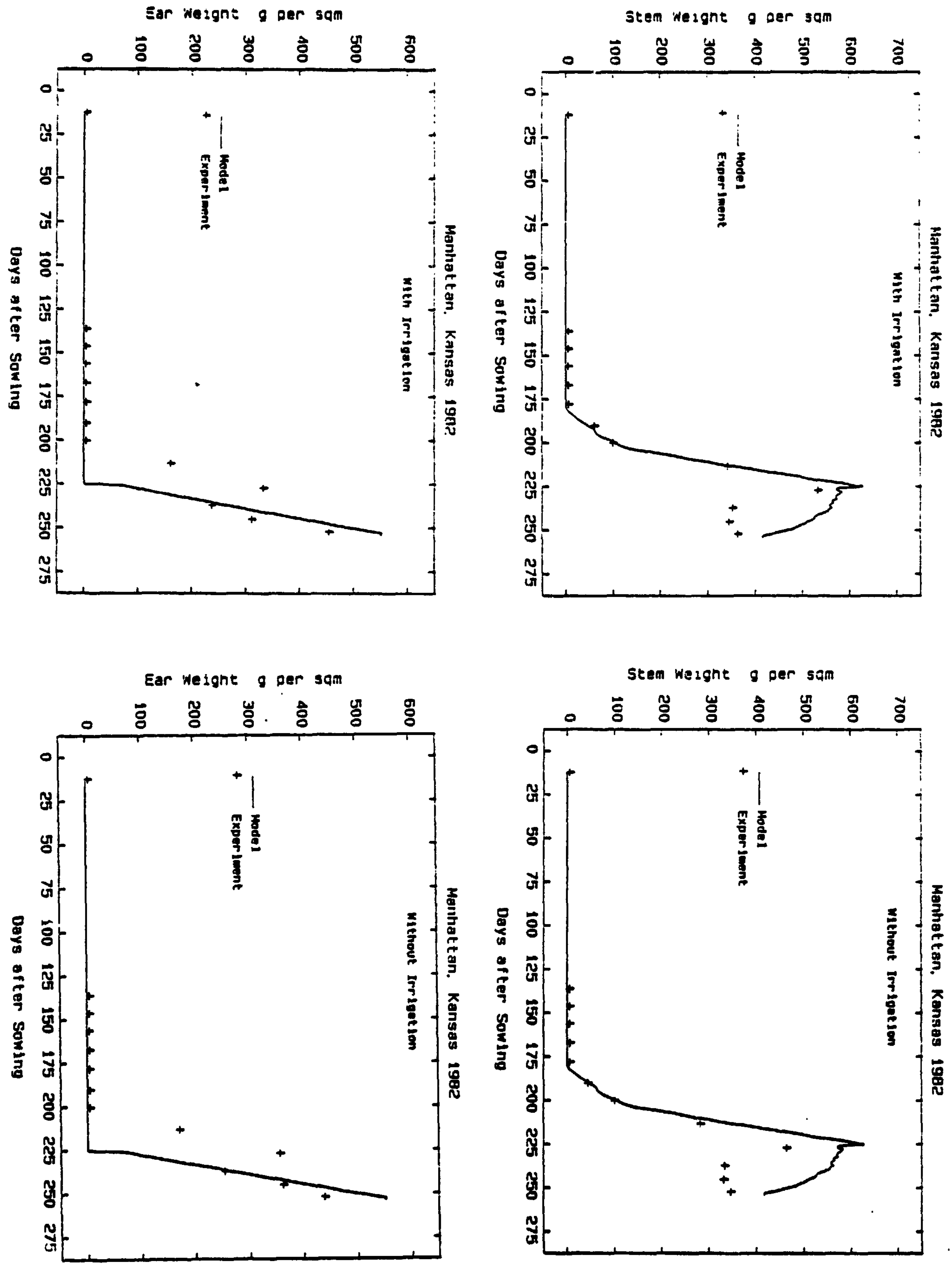

Garden City, Kansas 1982
Irrigation 1
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

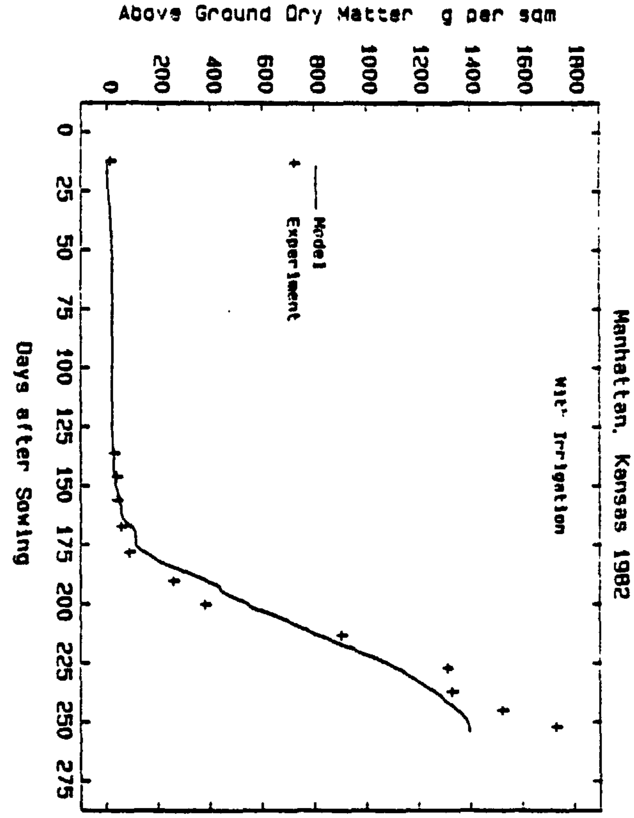

Garden City, Kansas 1982
Irrigation 2
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

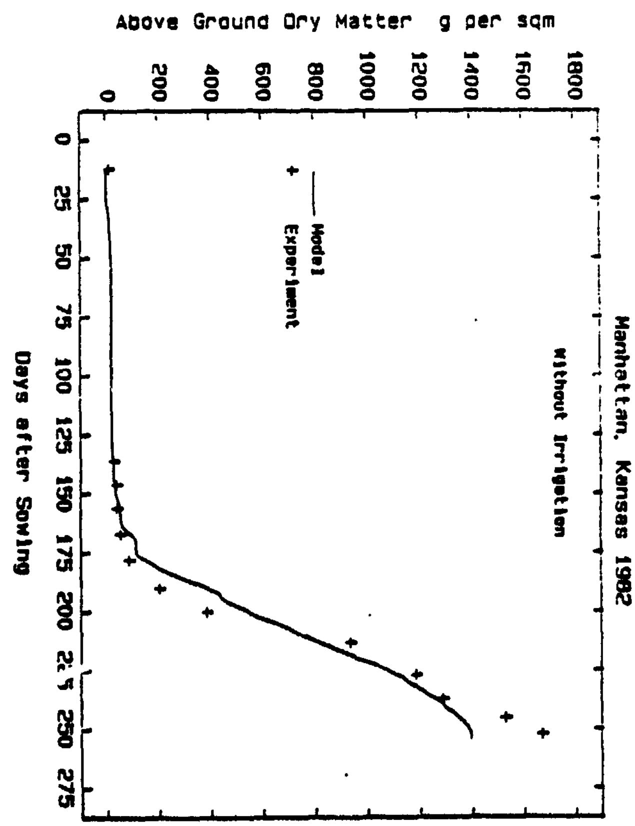

Garden City, Kansas 1982
Irrigation 3
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

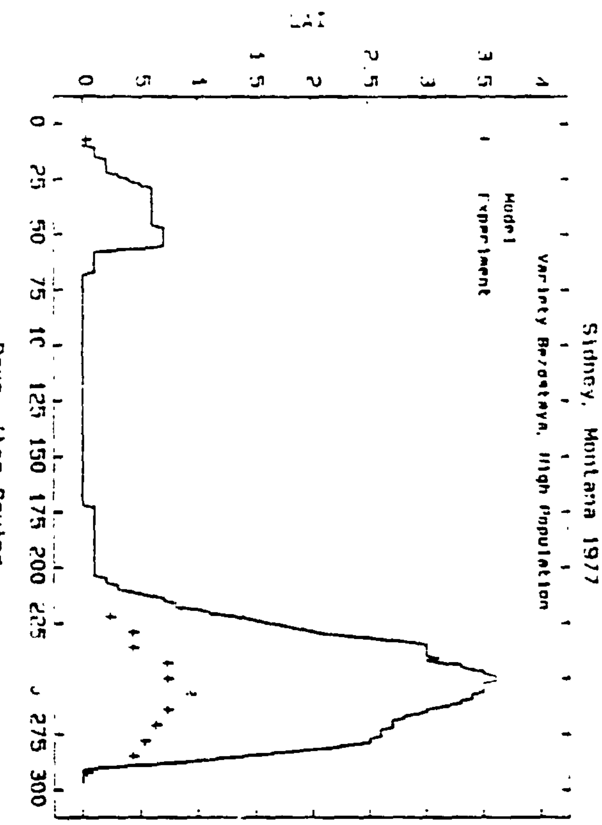

Garden City, Kansas 1982
Irrigation 4
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

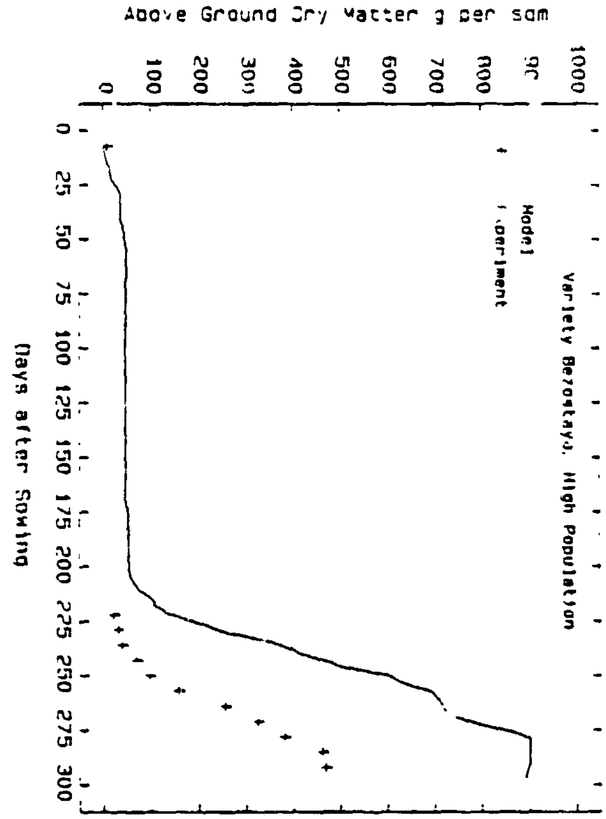

Manhattan, Kansas 1982
With Irrigation
LAI
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
Without Irrigation
LAI
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
With Irrigation
Leaf Weight g per sqm
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
Without Irrigation
Leaf Weight g per sqm
Model
Experiment
Days after Sowing

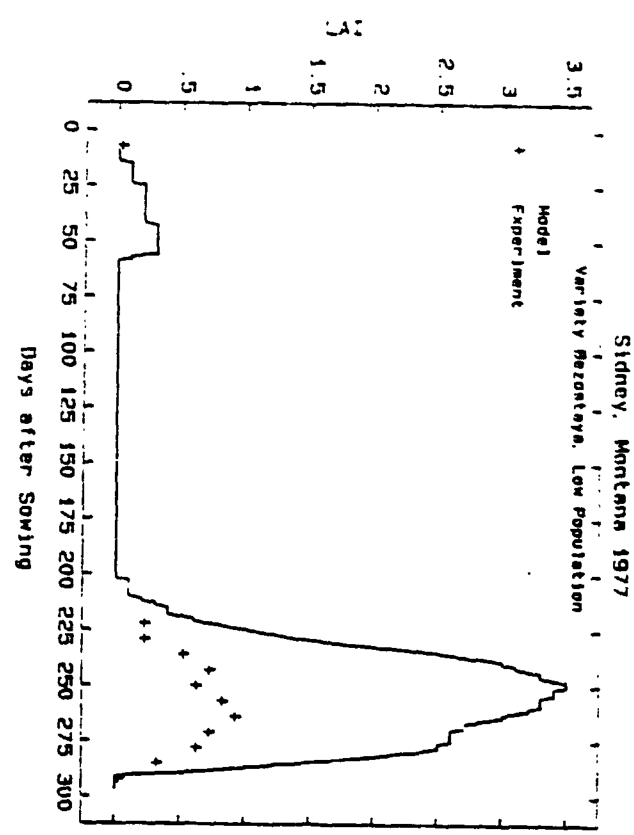

Manhattan, Kansas 1982
With Irrigation
Stem Weight g per sqm
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
With Irrigation
Ear Weight g per sqm
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
Without Irrigation
Stem Weight g per sqm
Model
Experiment
Days after Sowing
Manhattan, Kansas 1982
Without Irrigation
Ear Weight g per sqm
Model
Experiment
Days after Sowing

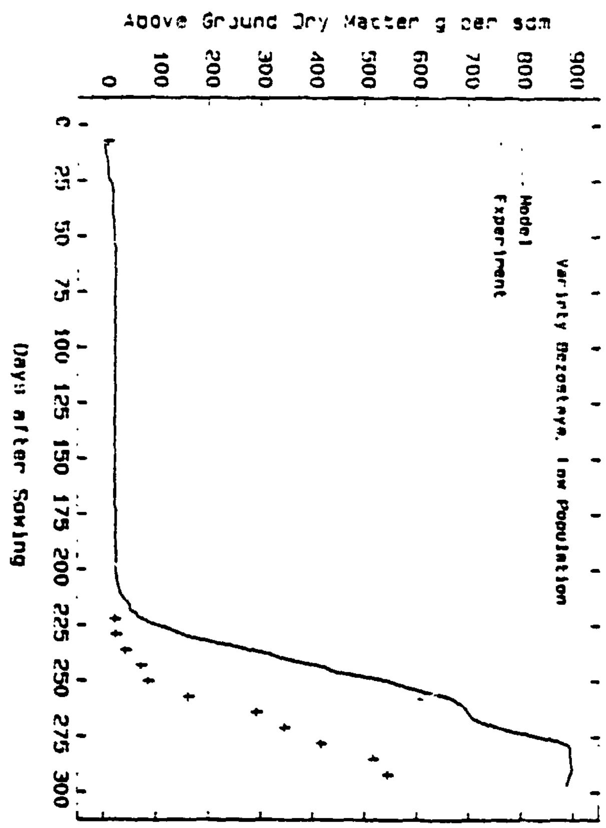

Manhattan, Kansas 1982
With Irrigation
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
Days after Sowing
0
25
50
75
100
125
150
175
200
225
250
275

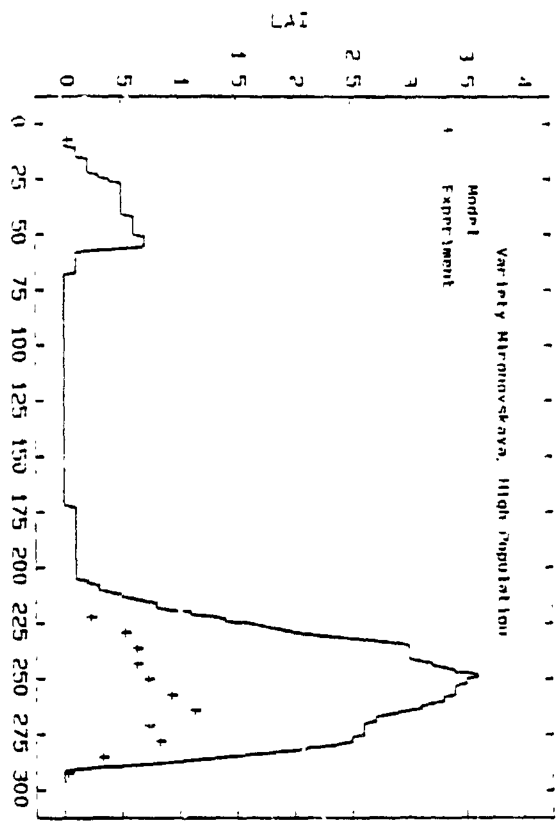

Manhattan, Kansas 1982
Without Irrigation
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
1800
Days after Sowing
0
25
50
75
100
125
150
175
200
225
250
275

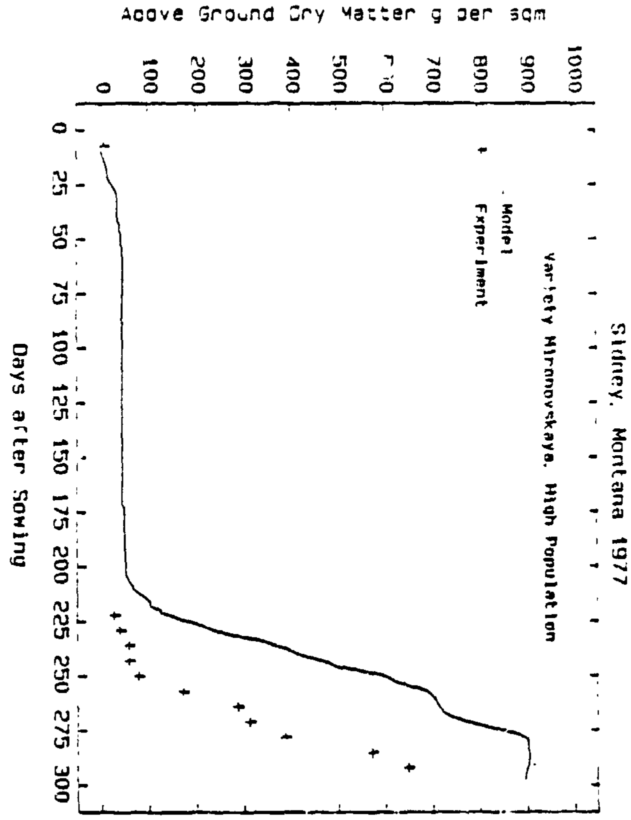

Sidney, Montana 1977
Variety Bezostaya, High Population
Model
Experiment
LAI
0
.5
1
1.5
2
2.5
3
3.5
4
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

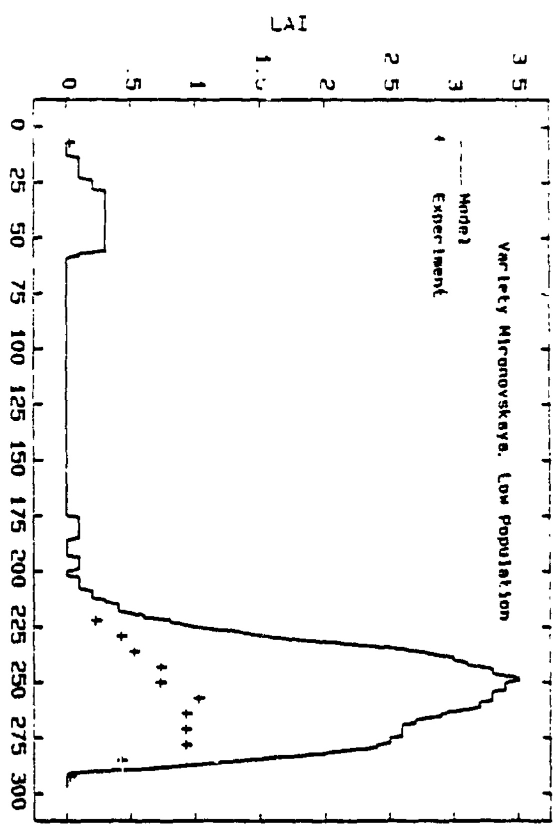

Sidney, Montana 1977
Variety Bezostaya, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
0
100
200
300
400
500
600
700
800
900
1000
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

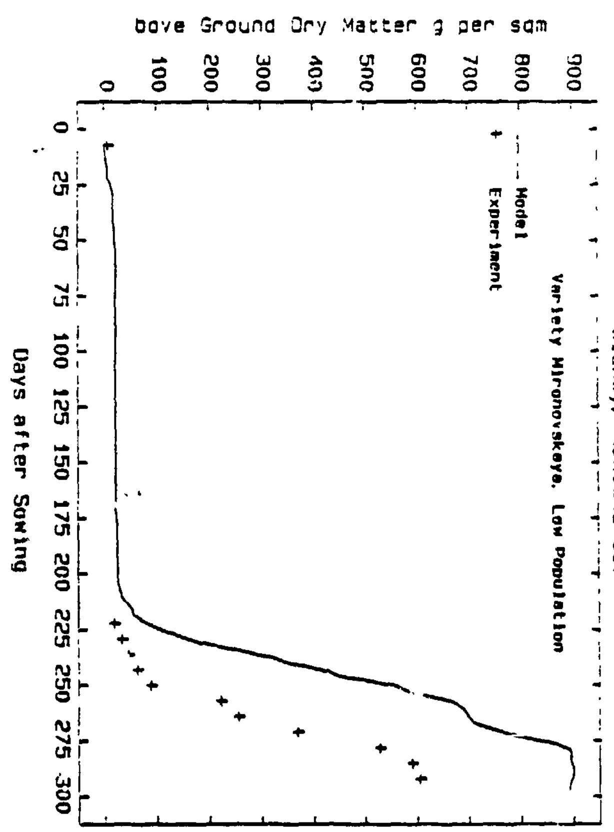

Sidney, Montana 1977
Variety Bezostaya, Low Population
Model
Experiment
LAI
0
.5
1
1.5
2
2.5
3
3.5
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

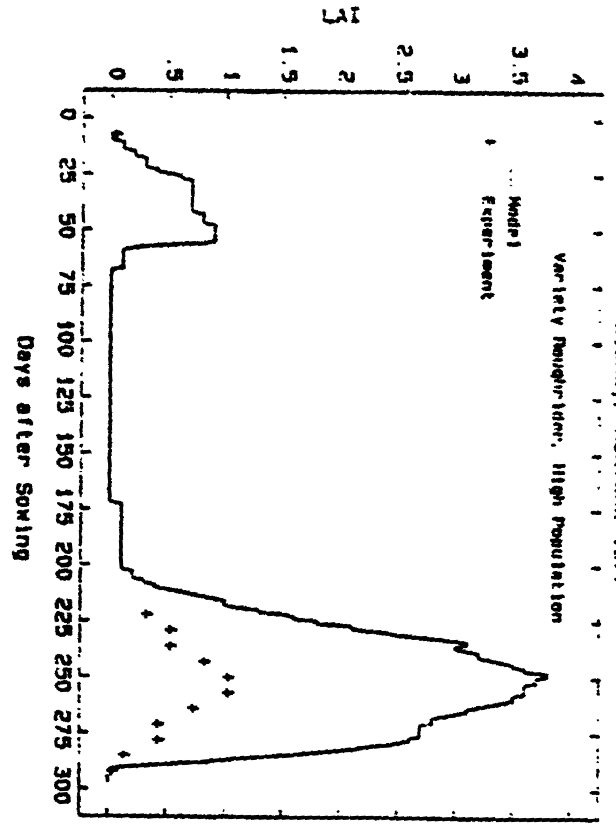

Sidney, Montana 1977
Variety Bezostaya, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
0
100
200
300
400
500
600
700
800
900
Days after Sowing
0 25 50 75 100 125 150 175 200 225 250 275 300

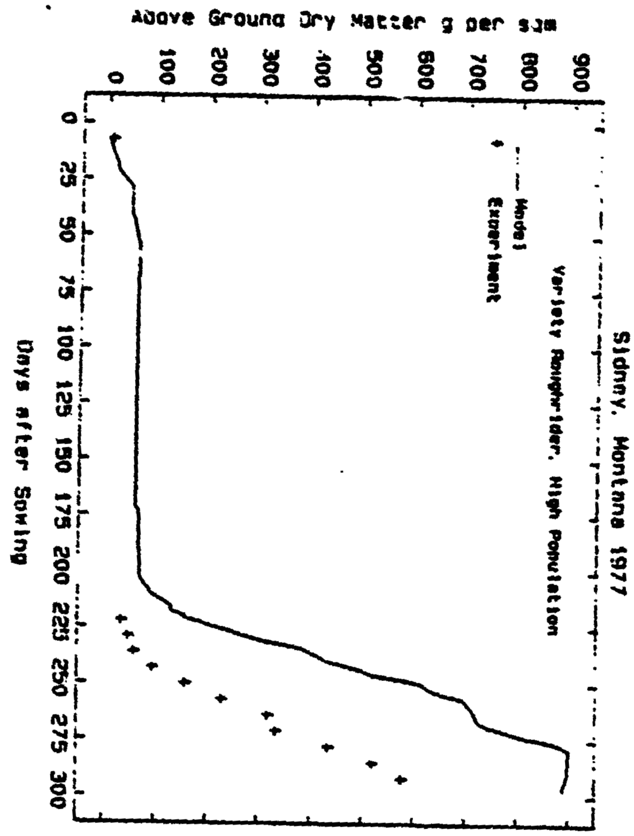

Sidney, Montana 1977
Variety Mironovskaya, High Population
Model
Experiment
LAI
Days after Sowing

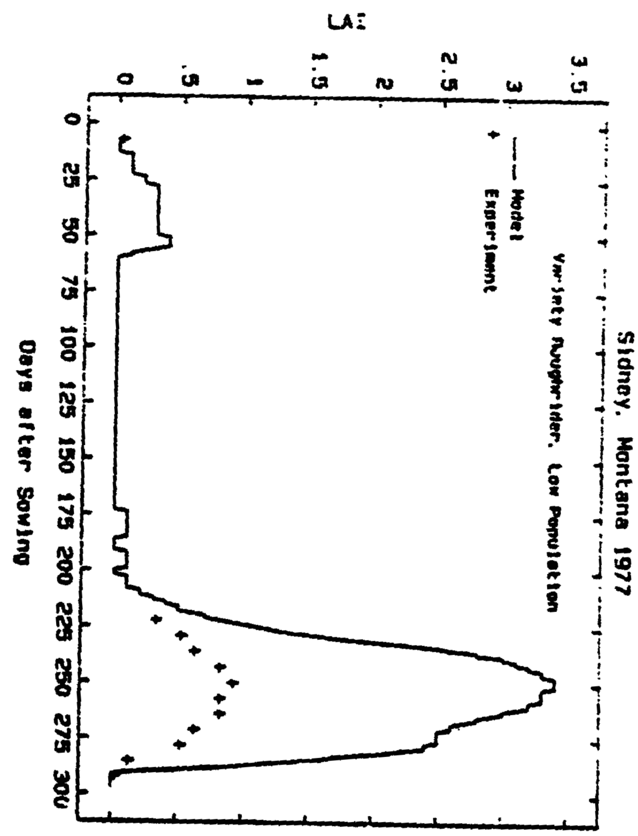

Sidney, Montana 1977
Variety Mironovskaya, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

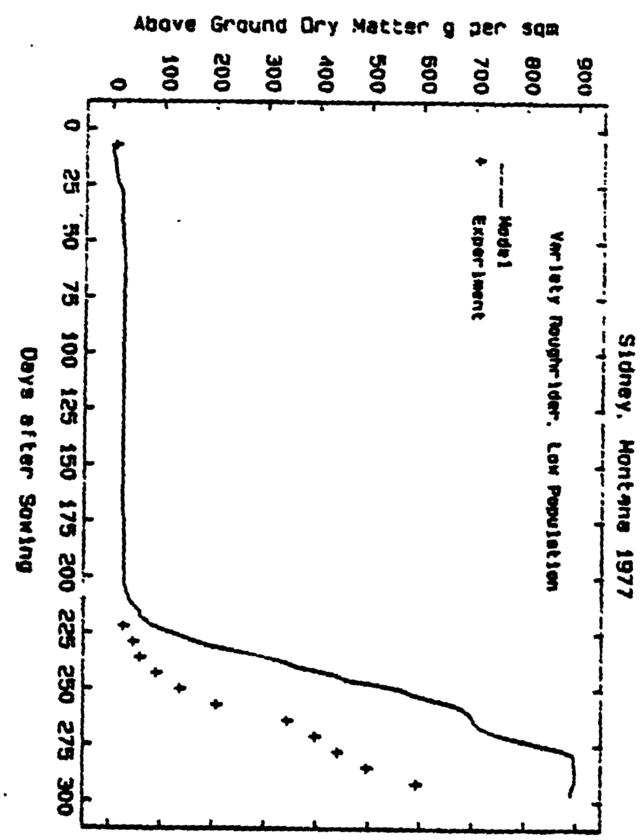

Sidney, Montana 1977
Variety Mironovskaya, Low Population
Model
Experiment
LAI
Days after Sowing

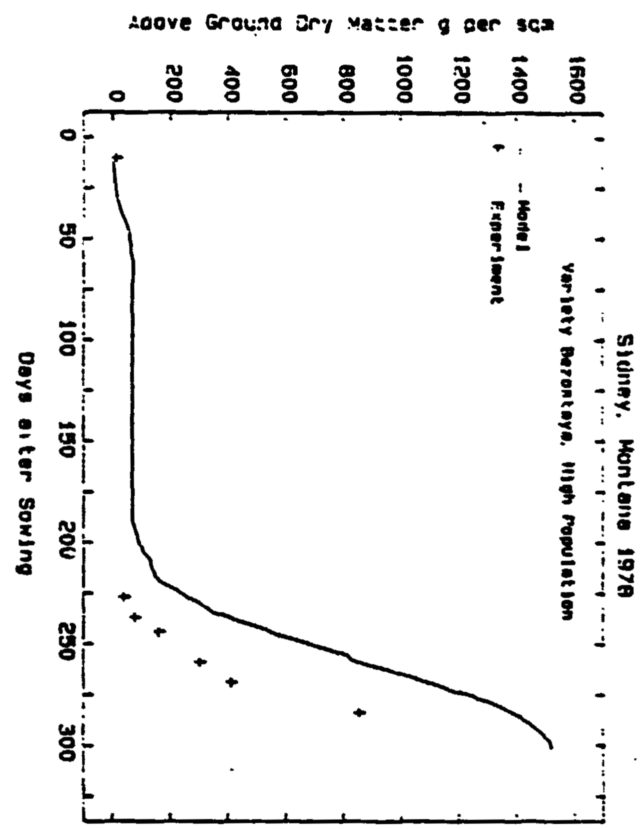

Sidney, Montana 1977
Variety Mironovskaya, Low Population
Model
Experiment
bove Ground Dry Matter g per sqm
Days after Sowing

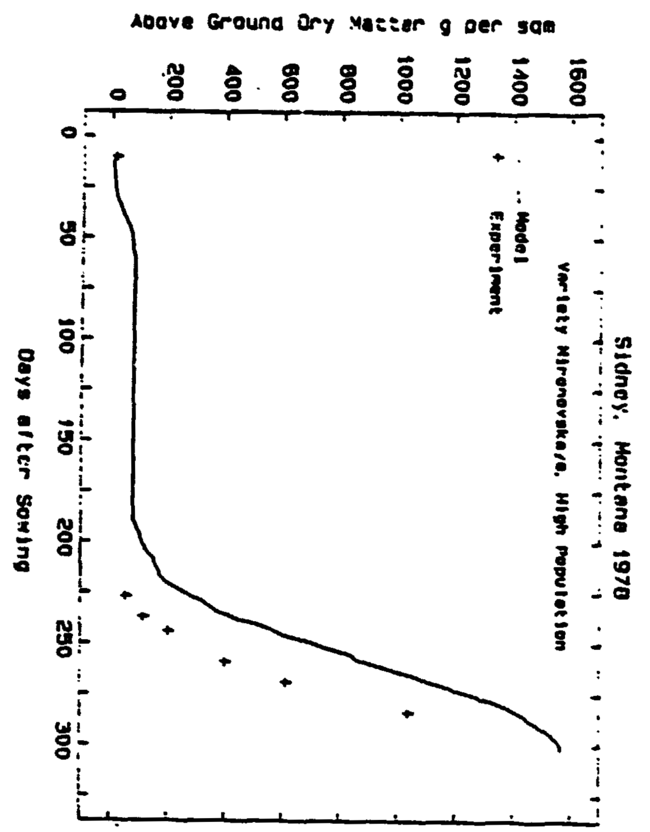

Sidney, Montana 1977
Variety Roughrider, High Population
Model
Experiment
LAI
Days after Sowing

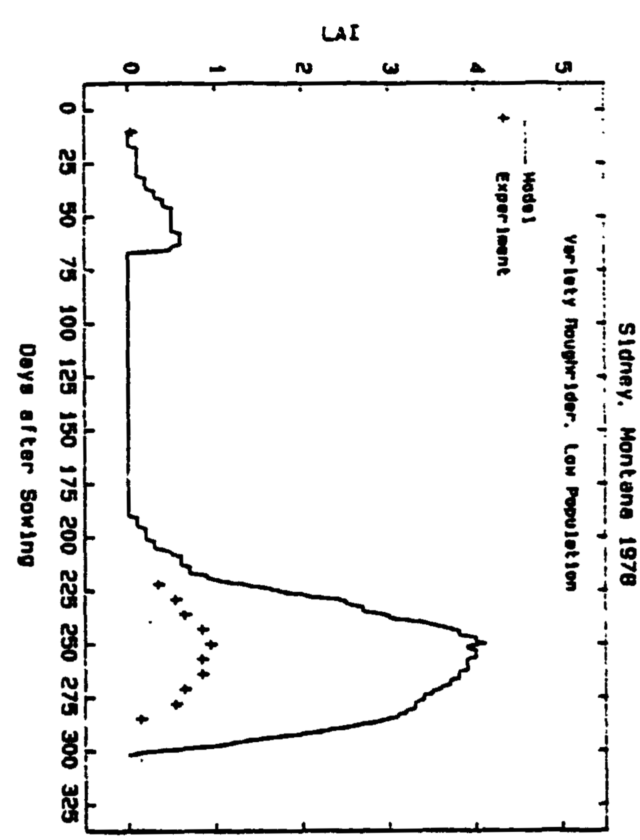

Sidney, Montana 1977
Variety Roughrider, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

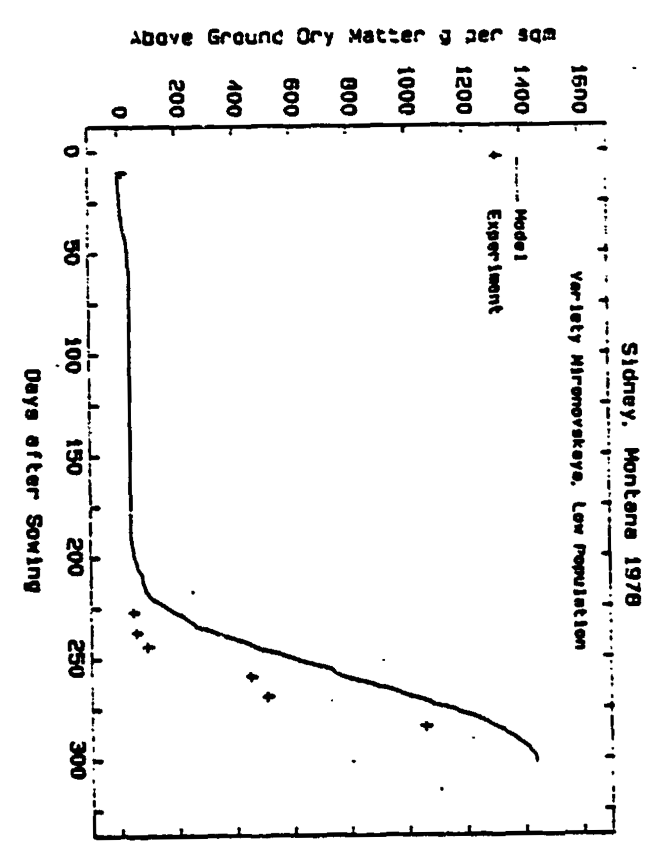

Sidney, Montana 1977
Variety Roughrider, Low Population
Model
Experiment
LAI
Days after Sowing

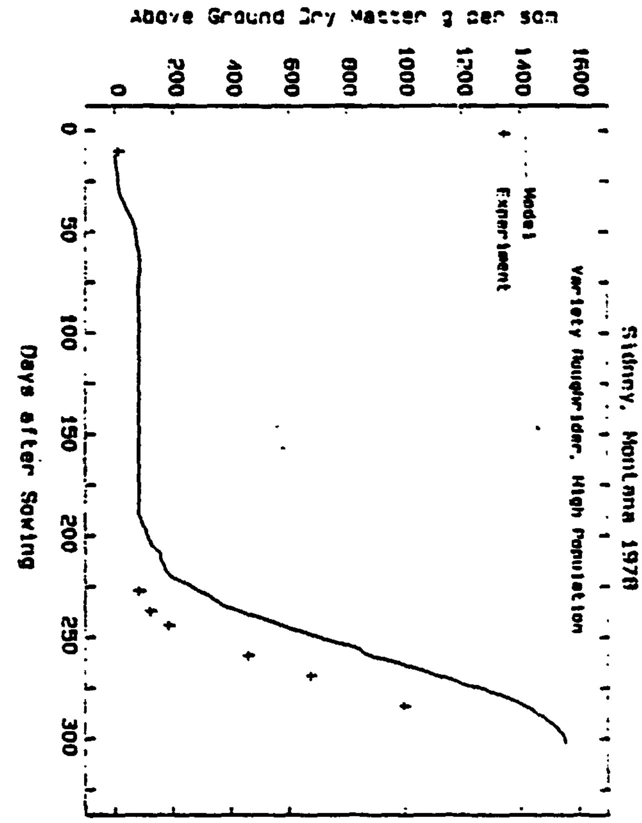

Sidney, Montana 1977
Variety Roughrider, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

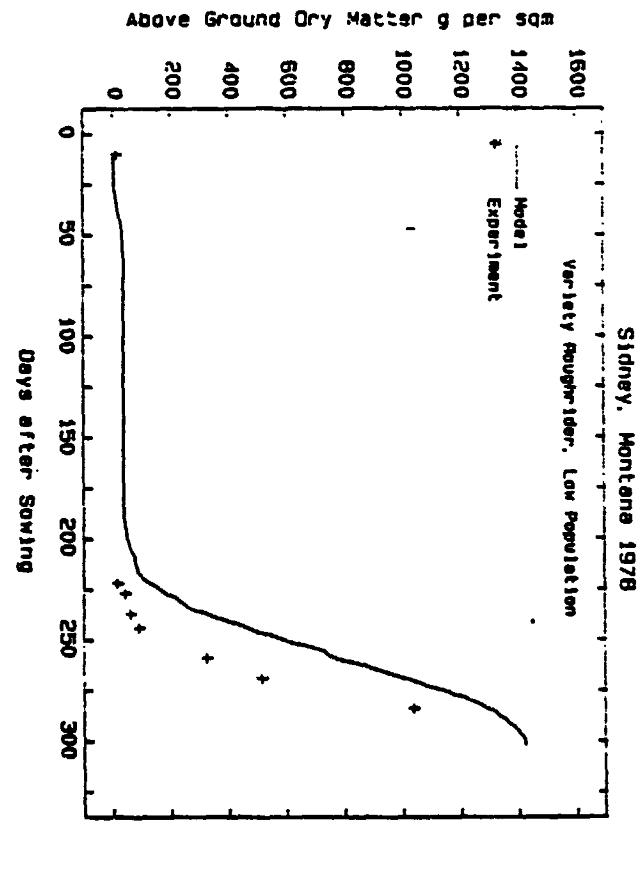

Sidney, Montana 1978
Variety Berentaya, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

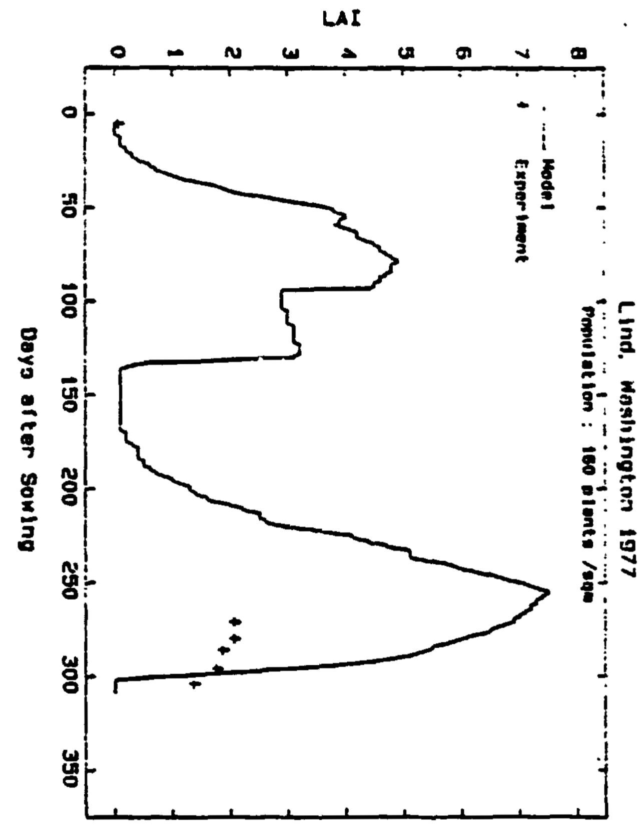

Sidney, Montana 1978
Variety Mironovskaya, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

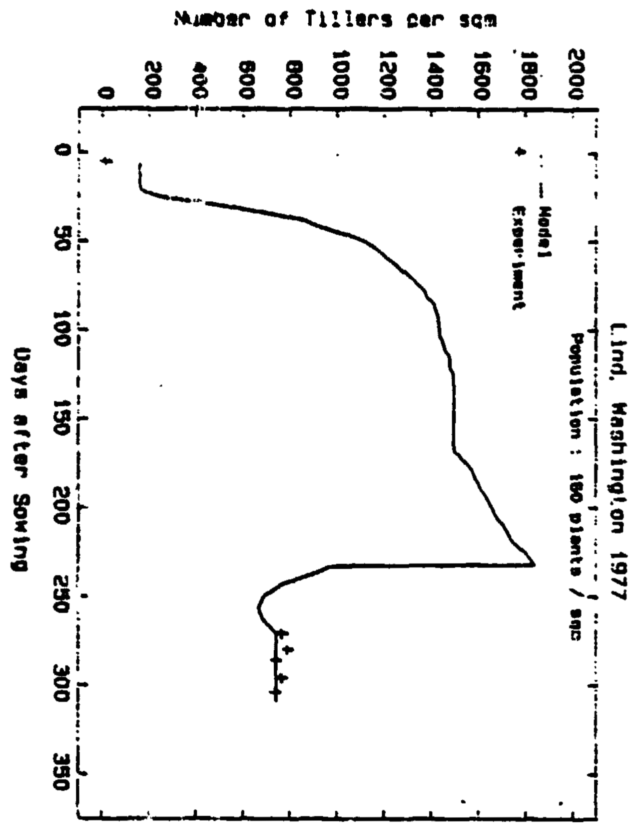

Sidney, Montana 1978
Variety Roughrider, Low Population
Model
Experiment
LAI
Days after Sowing

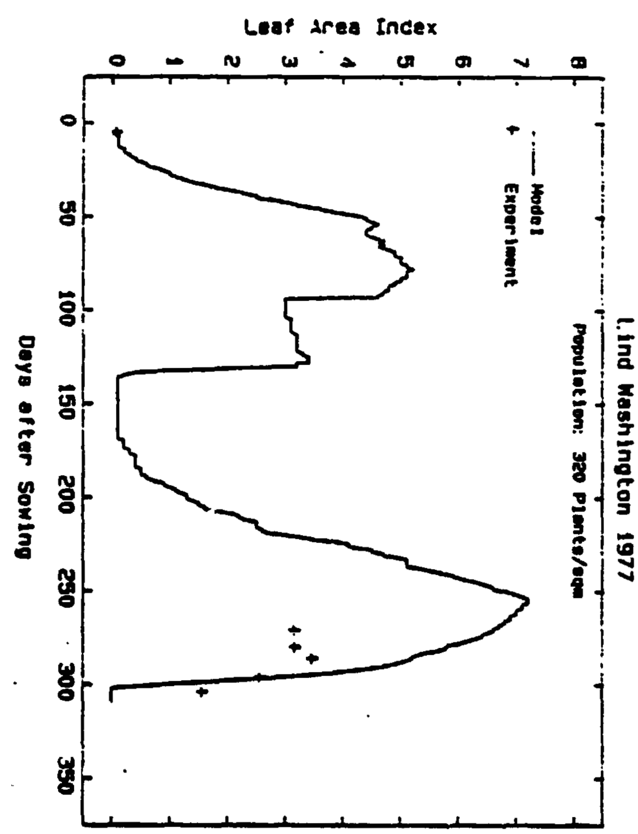

Sidney, Montana 1978
Variety Mironovskaya, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

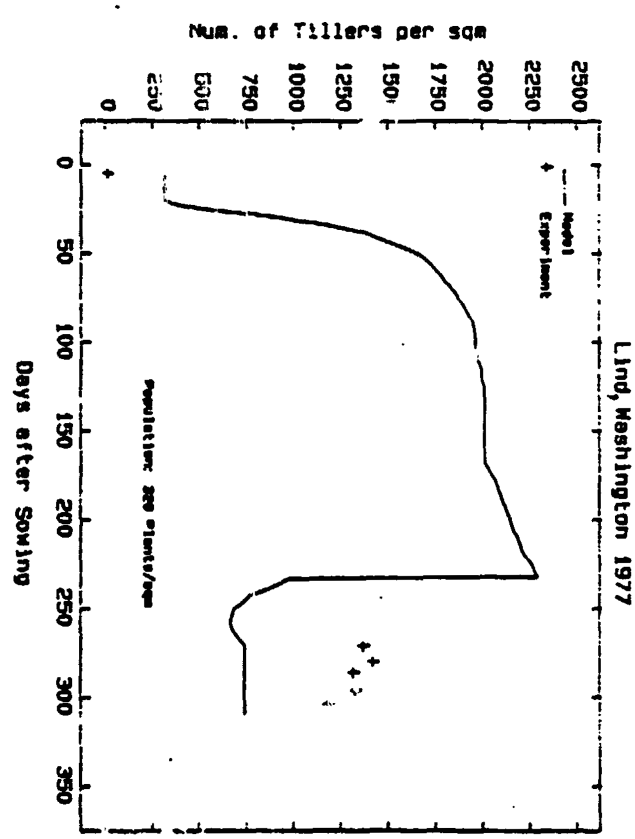

Sidney, Montana 1978
Variety Roughrider, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
50
100
150
200
250
300

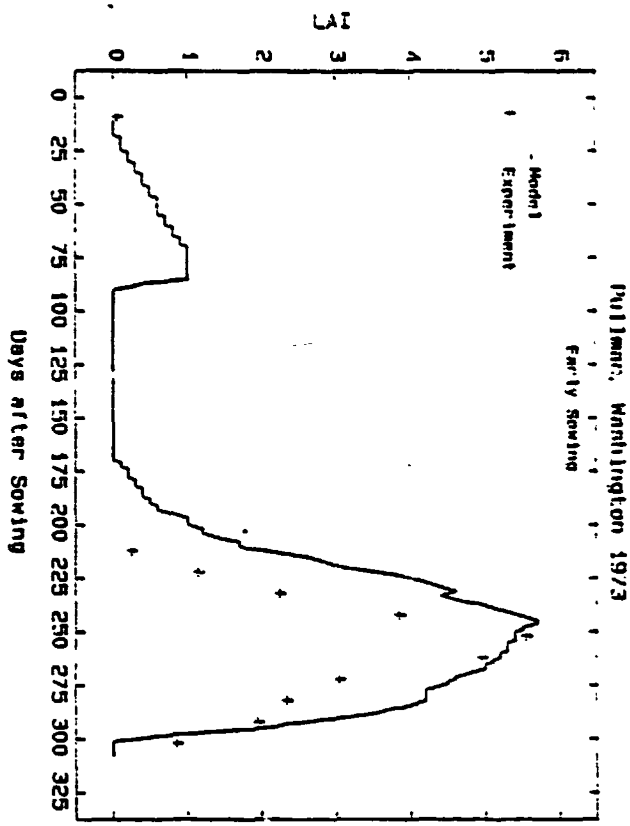

Sidney, Montana 1978
Variety Roughrider, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
0
200
400
600
800
1000
1200
1400
1600
Days after Sowing
0
50
100
150
200
250
300

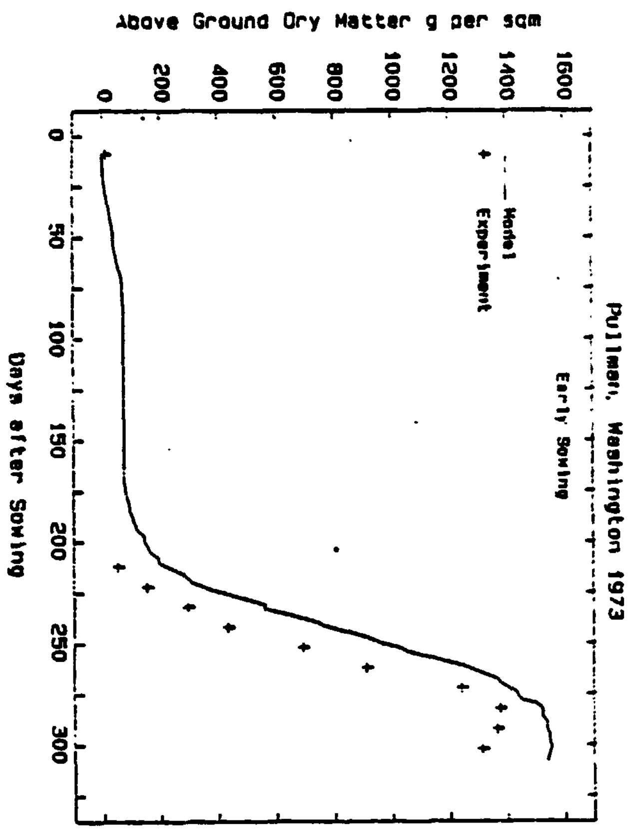

Lind, Washington 1977
Population : 160 plants /sqm
Model
Experiment
LAI
Days after Sowing

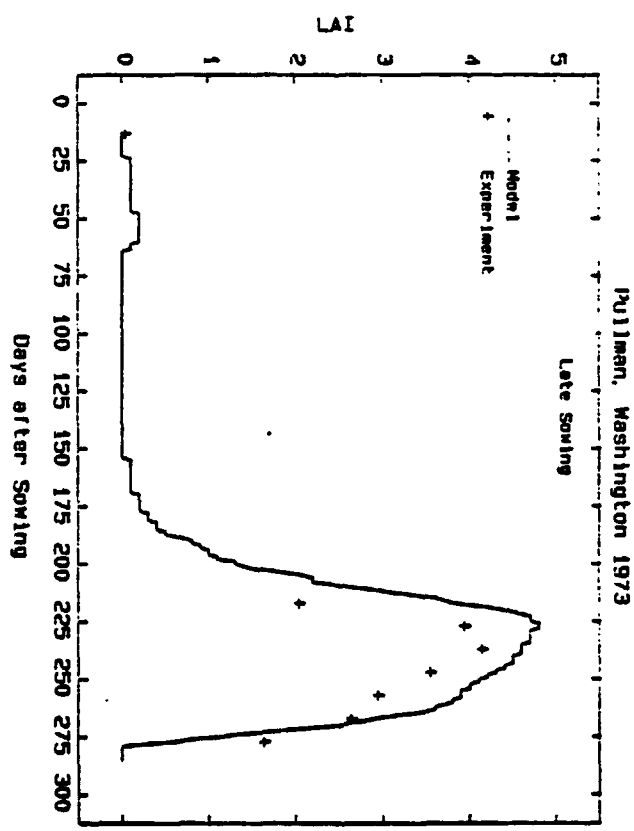

Lind, Washington 1977
Population : 160 plants / sqm
Model
Experiment
Number of Tillers per sqm
Days after Sowing

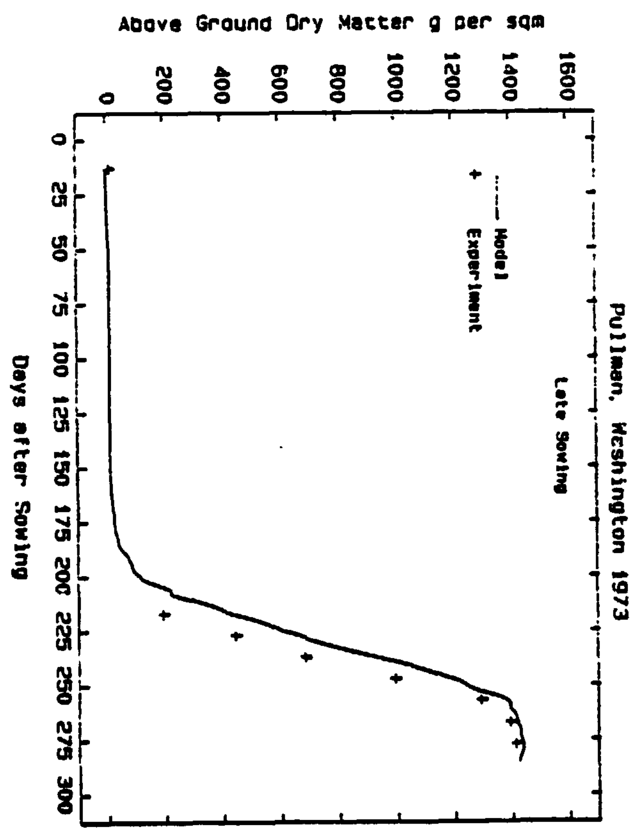

Lind Washington 1977
Population: 320 Plants/sqm
Model
Experiment
Leaf Area Index
Days after Sowing

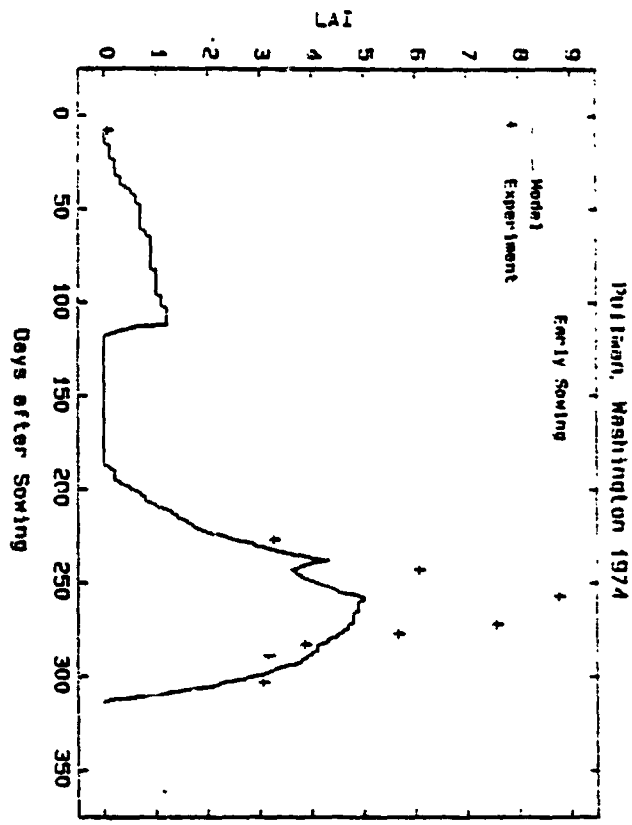

Lind, Washington 1977
Model
Experiment
Num. of Tillers per sqm
Days after Sowing

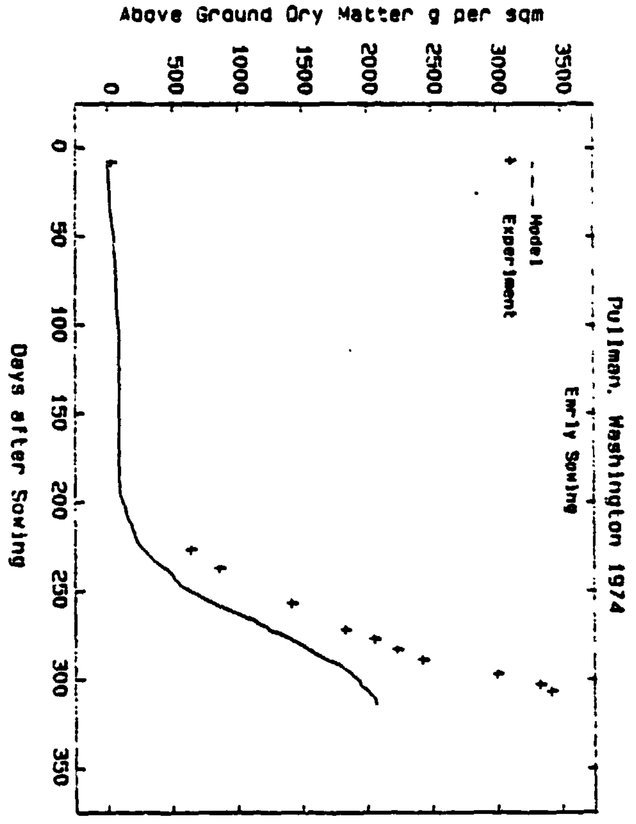

Pullman, Washington 1973
Early Sowing
Model
Experiment
LAI
Days after Sowing

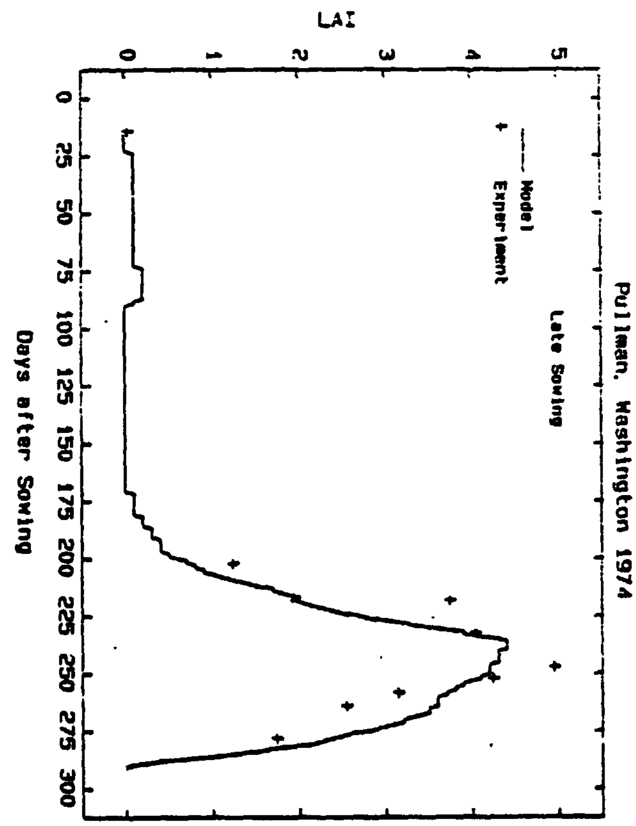

Pullman, Washington 1973
Early Sowing
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

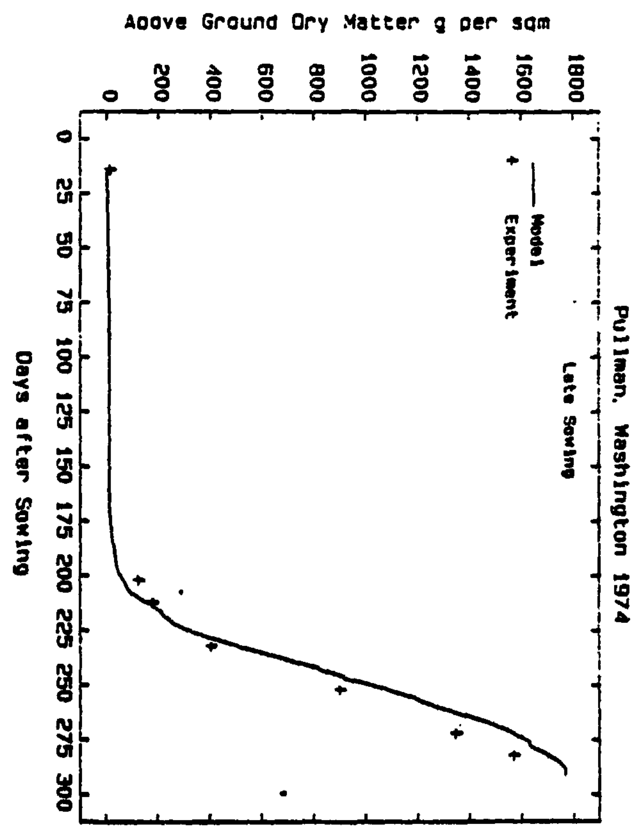

Pullman, Washington 1973
Late Sowing
Model
Experiment
LAI
Days after Sowing

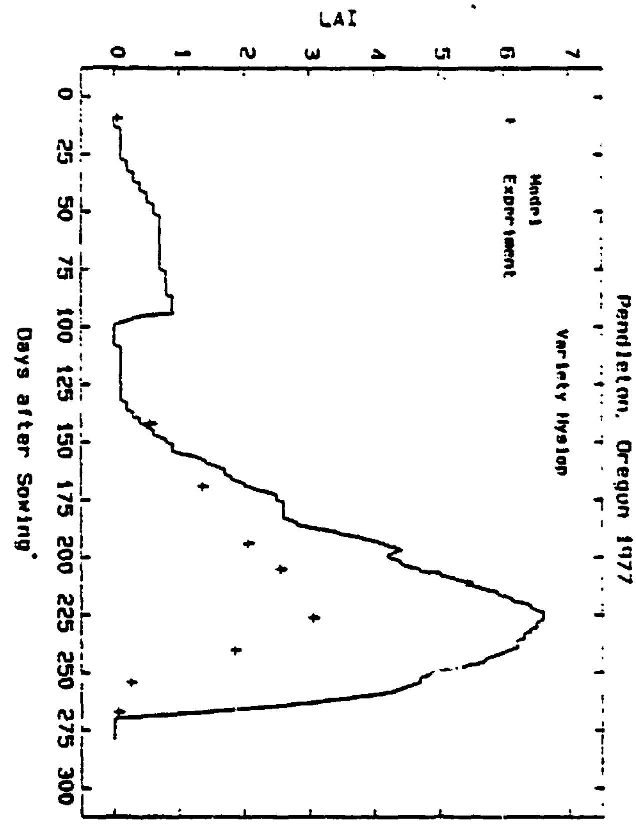

Pullman, Washington 1973
Late Sowing
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

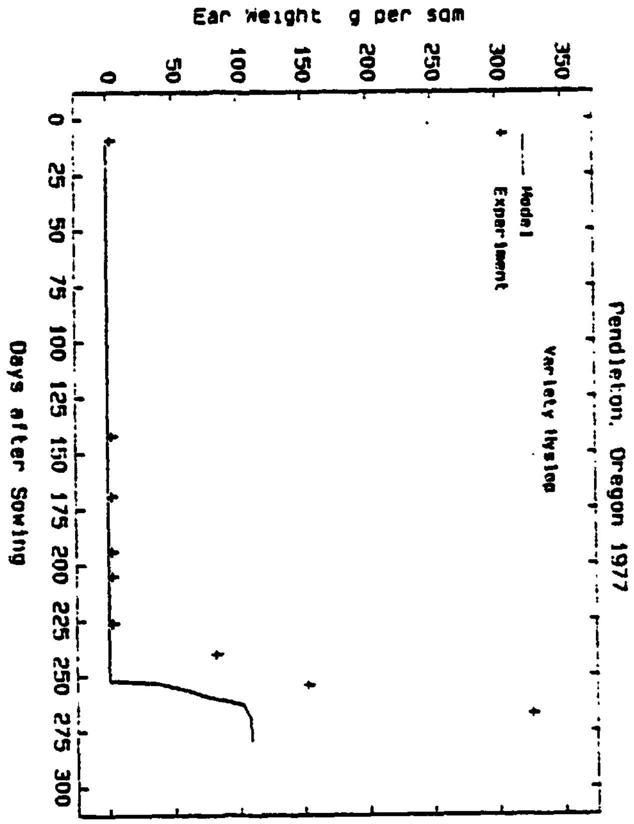

Pullman, Washington 1974
Early Sowing
Model
Experiment
LAI
Days after Sowing

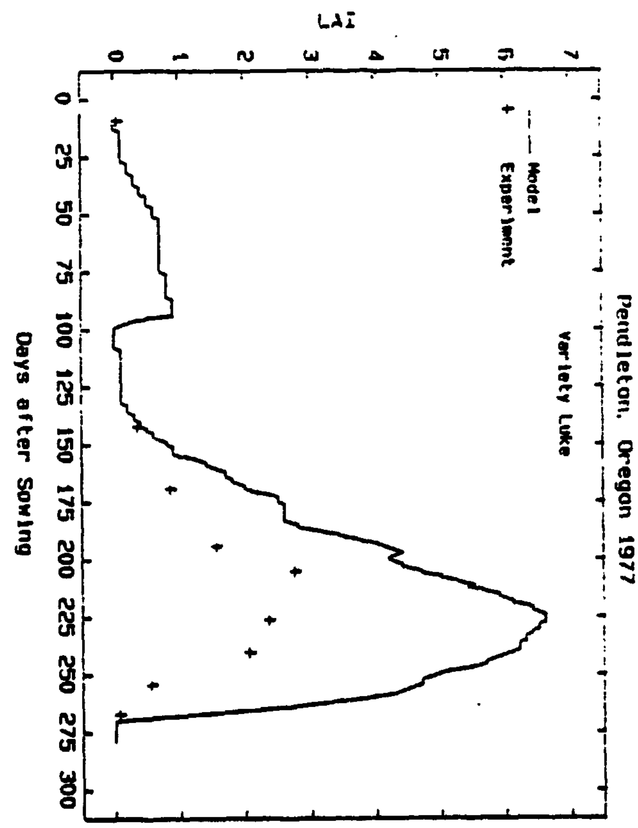

Pullman, Washington 1974
Early Sowing
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

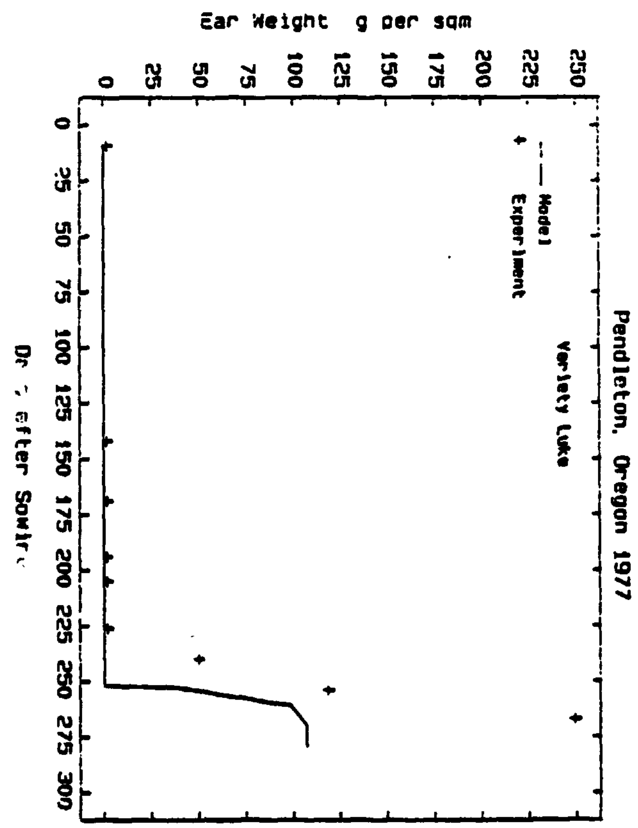

Pullman, Washington 1974
Late Sowing
Model
Experiment
LAI
Days after Sowing

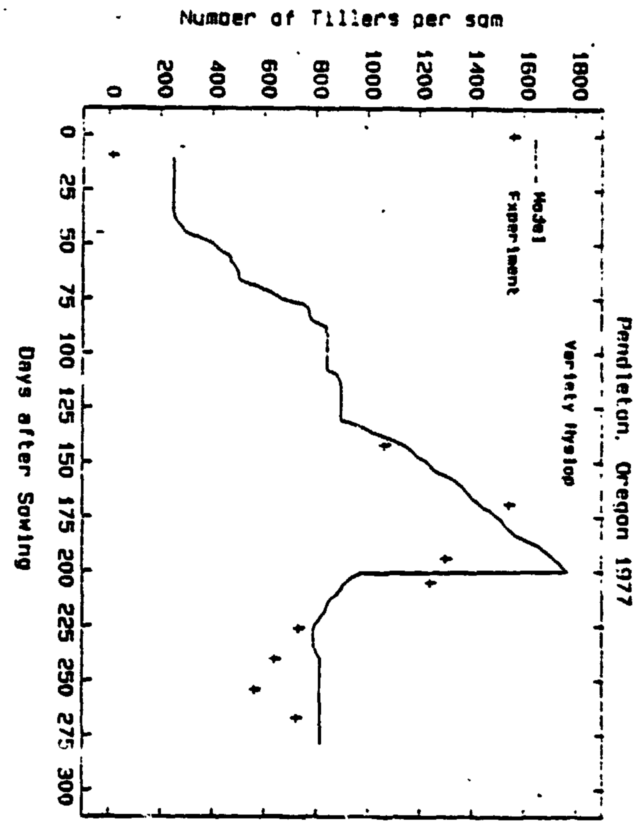

Pullman, Washington 1974
Late Sowing
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

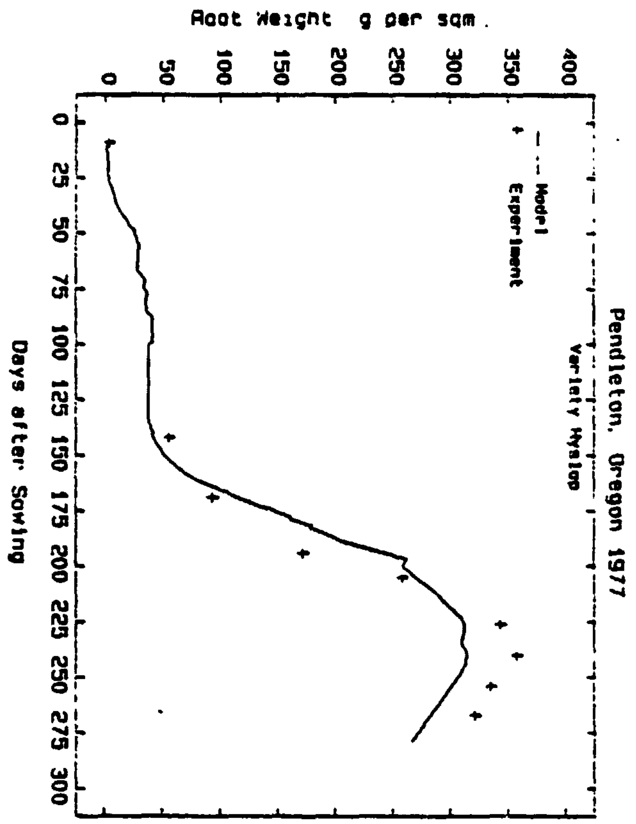

Pendleton, Oregon 1977
Variety Hyslop
Model
Experiment
LAI
Days after Sowing

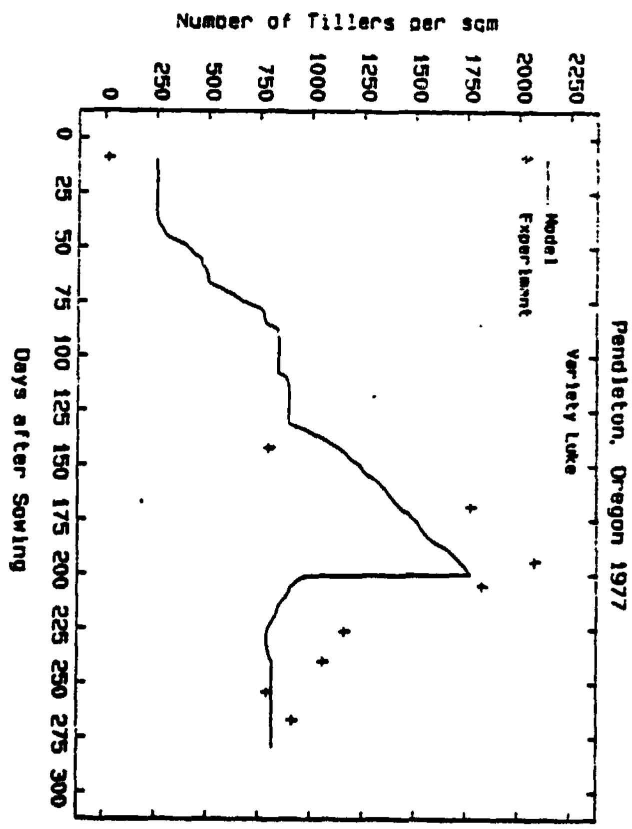

Pendleton, Oregon 1977
Variety Hyslop
Model
Experiment
Ear Weight g per sqm
Days after Sowing

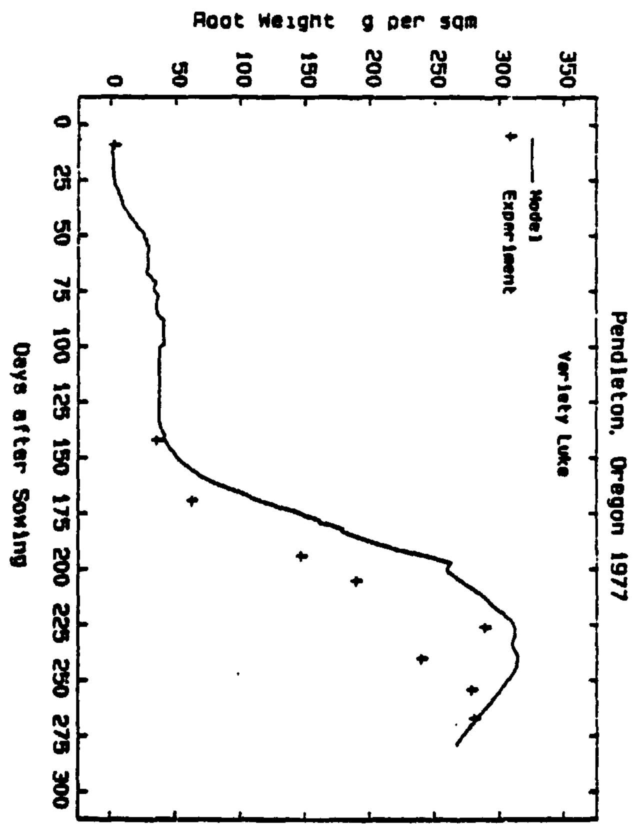

Pendleton, Oregon 1977
Variety Luke
Model
Experiment
LAI
Days after Sowing

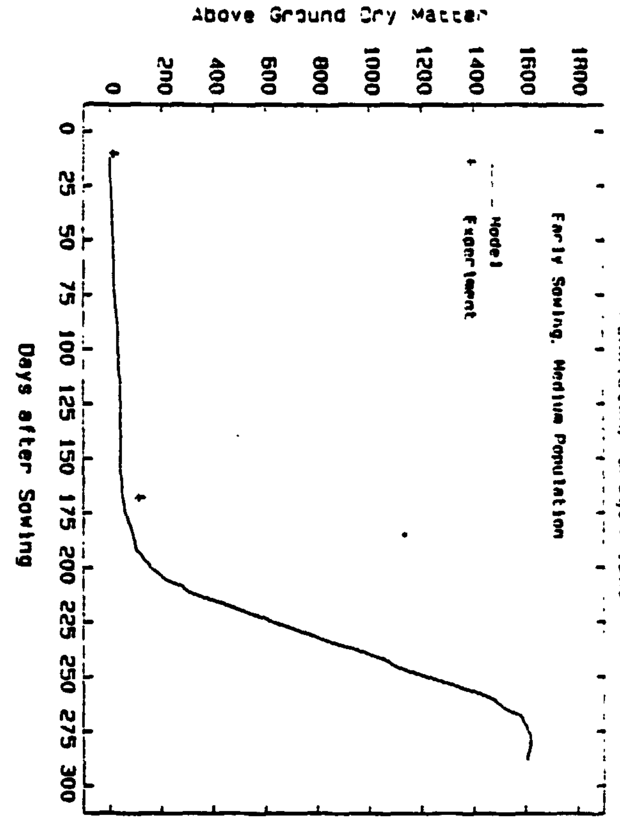

Pendleton, Oregon 1977
Variety Luke
Model
Experiment
Ear Weight g per sqm

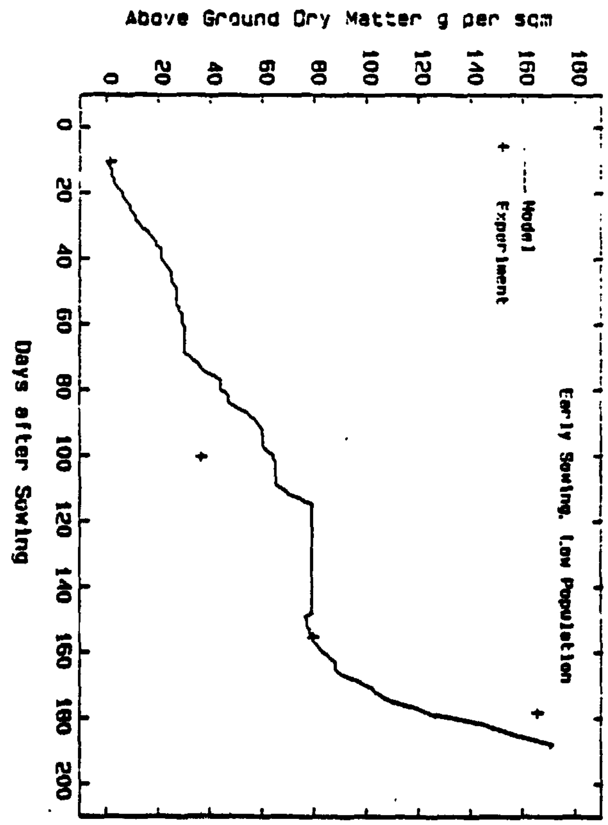

Pendleton, Oregon 1977
Variety Hyslop
Model
Experiment
Number of Tillers per sqm
Days after Sowing

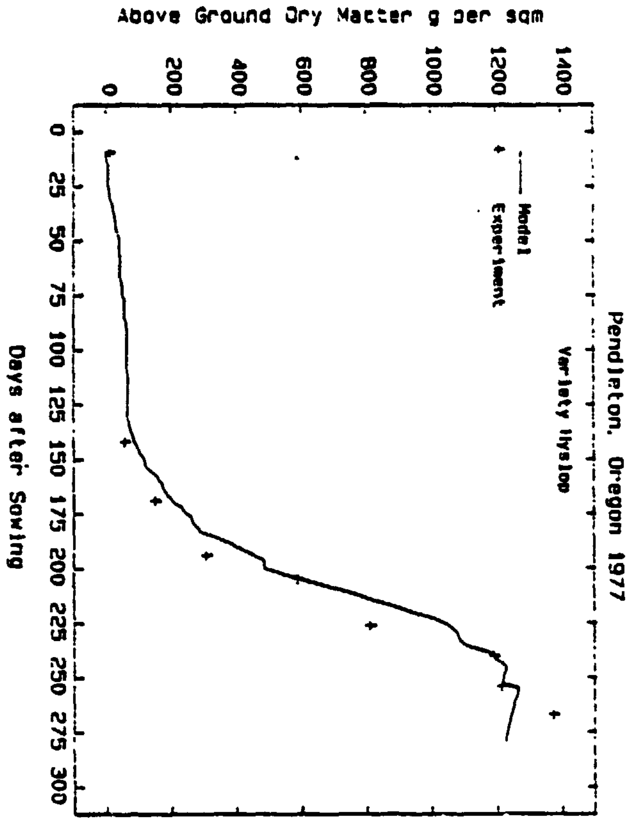

Pendleton, Oregon 1977
Variety Hyslop
Model
Experiment
Root Weight g per sqm
Days after Sowing

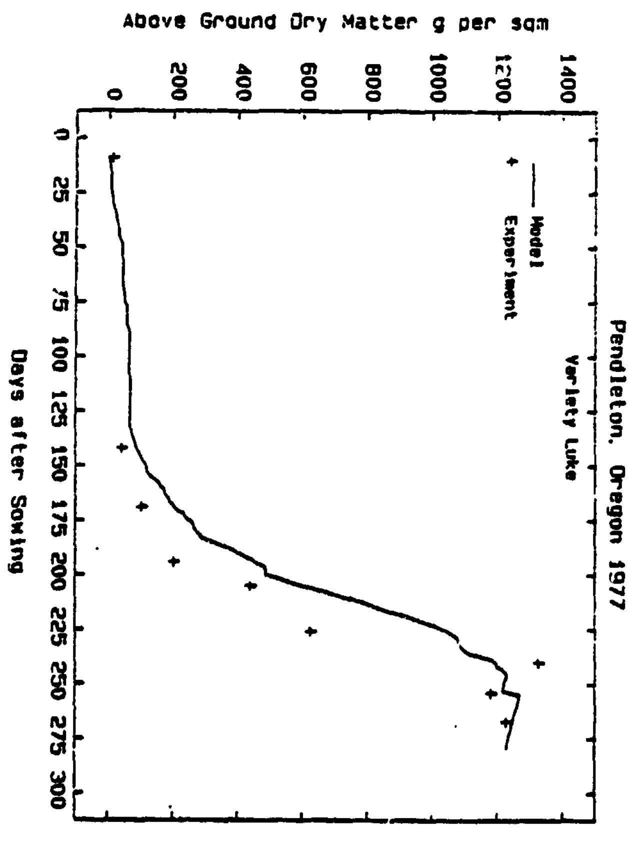

Pendleton, Oregon 1977
Variety Luke
Model
Experiment
Number of Tillers per sqm
Days after Sowing

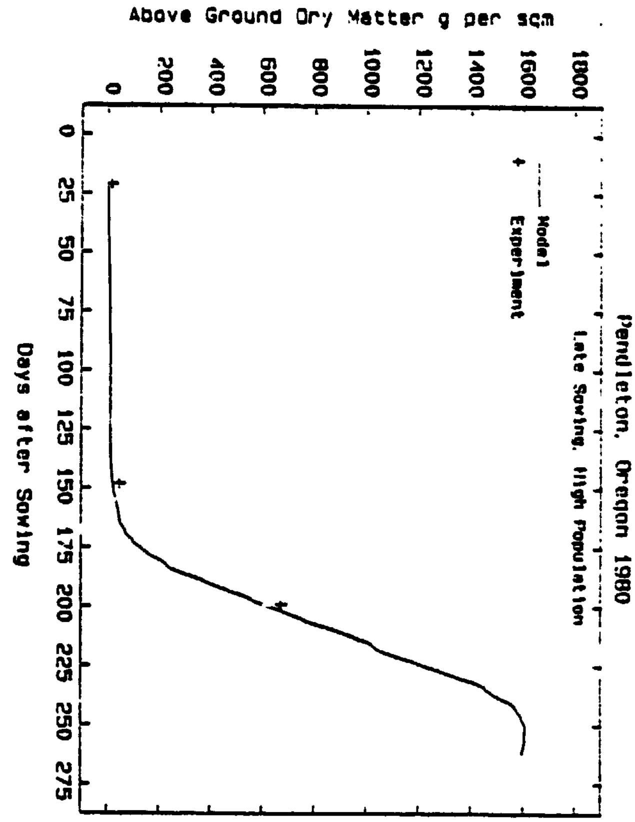

Pendleton, Oregon 1977
Variety Luke
Model
Experiment
Root Weight g per sqm
Days after Sowing

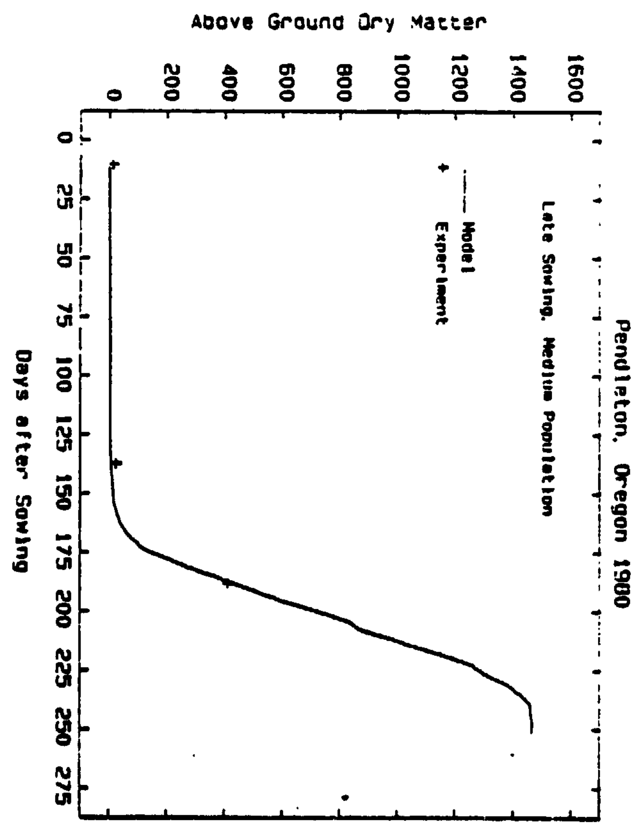

Pendleton, Oregon 1980
Early Sowing, Medium Population
Model
Experiment
Above Ground Dry Matter
Days after Sowing

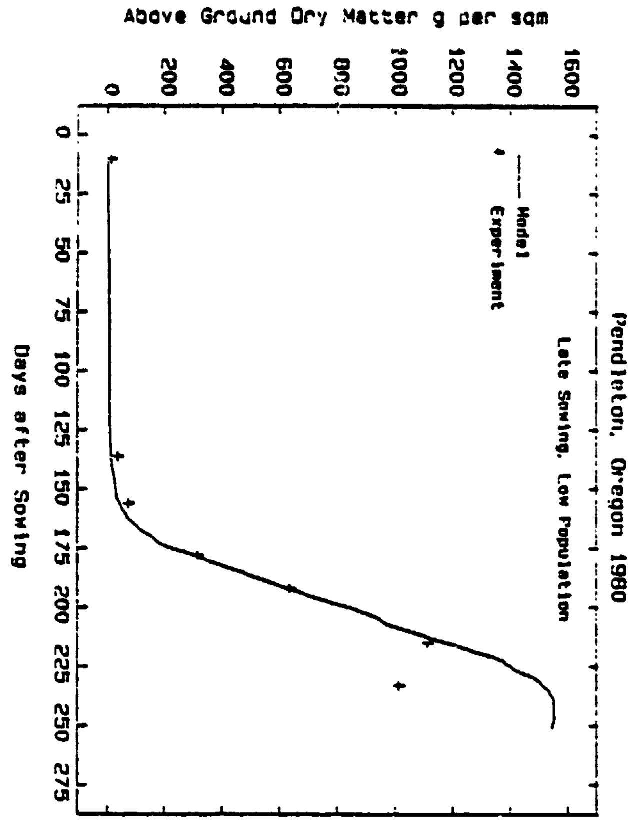

Pendleton, Oregon 1980
Early Sowing, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

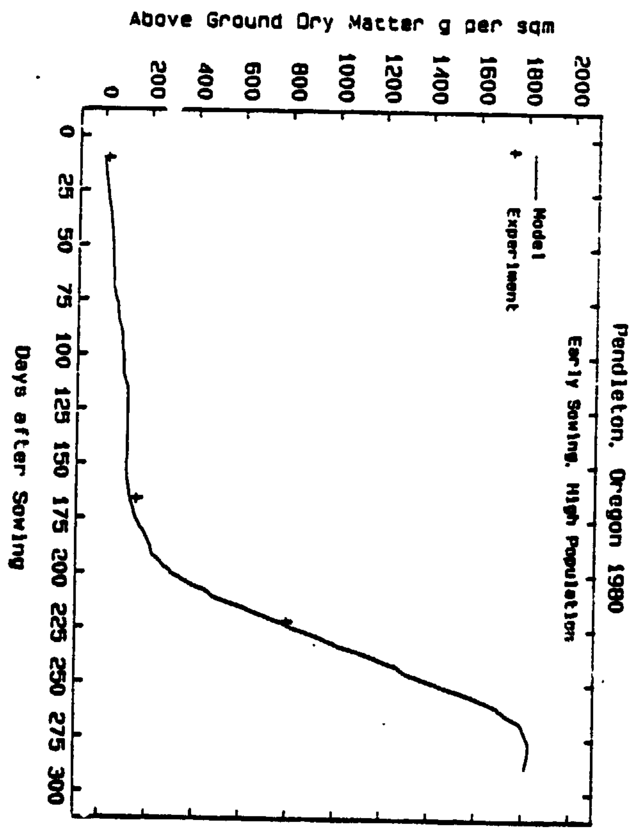

Pendleton, Oregon 1977
Variety Hyslop
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

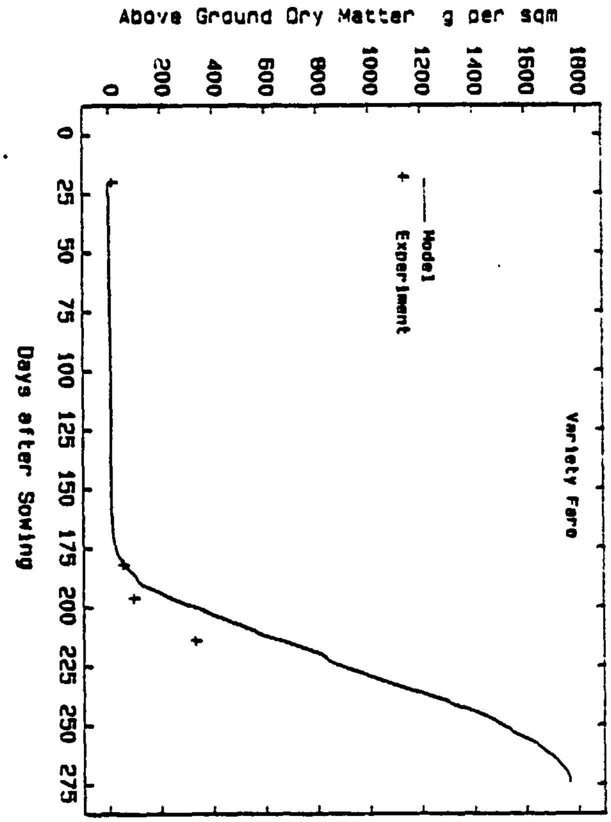

Pendleton, Oregon 1977
Variety Luke
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

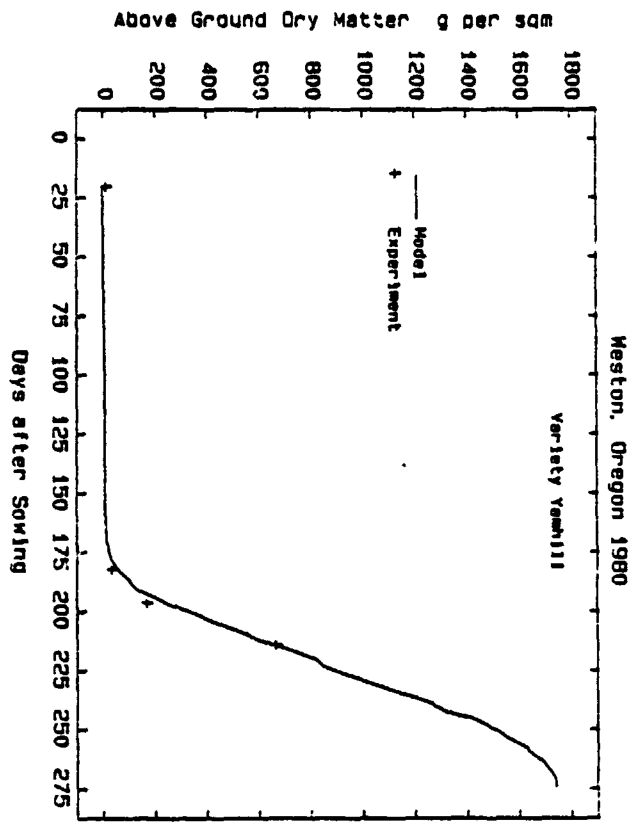

Pendleton, Oregon 1980
Late Sowing, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing
0 200 400 600 800 1000 1200 1400 1600 1800
0 25 50 75 100 125 150 175 200 225 250 275

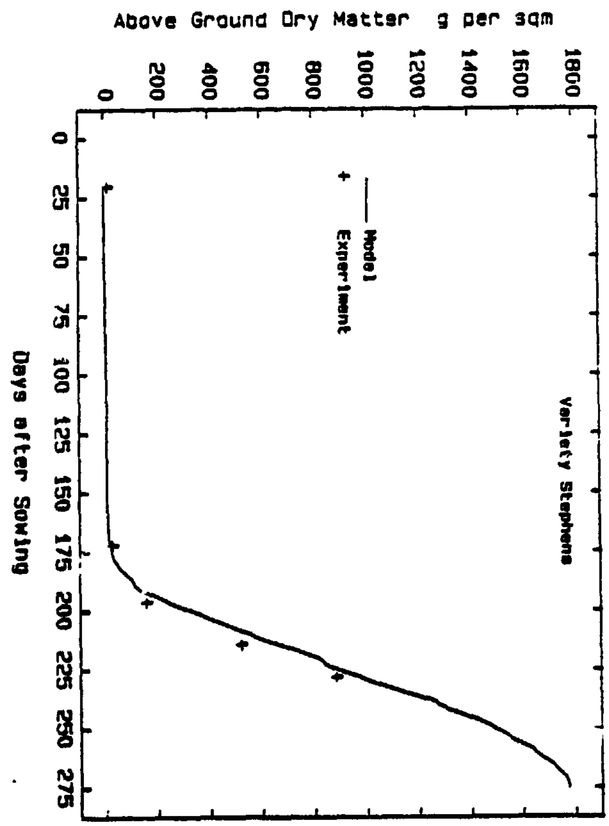

Pendleton, Oregon 1980
Late Sowing, Medium Population
Model
Experiment
Above Ground Dry Matter
Days after Sowing
0 200 400 600 800 1000 1200 1400 1600
0 25 50 75 100 125 150 175 200 225 250 275

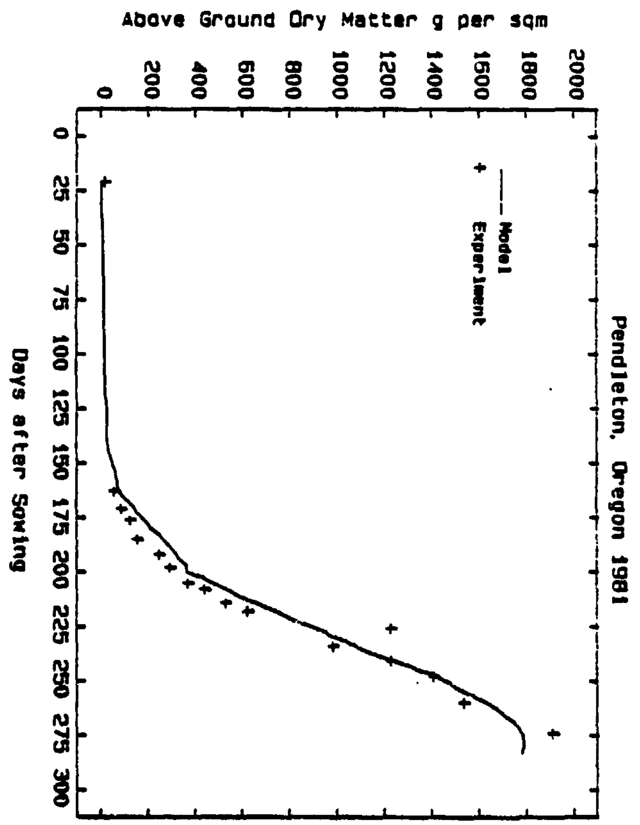

Pendleton, Oregon 1980
Late Sowing, Low Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing
0 200 400 600 800 1000 1200 1400 1600
0 25 50 75 100 125 150 175 200 225 250 275


Pendleton, Oregon 1980
Early Sowing, High Population
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing
0 200 400 600 800 1000 1200 1400 1600 1800 2000
0 25 50 75 100 125 150 175 200 225 250 275 300


Weston, Oregon 1980
Variety Faro
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing


Weston, Oregon 1980
Variety Yamhill
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing


Weston, Oregon 1980
Variety Stephens
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing


Pendleton, Oregon 1981
Model
Experiment
Above Ground Dry Matter g per sqm
Days after Sowing

APPENDIX B

CERES-WHEAT-N MODEL VALIDATION

RESULTS FROM INDIVIDUAL EXPERIMENTS

PREDICTED VS. OBSERVED

Figure B.1. Comparison of predicted and observed response to applied N to the application pattern of N in individual data sets.

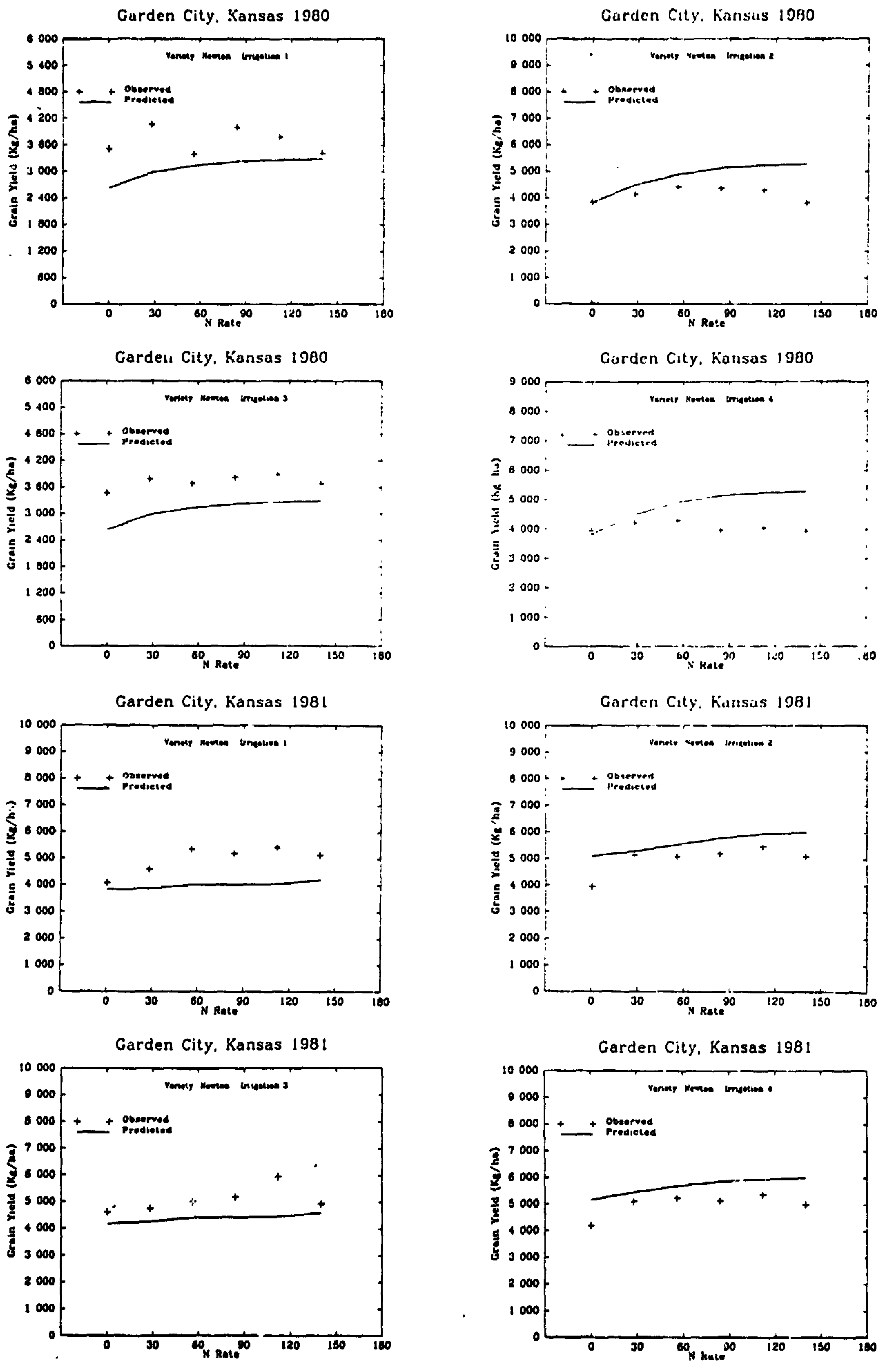


Figure B.1. Continued.

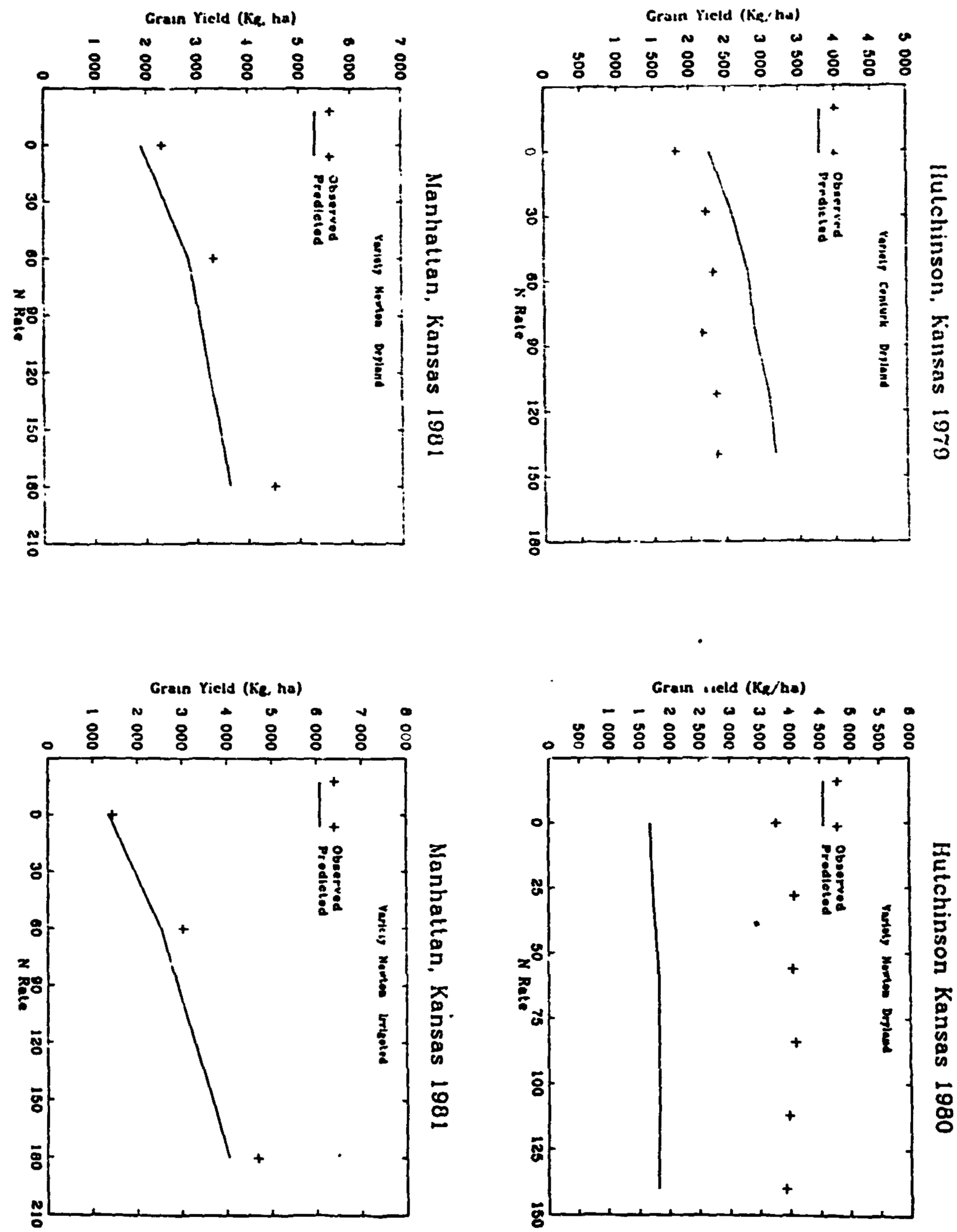


Figure B.1. Continued.

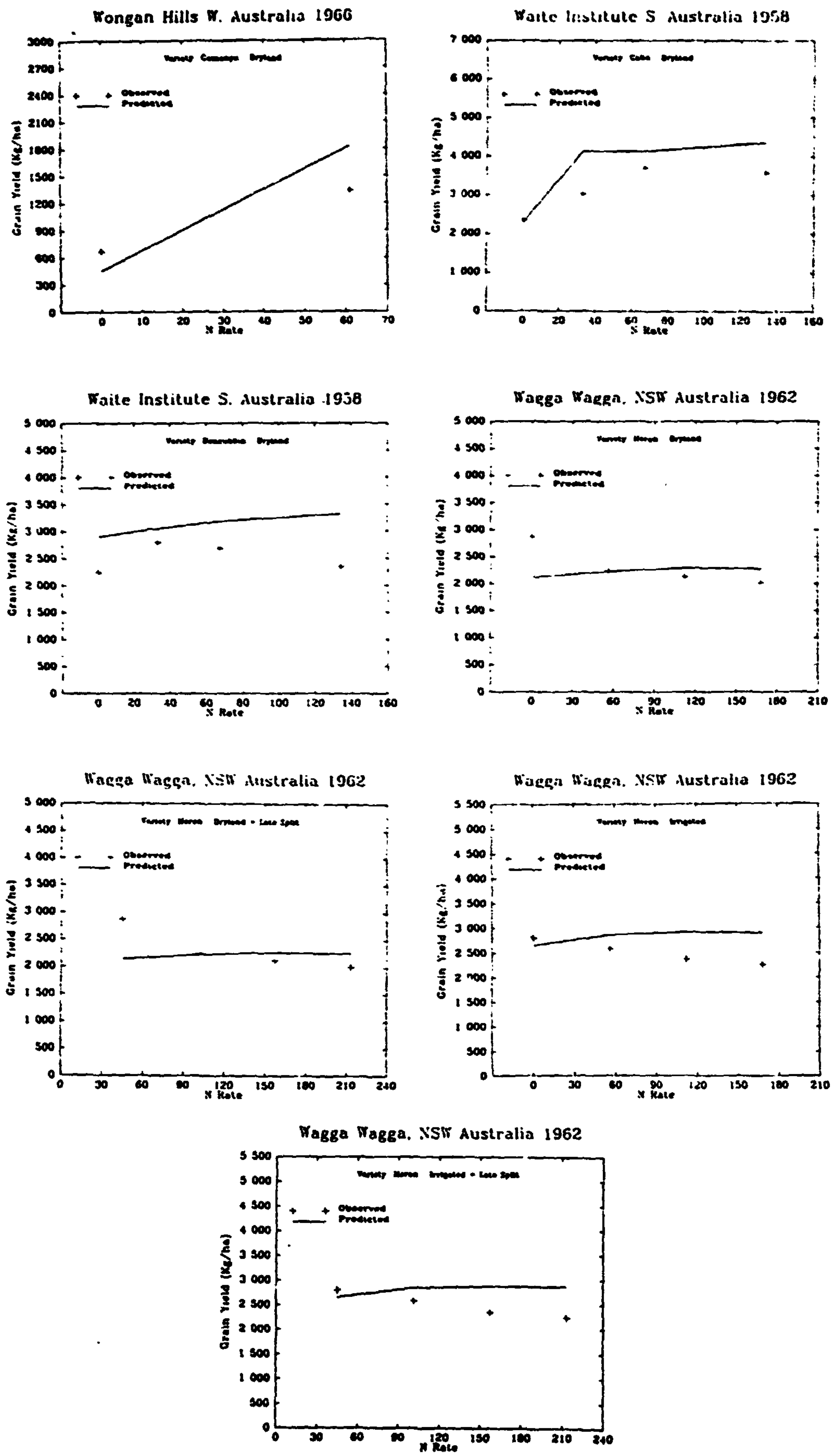


Figure B.1. Continued.

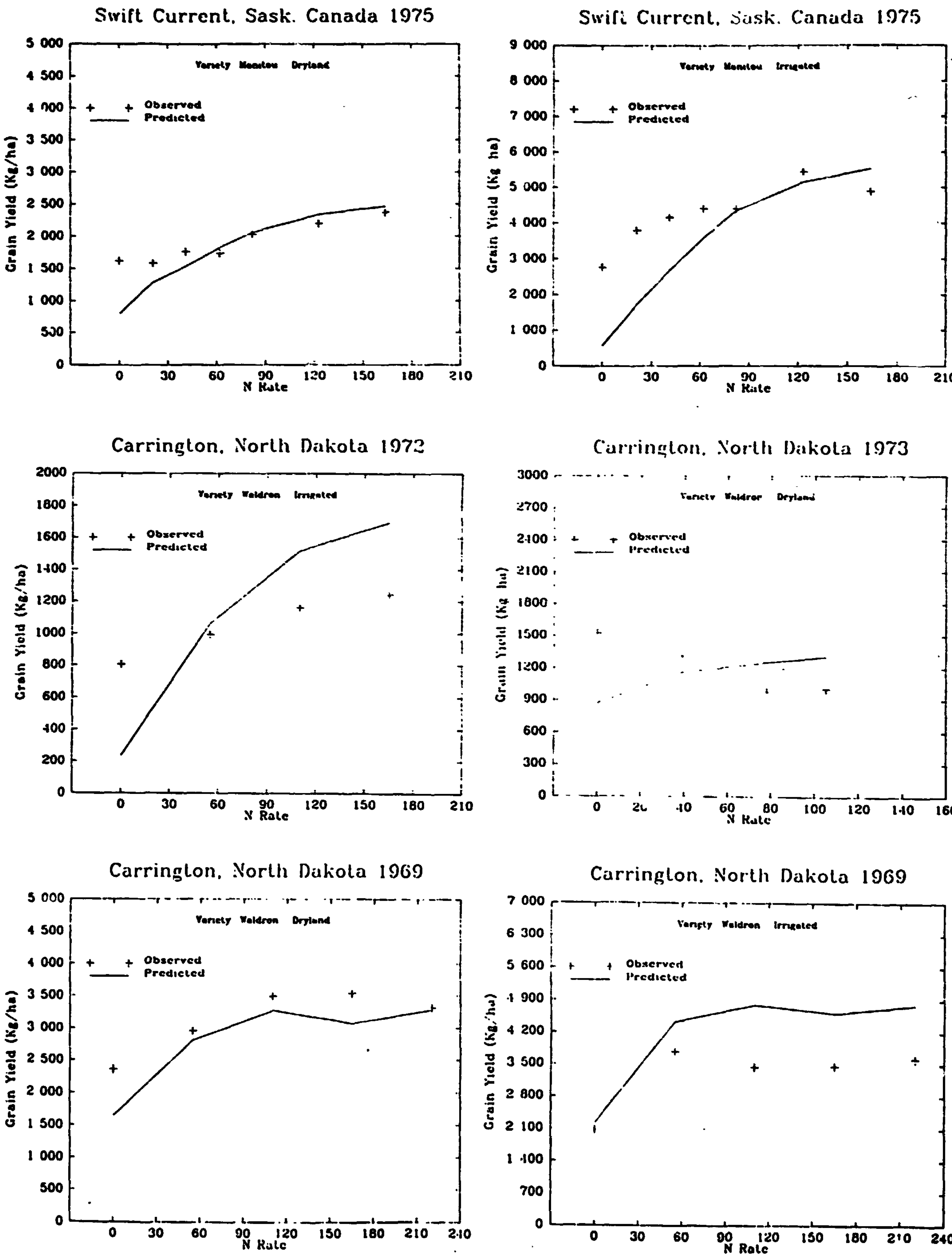


Figure B.1. Continued.

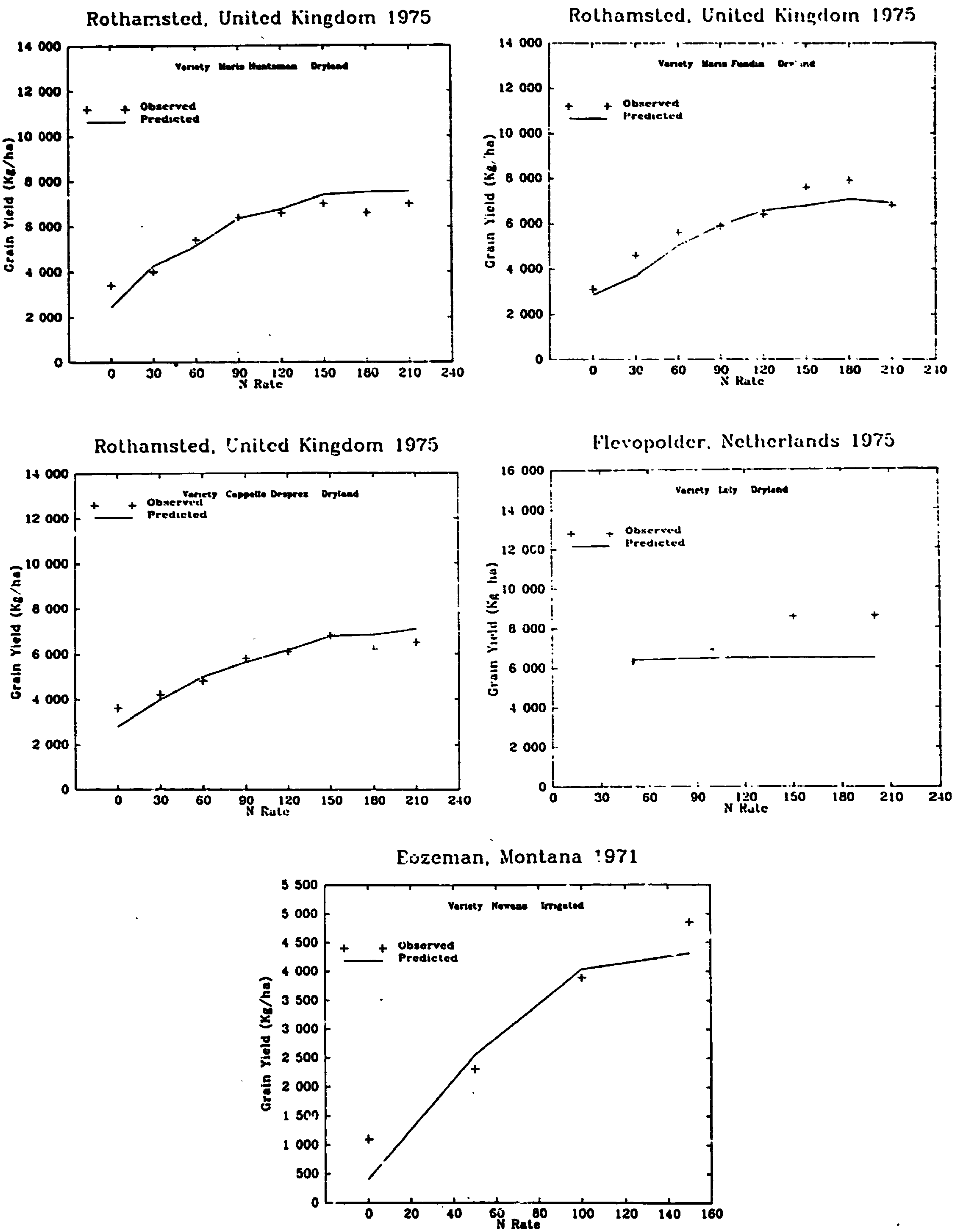
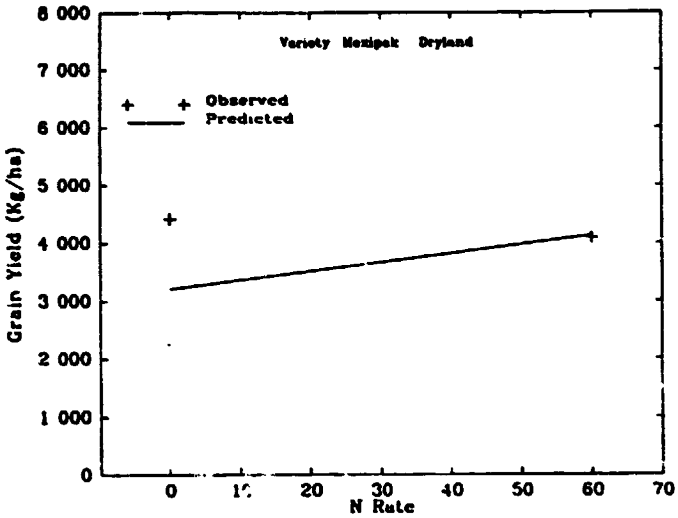
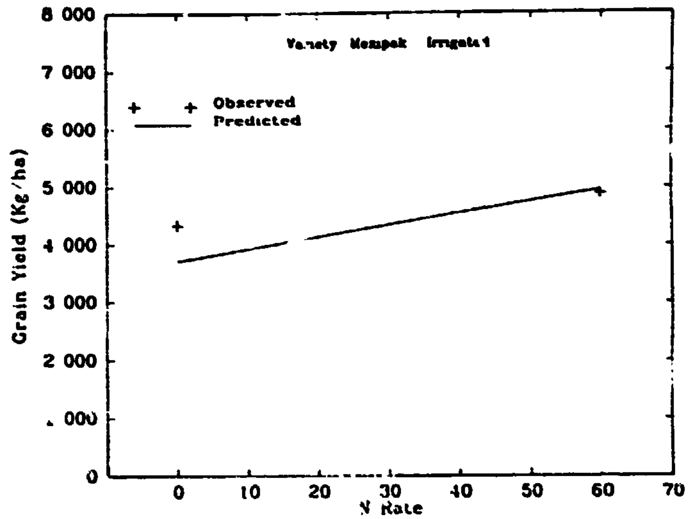


Figure B.1. Continued.

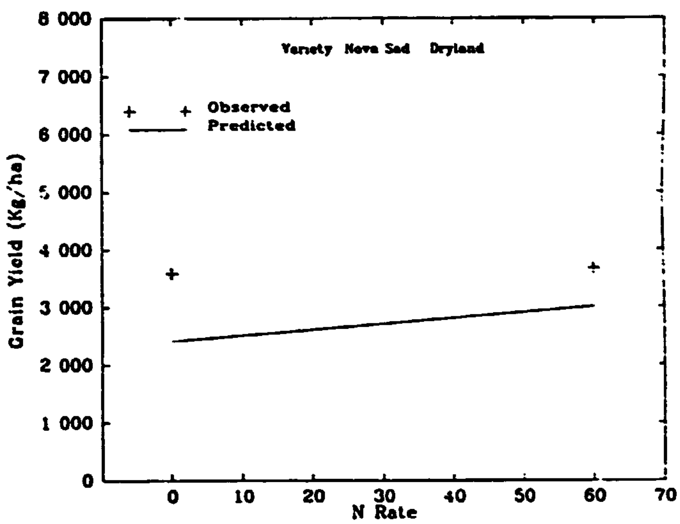
Tel Hadya, Syria 1979



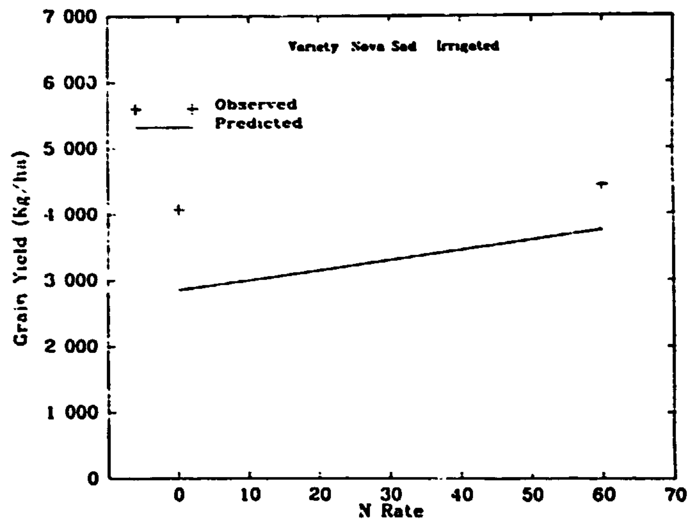
Tel Hadya, Syria 1979



Tel Hadya, Syria 1979



Tel Hadya, Syria 1979



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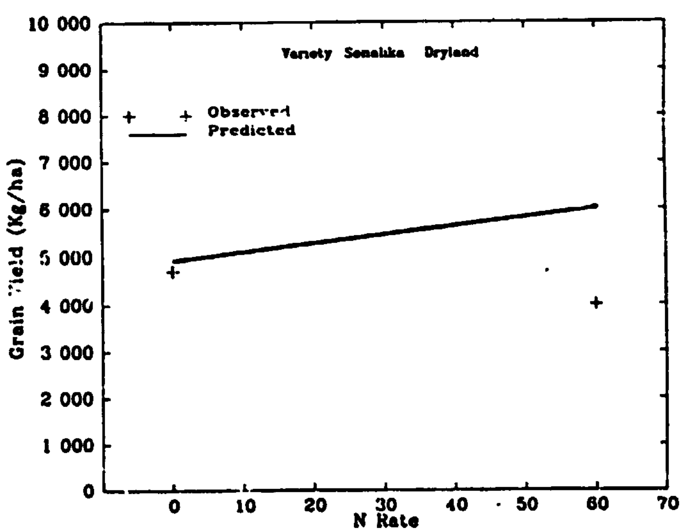


Tel Hadya, Syria 1979

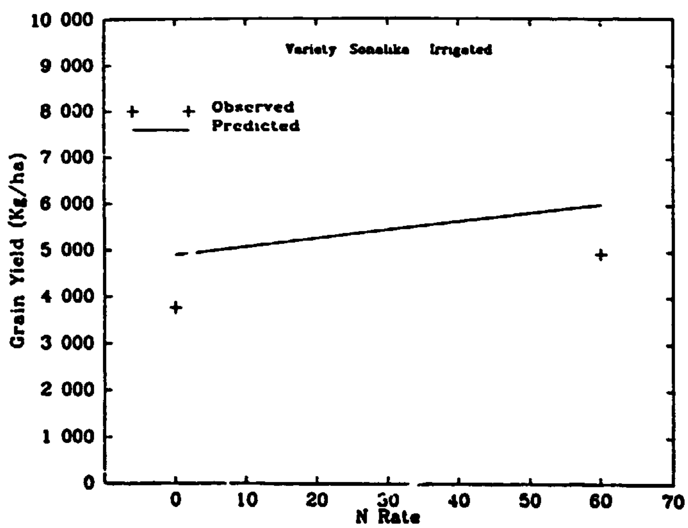


Figure B.1. Continued.

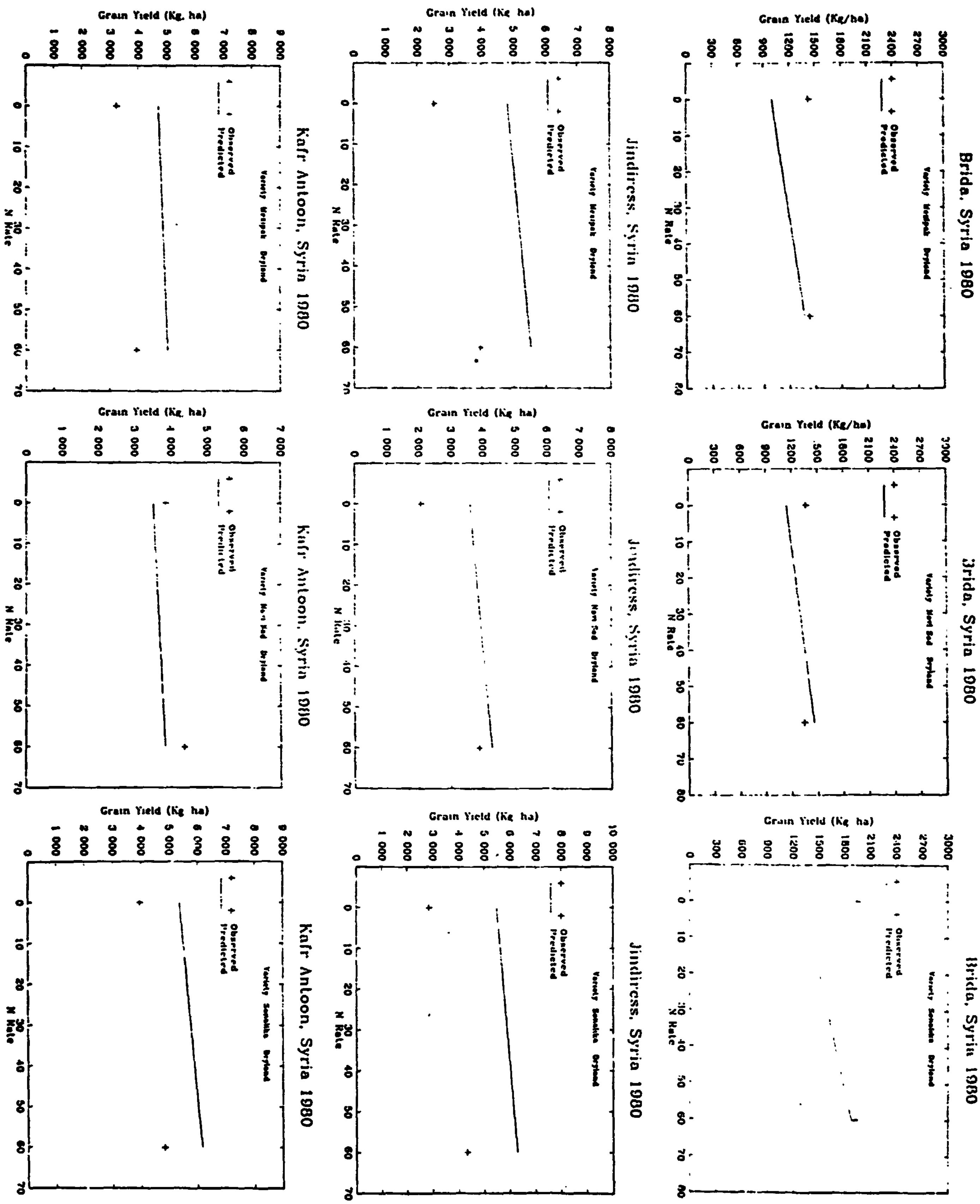
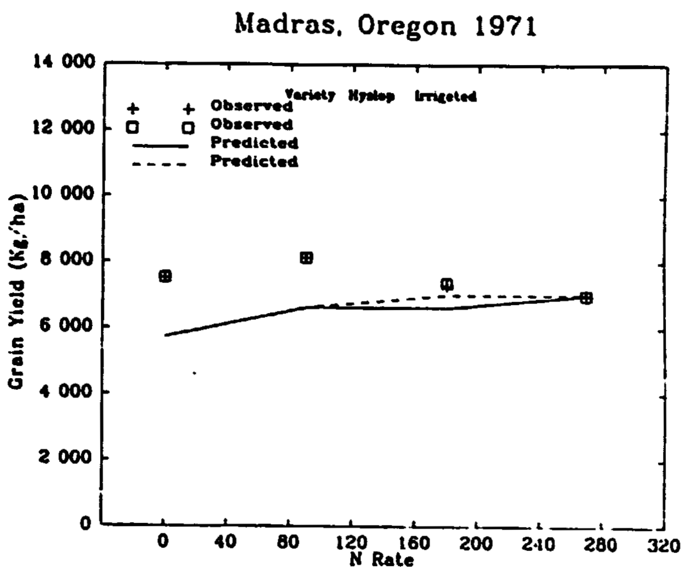
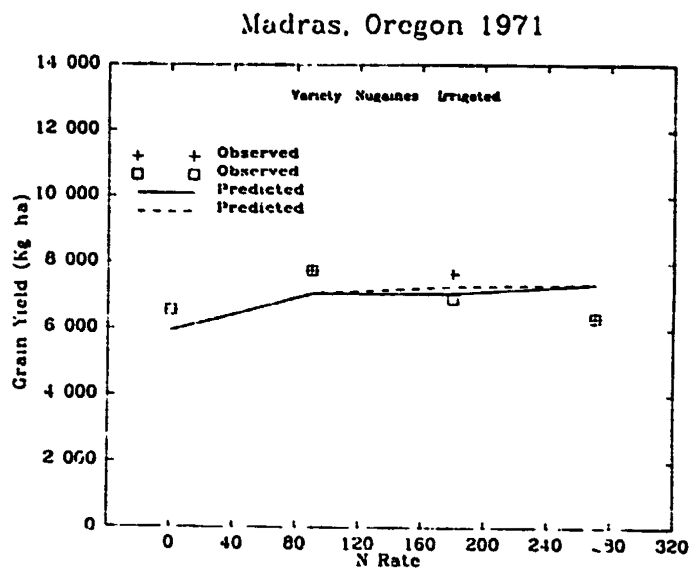
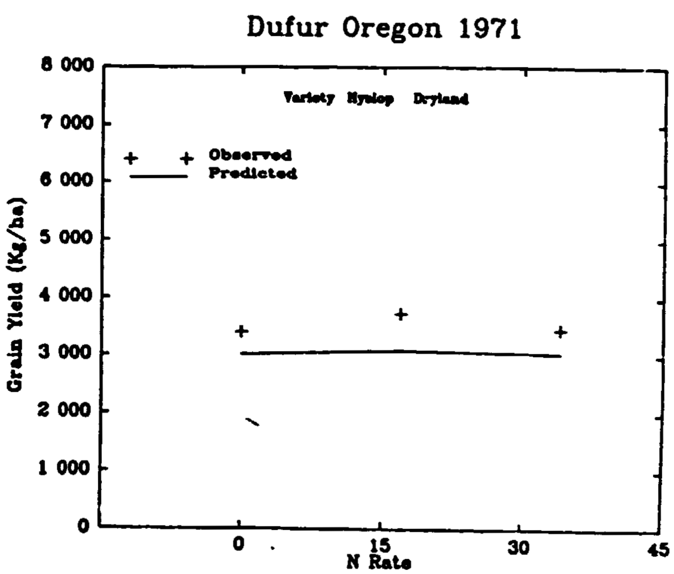
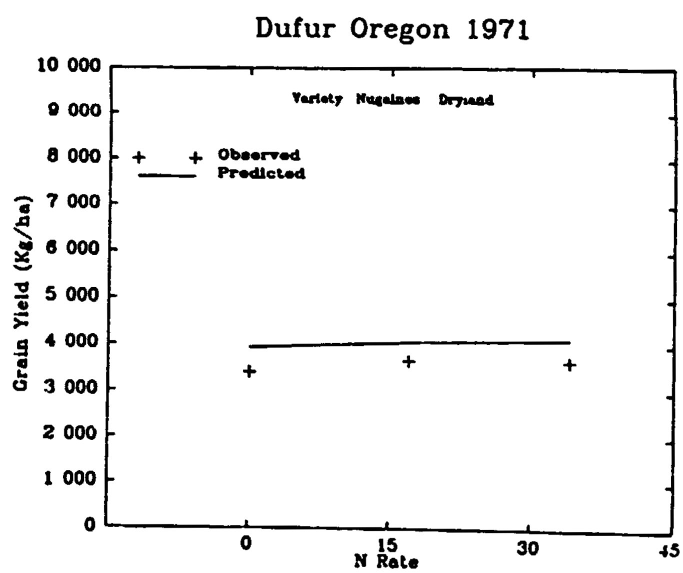


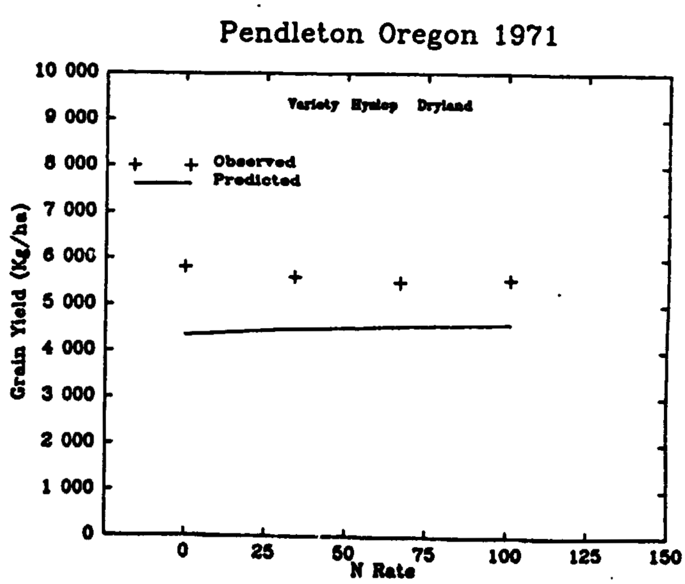
Figure B.1. Continued.











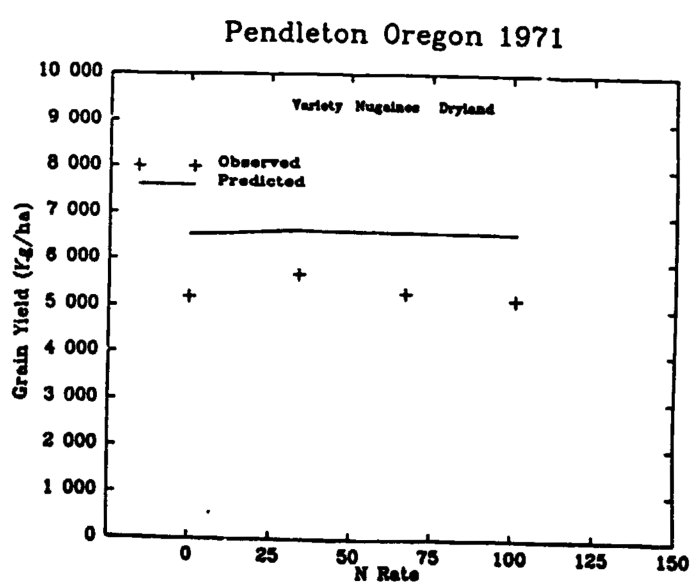
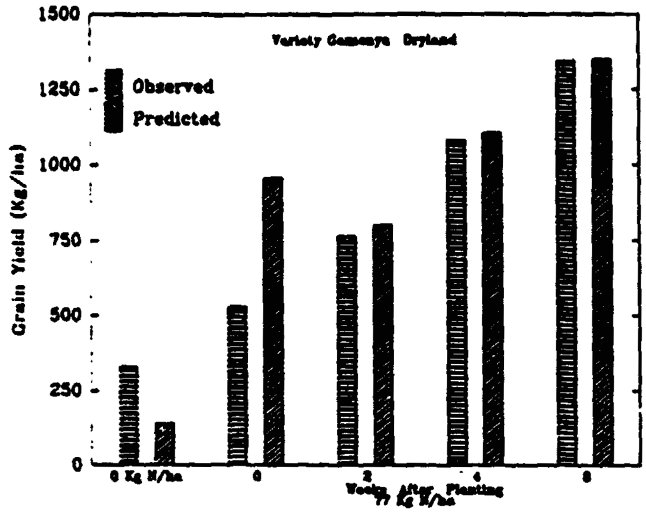
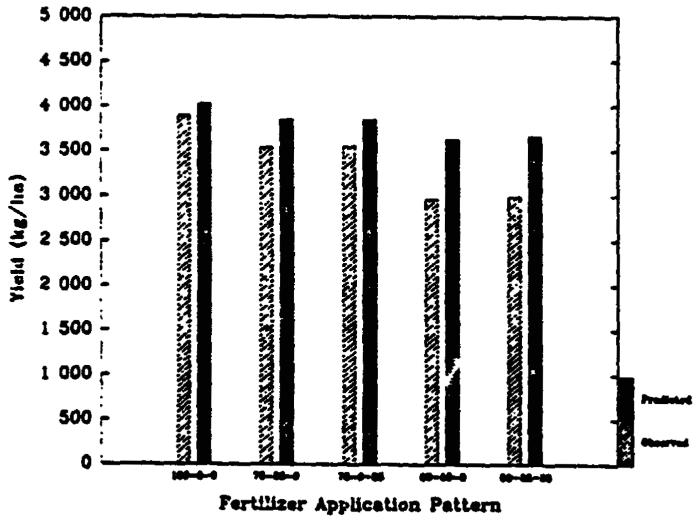


Figure B.2. Comparison of predicted and observed grain yield response to differing fertilizer split application patterns.

Lancelin, Western Australia 1967



BOZEMAN MONTANA 100 KG N/HA



Wageningen, Netherlands 1977

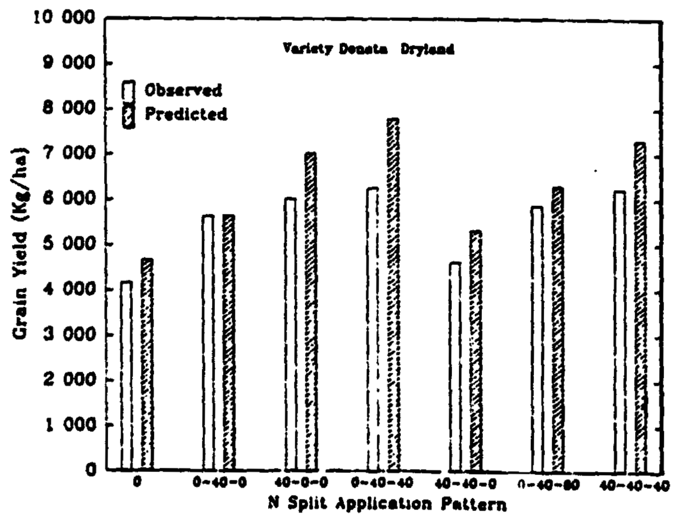


Figure B.3. Comparison of predicted and observed grain yields at differing fertilizer rates for three varieties with different irrigation strategies.

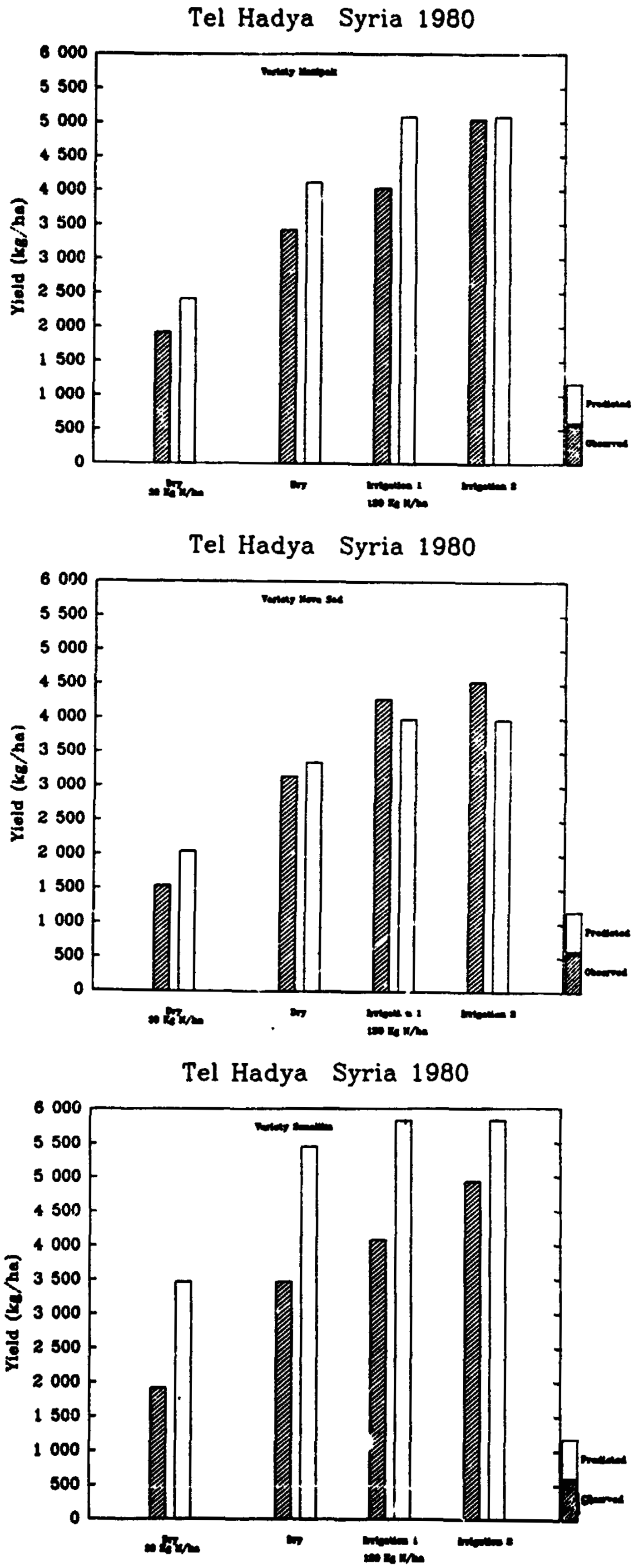
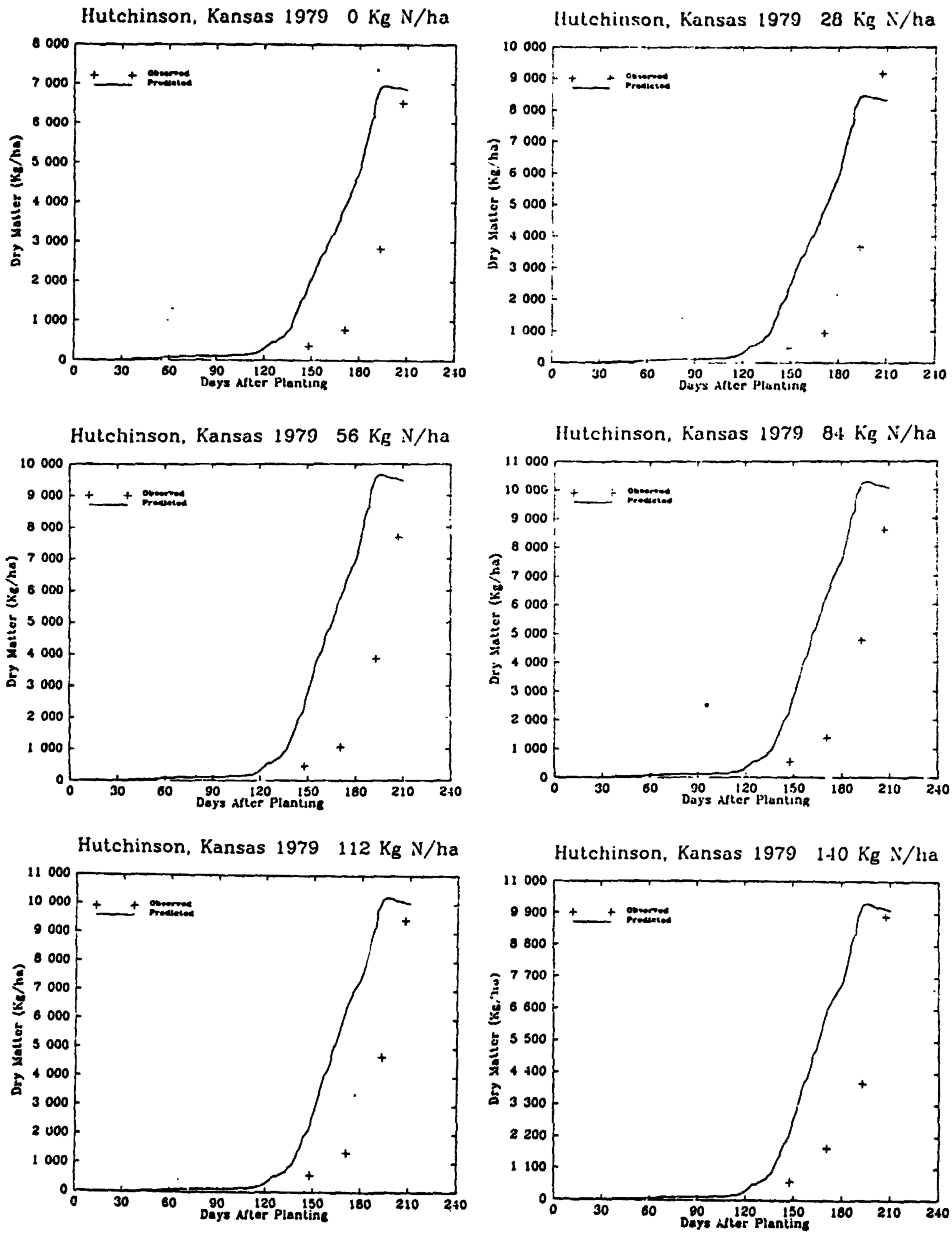


Figure B.4. Comparison of predicted and observed seasonal dry matter production for individual data sets.



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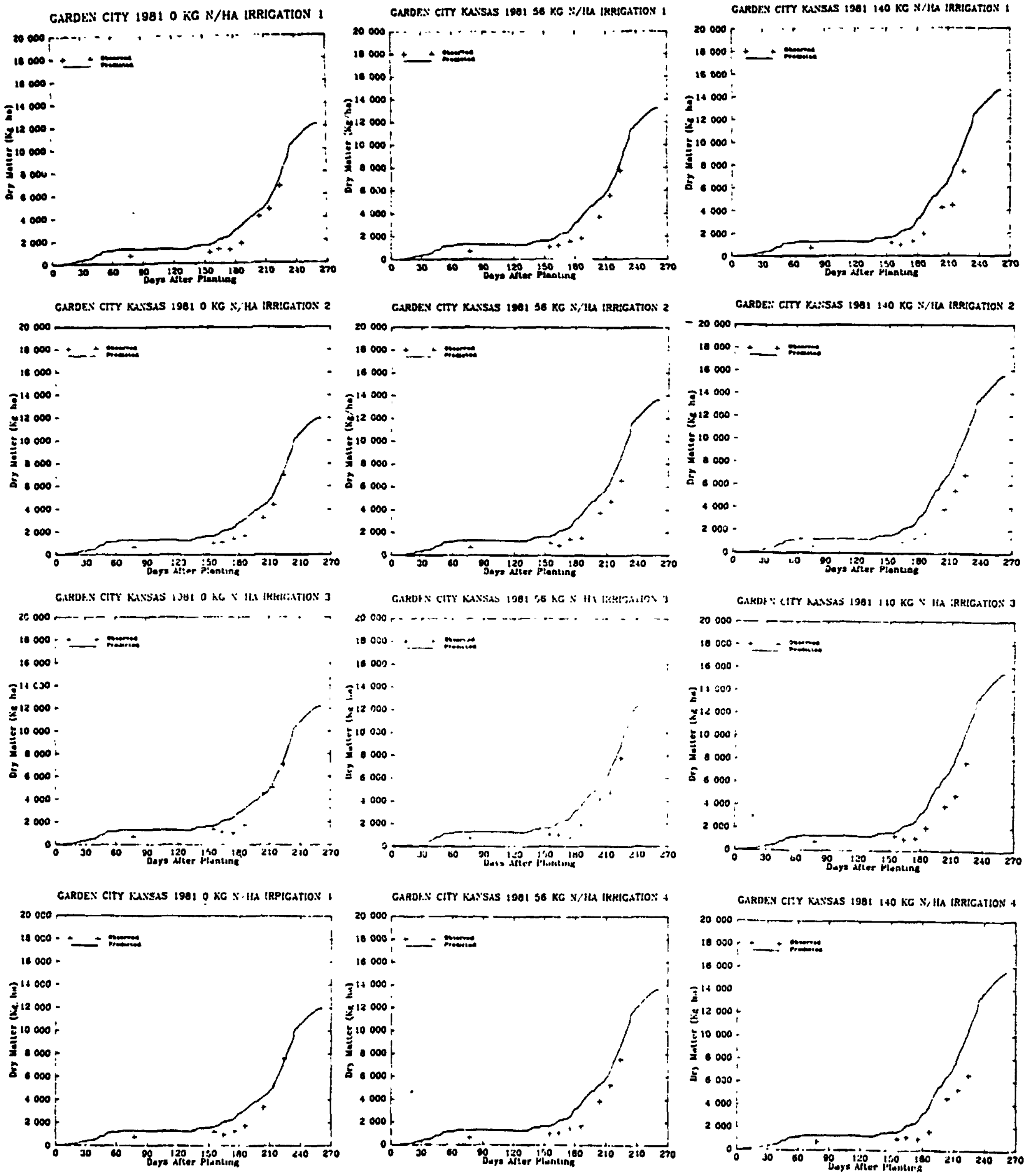

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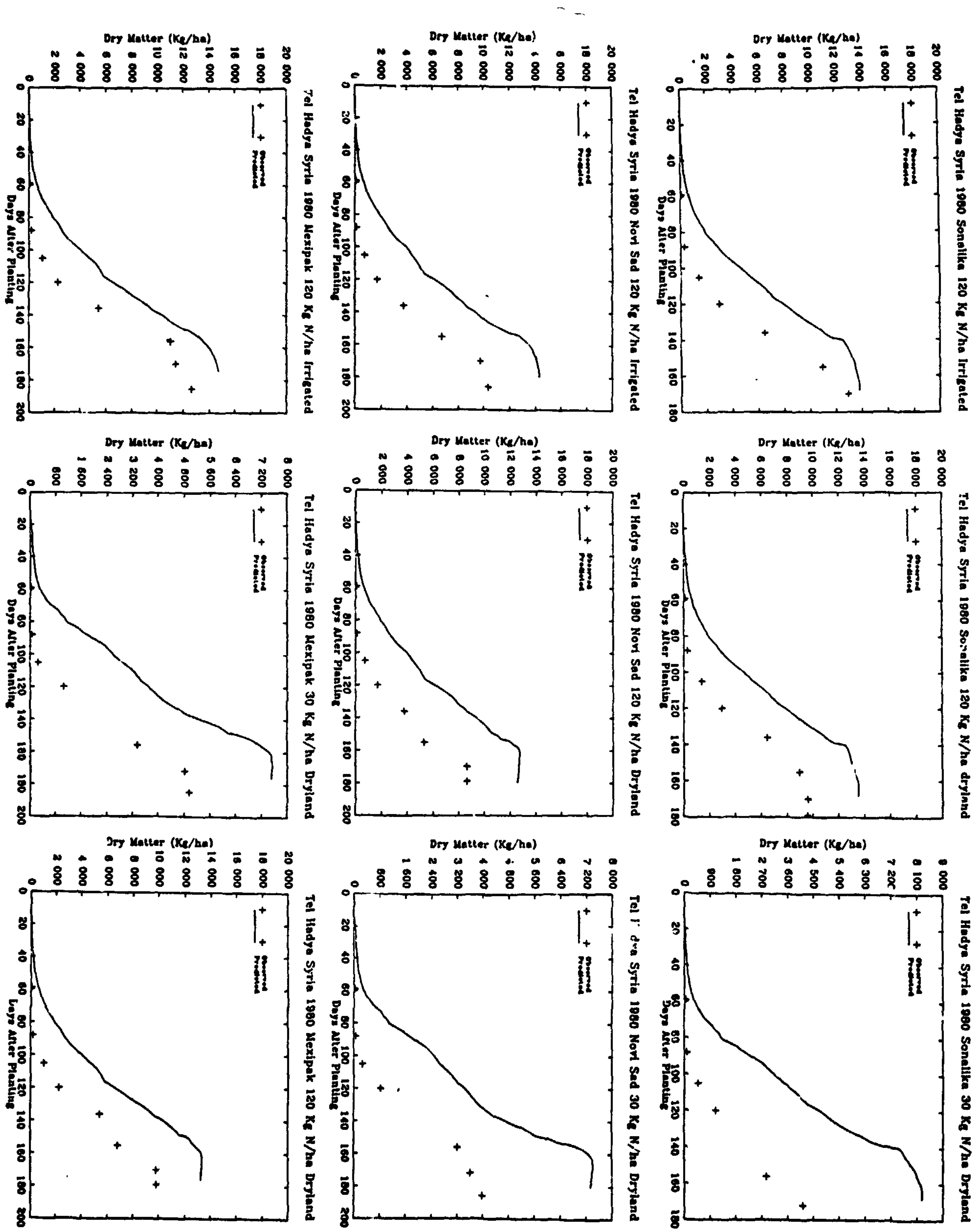

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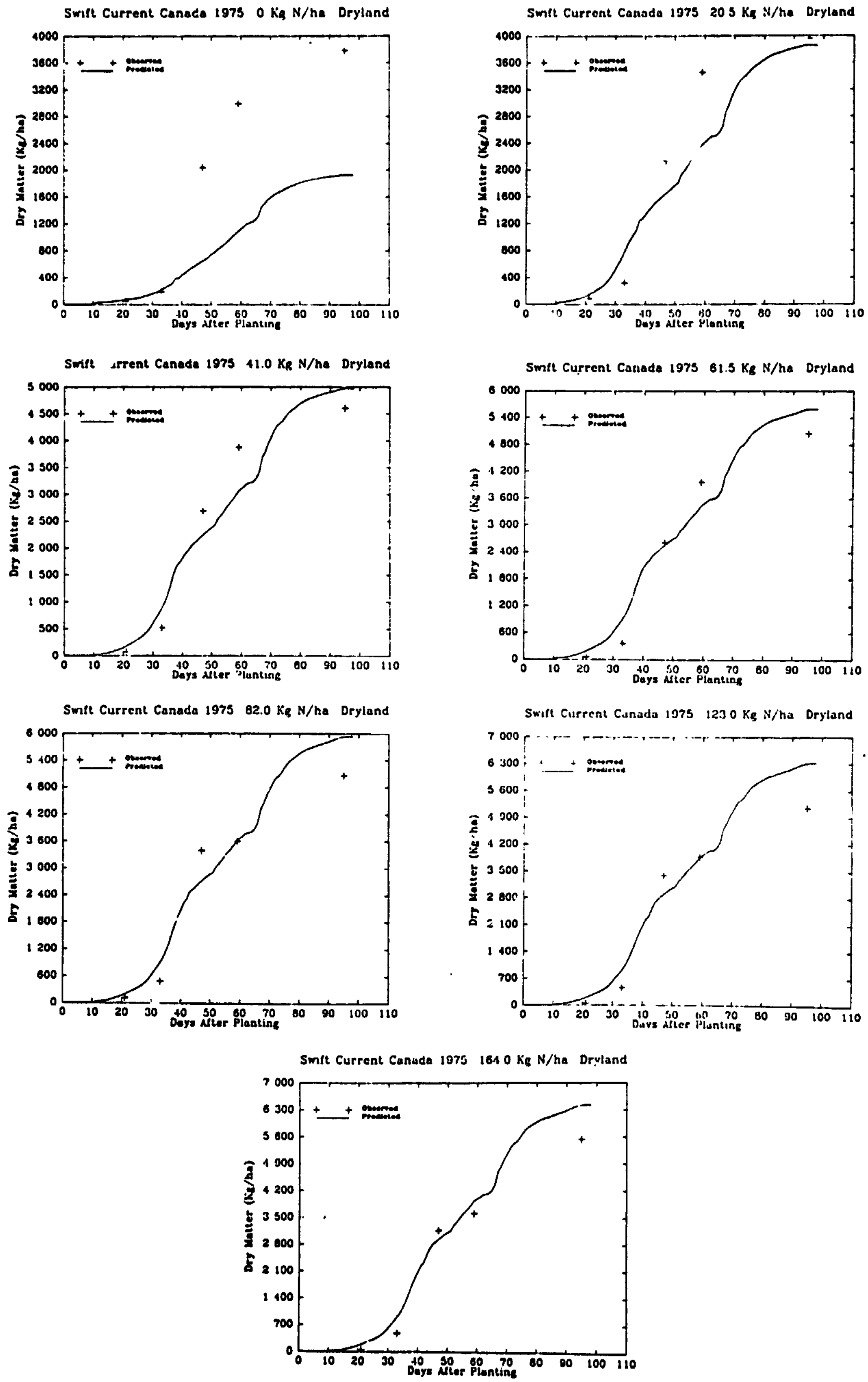


Figure B.4. Continued.

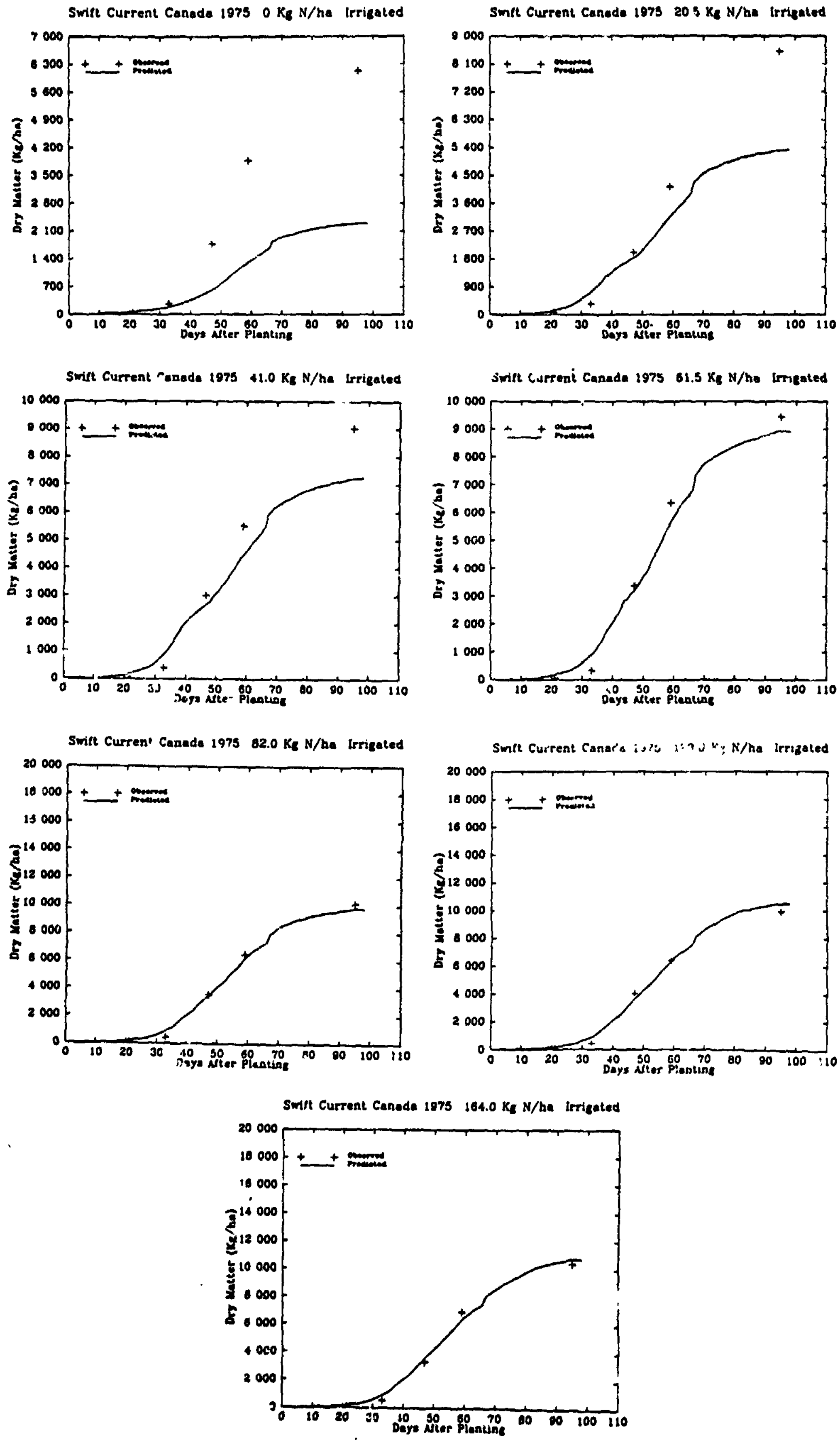
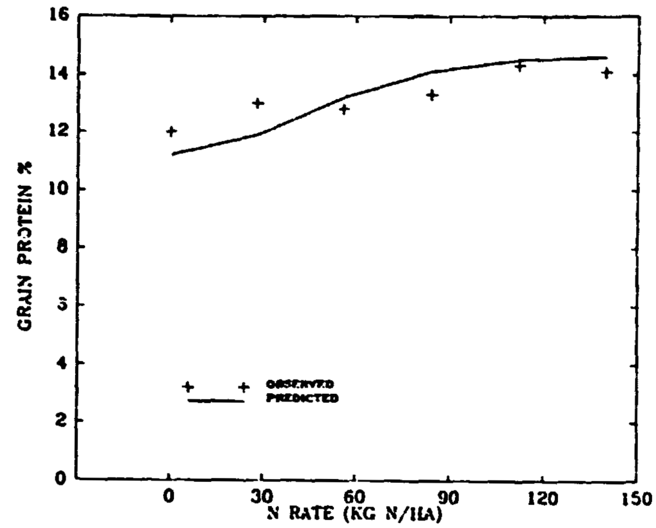
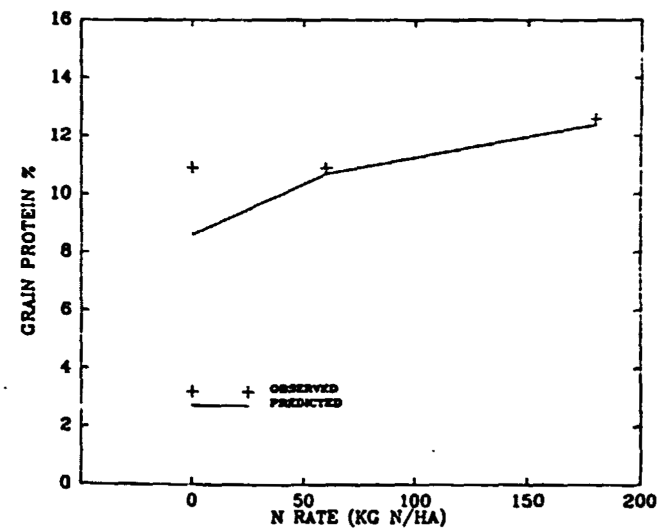


Figure B.5. Comparison of predicted and observed grain protein response to applied N in individual data sets.

HUTCHINSON KANSAS 1979 CENTURK DRYLAND



MANHATTAN KANSAS 1981 NEWTON DRYLAND



MANHATTAN KANSAS 1981 NEWTON IRRIGATED

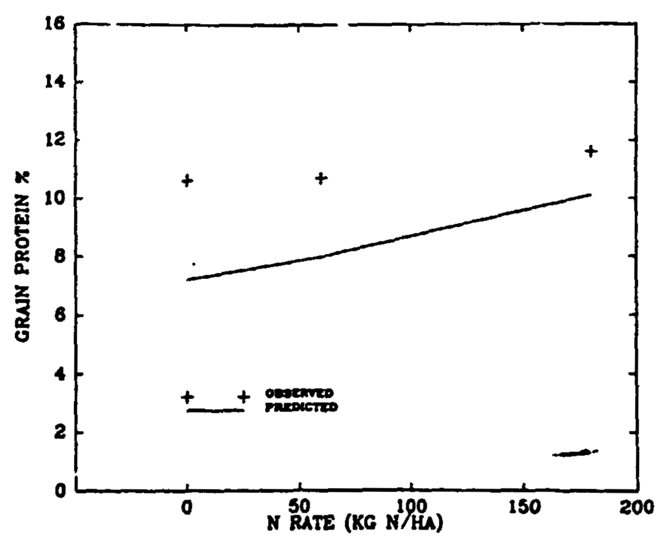
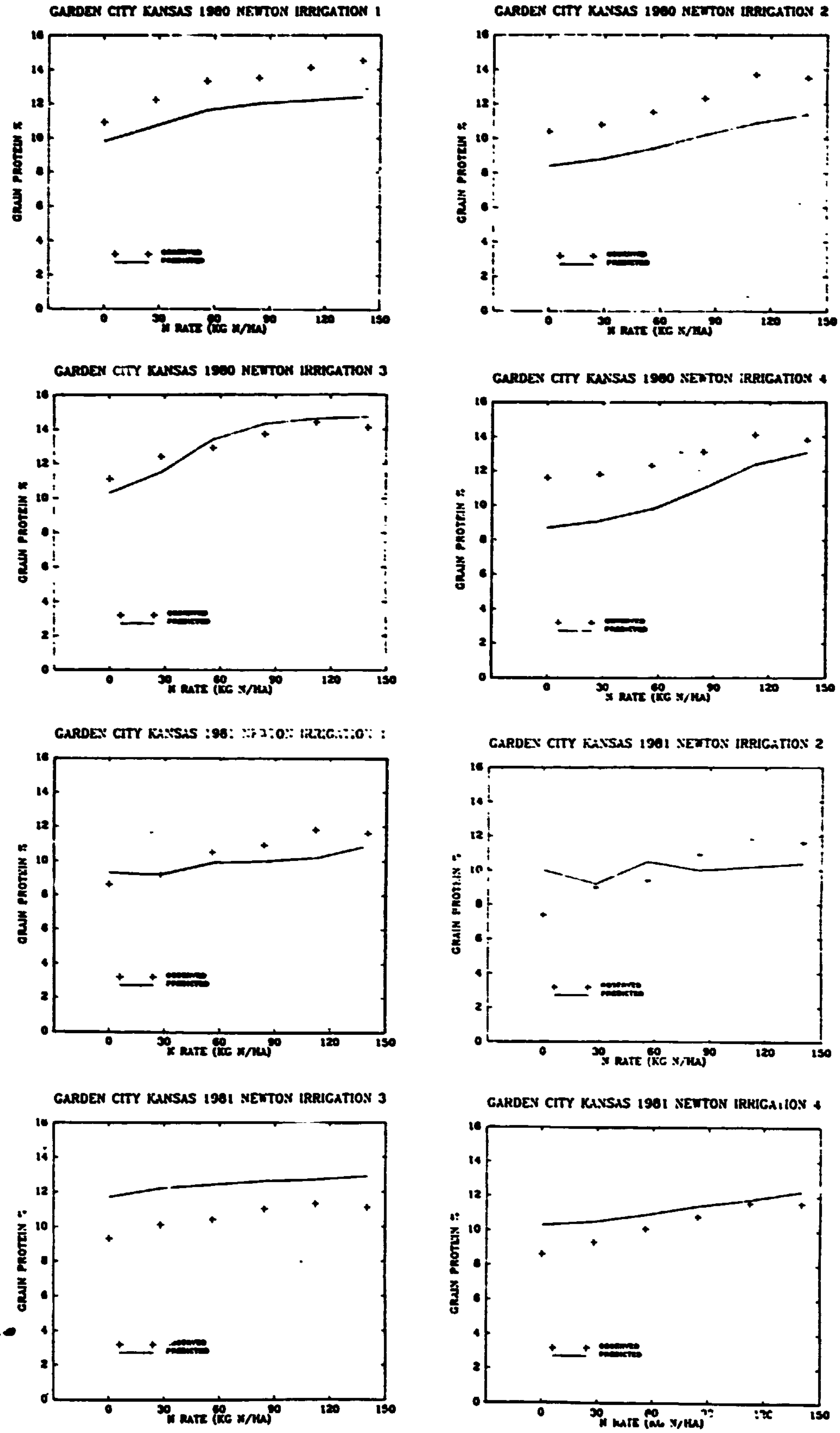


Figure B.5. Continued.



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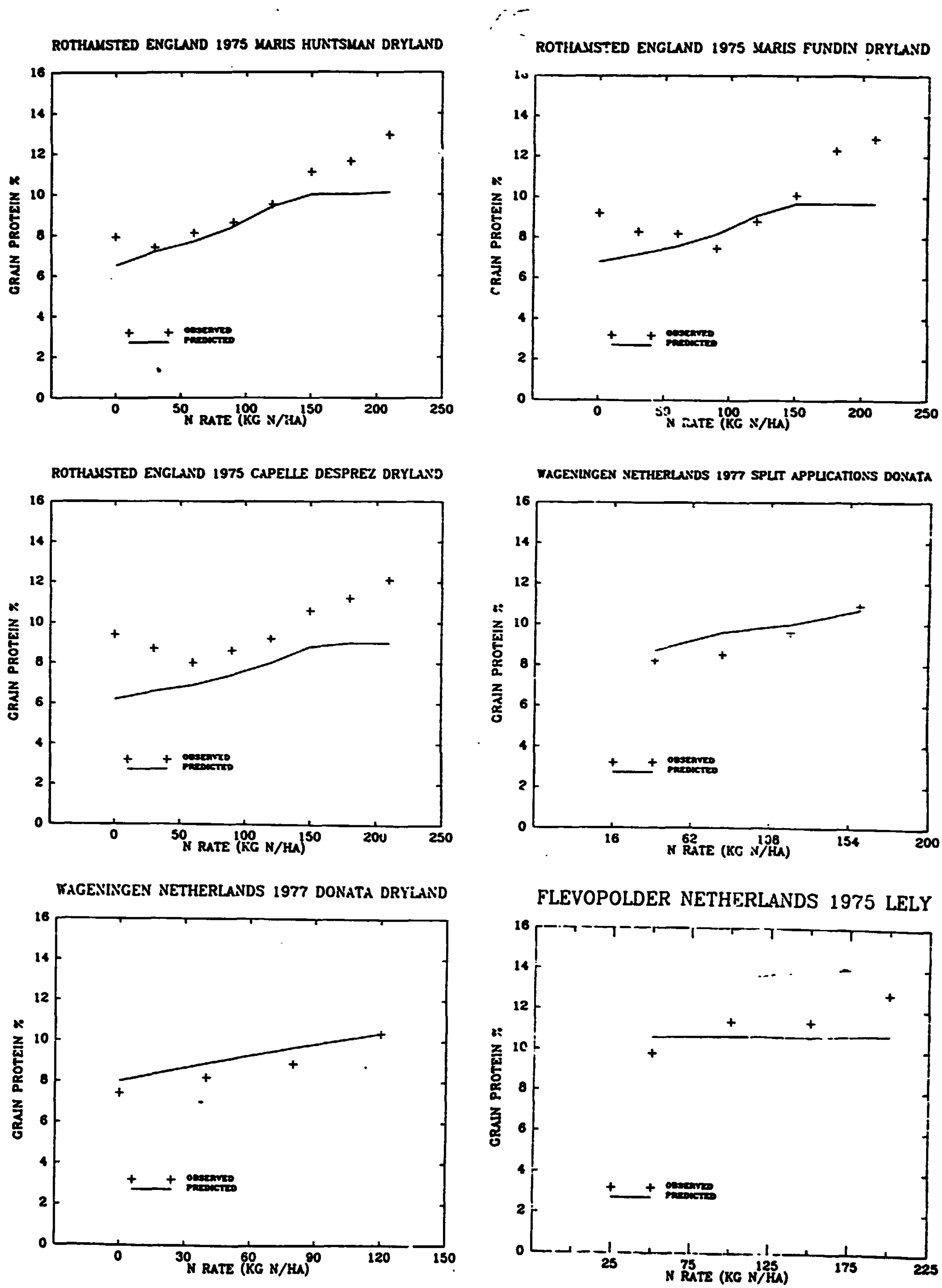

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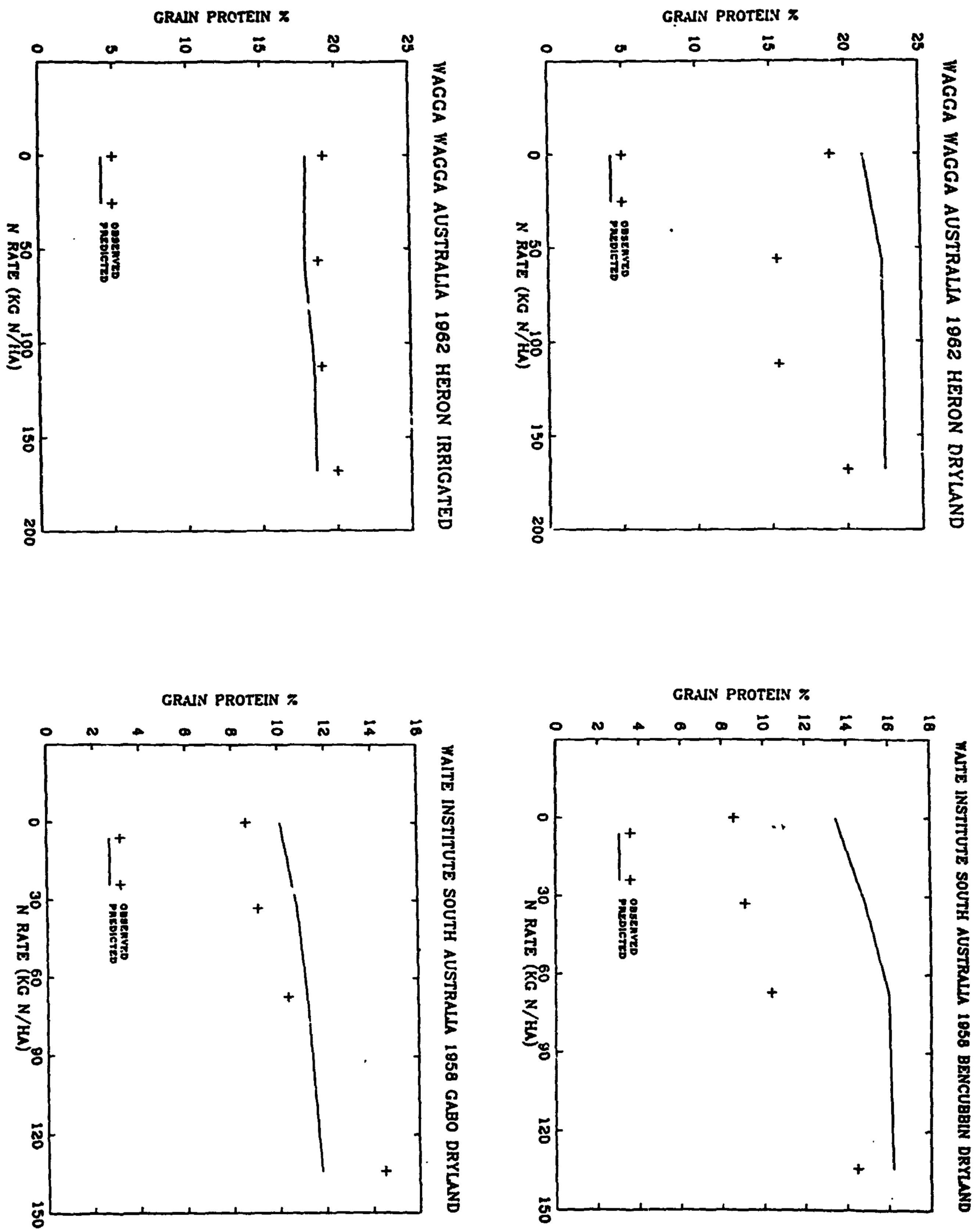

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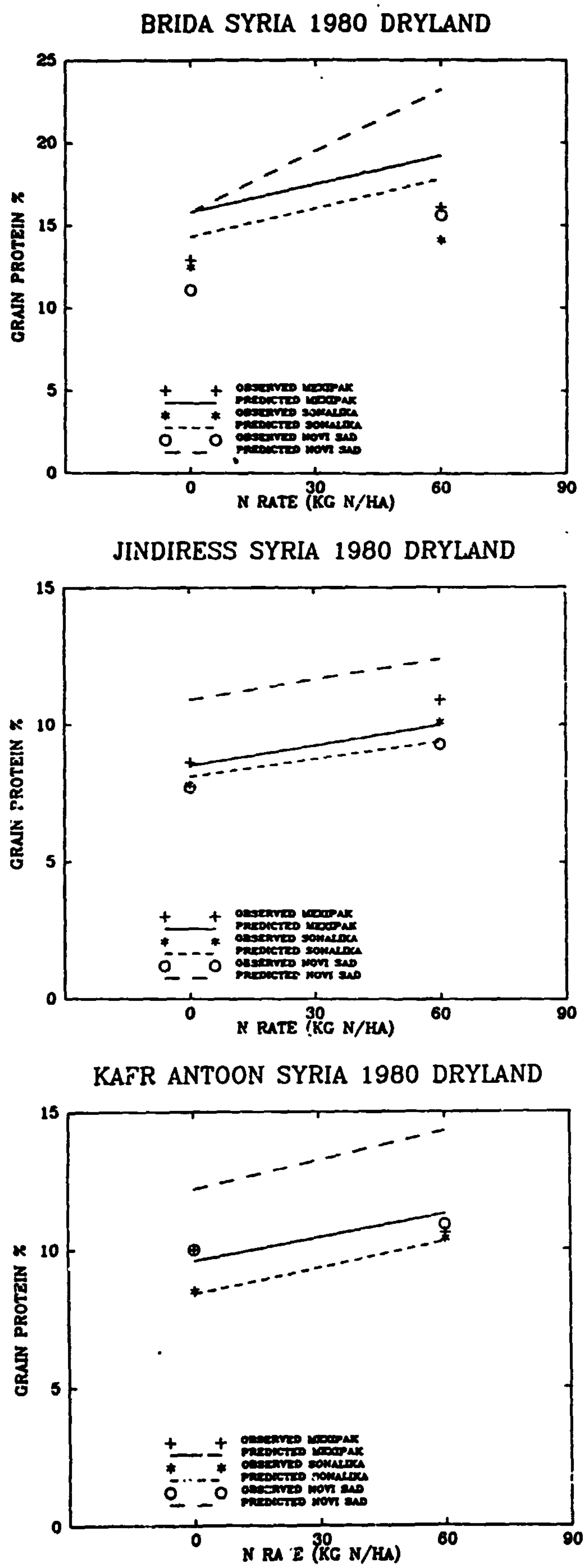

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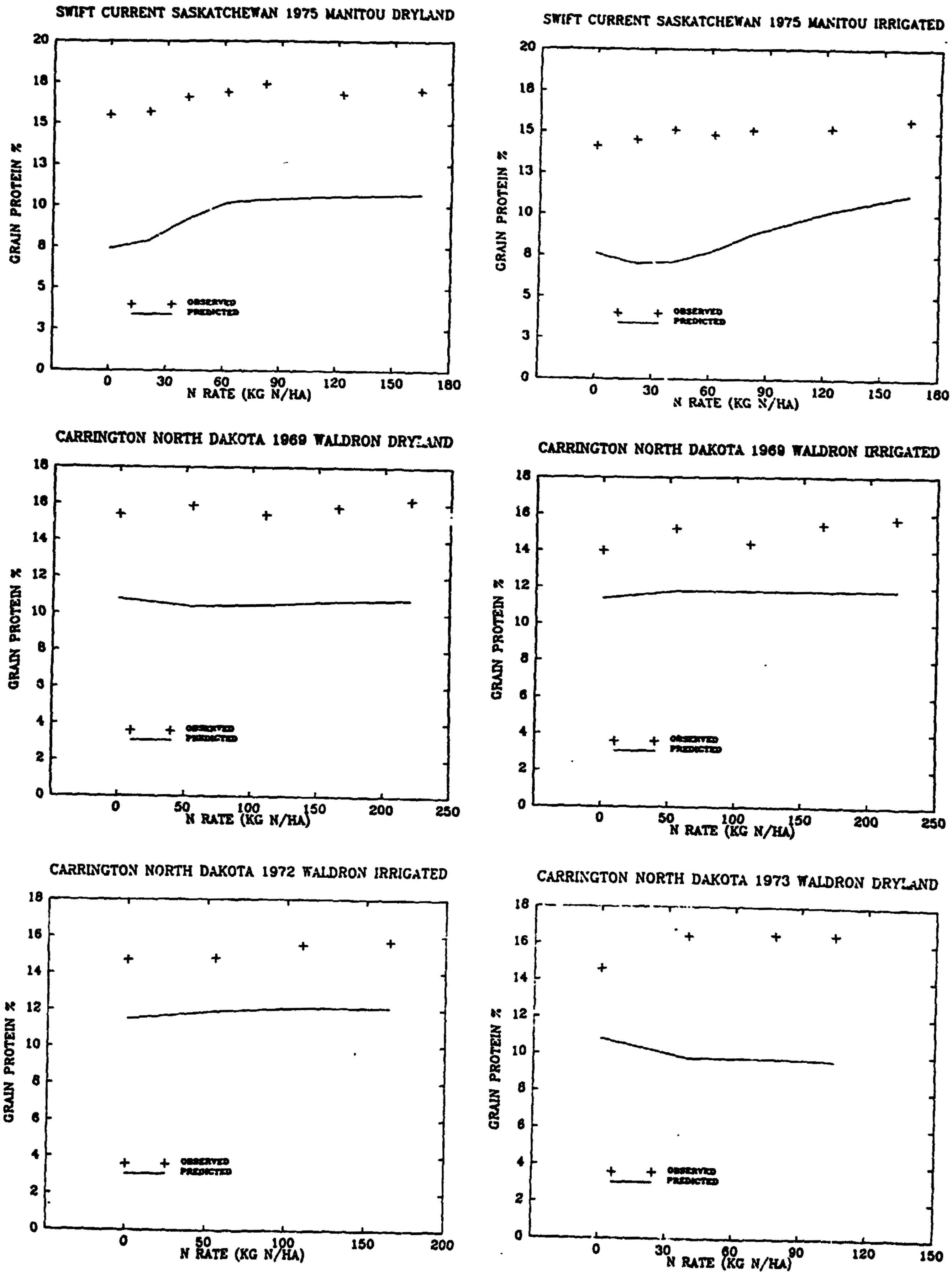

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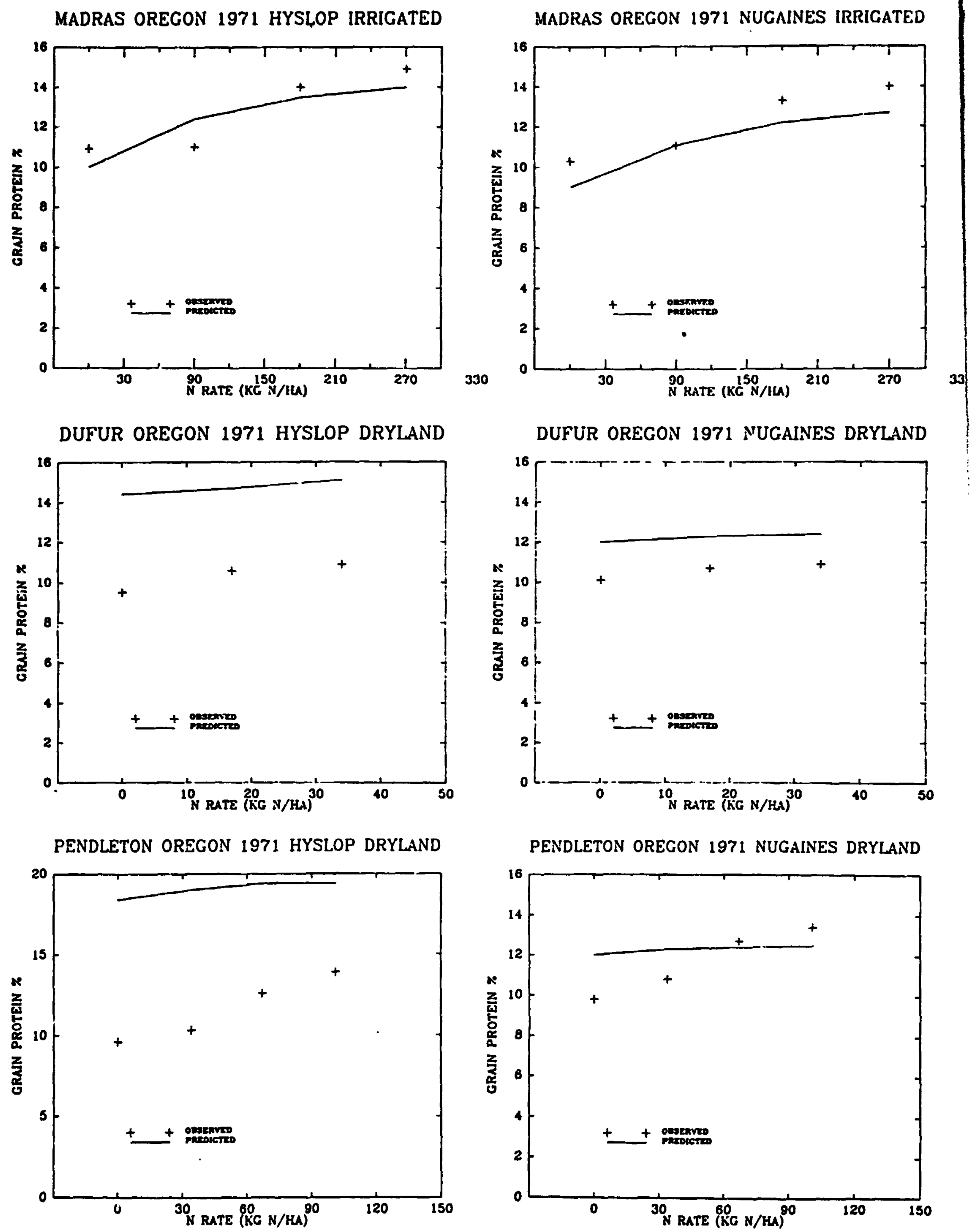
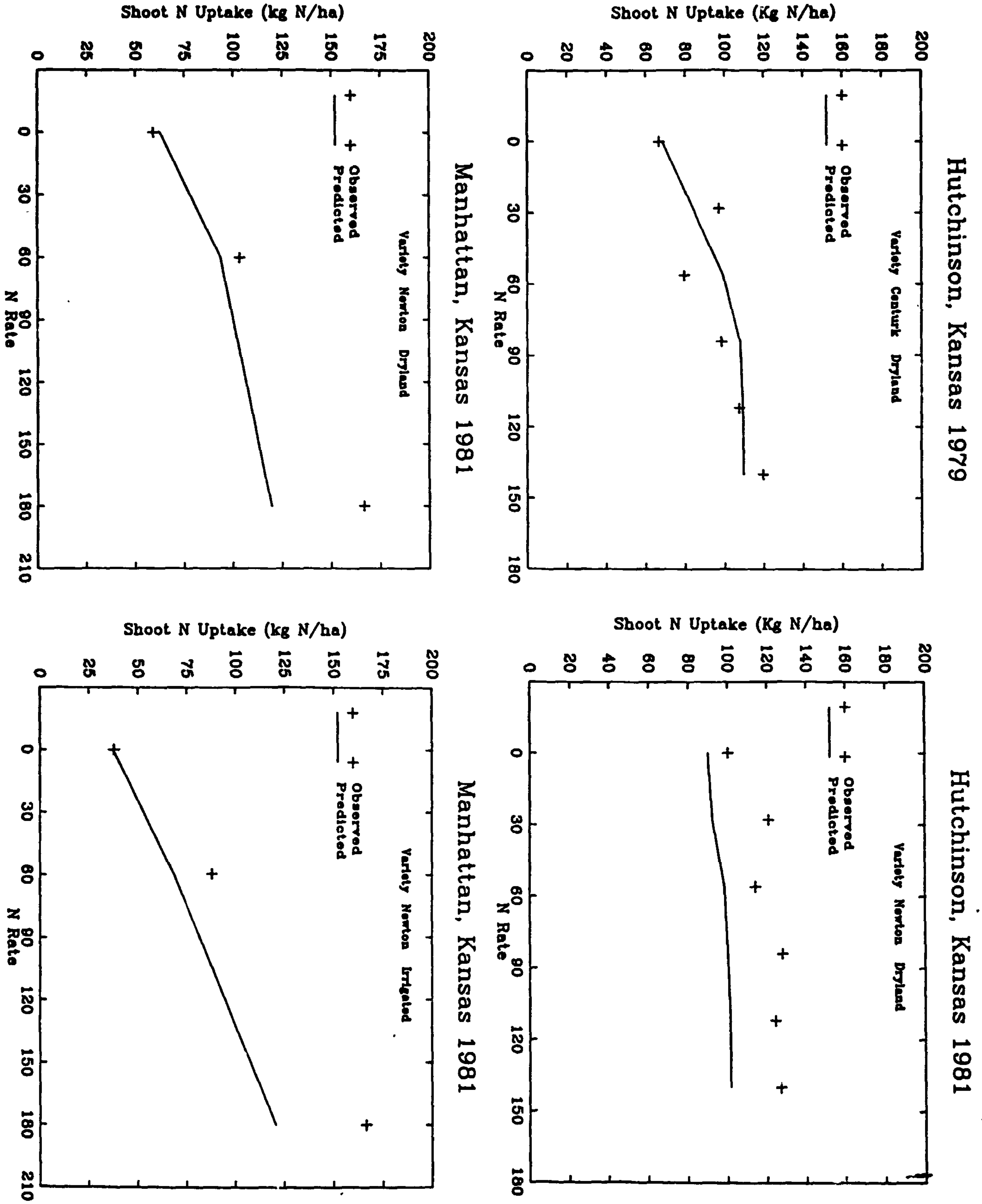


Figure B.6. Comparison of predicted and observed N uptake response to applied N in individual data sets.



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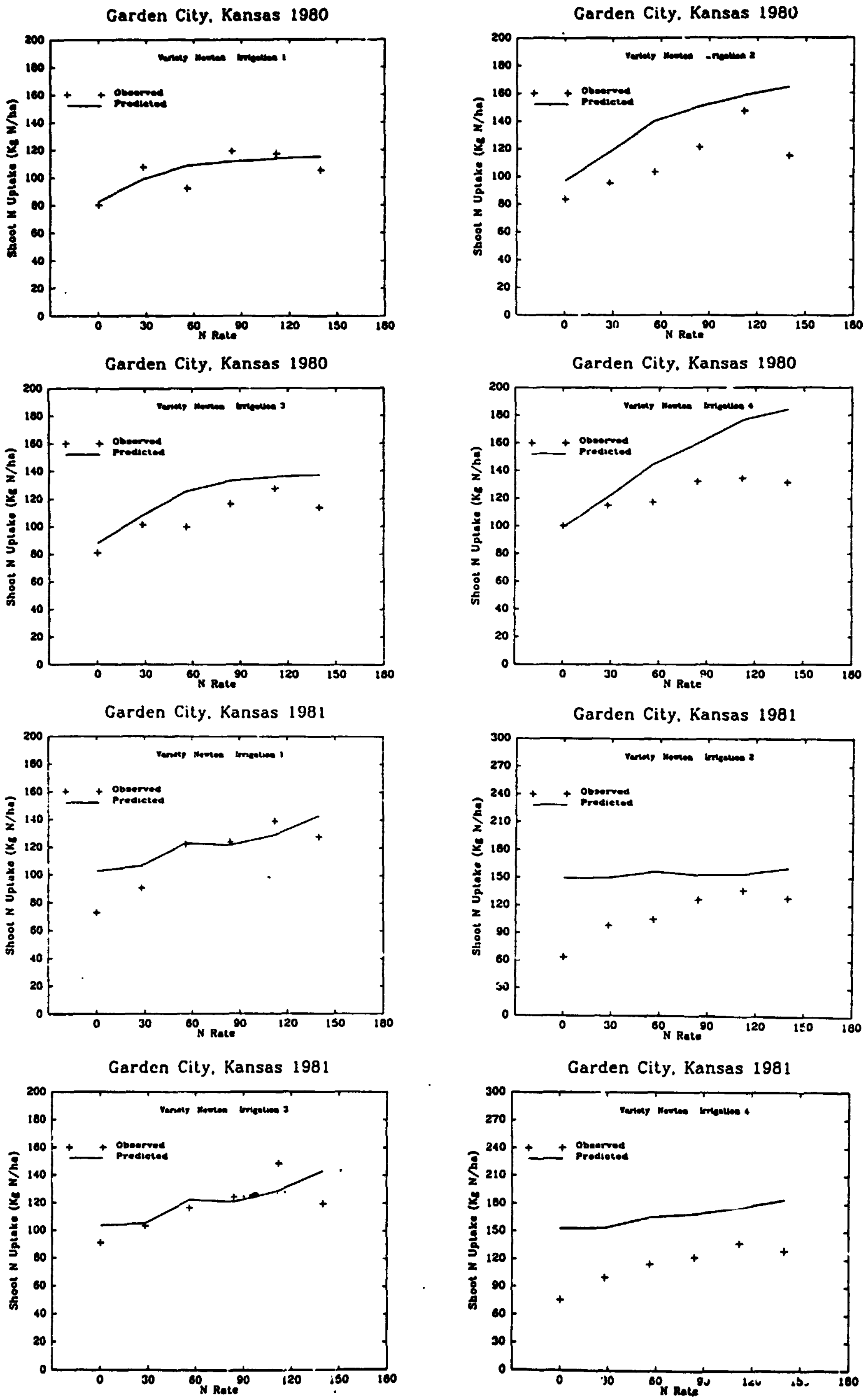
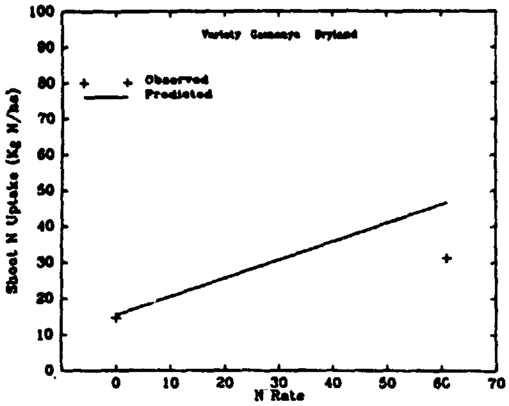
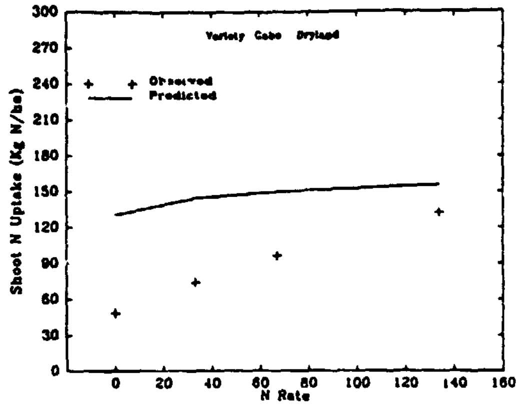


Figure B.6. Continued.

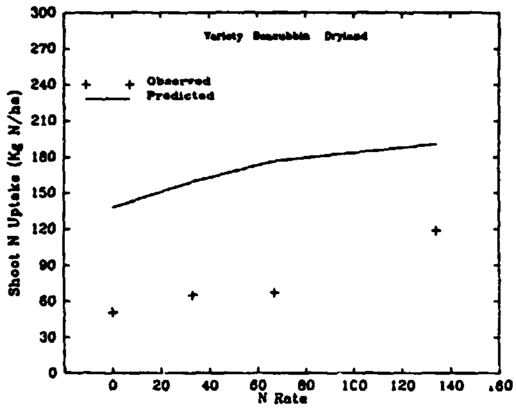
Wongan Hills W. Australia 1966



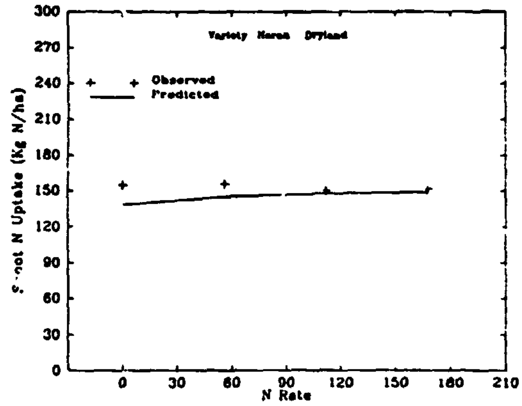
Waite Institute S. Australia 1958



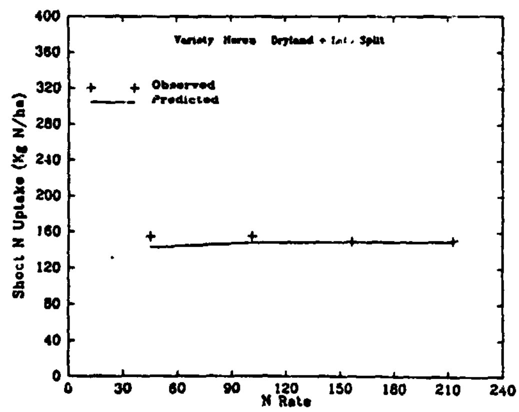
Waite Institute S. Australia 1958



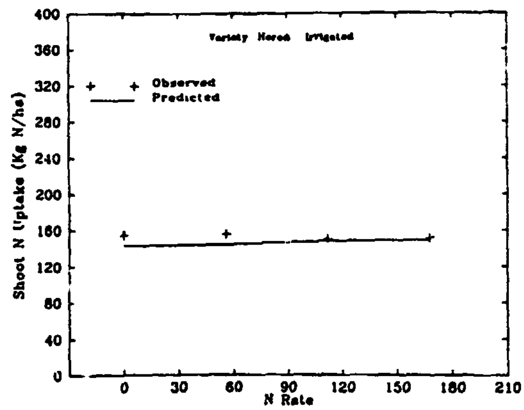
Wagga Wagga, NSW Australia 1962



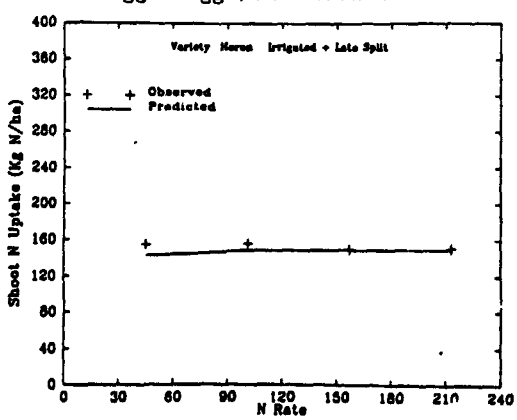
Wagga Wagga, NSW Australia 1962



Wagga Wagga, NSW Australia 1962



Wagga Wagga, NSW Australia 1962



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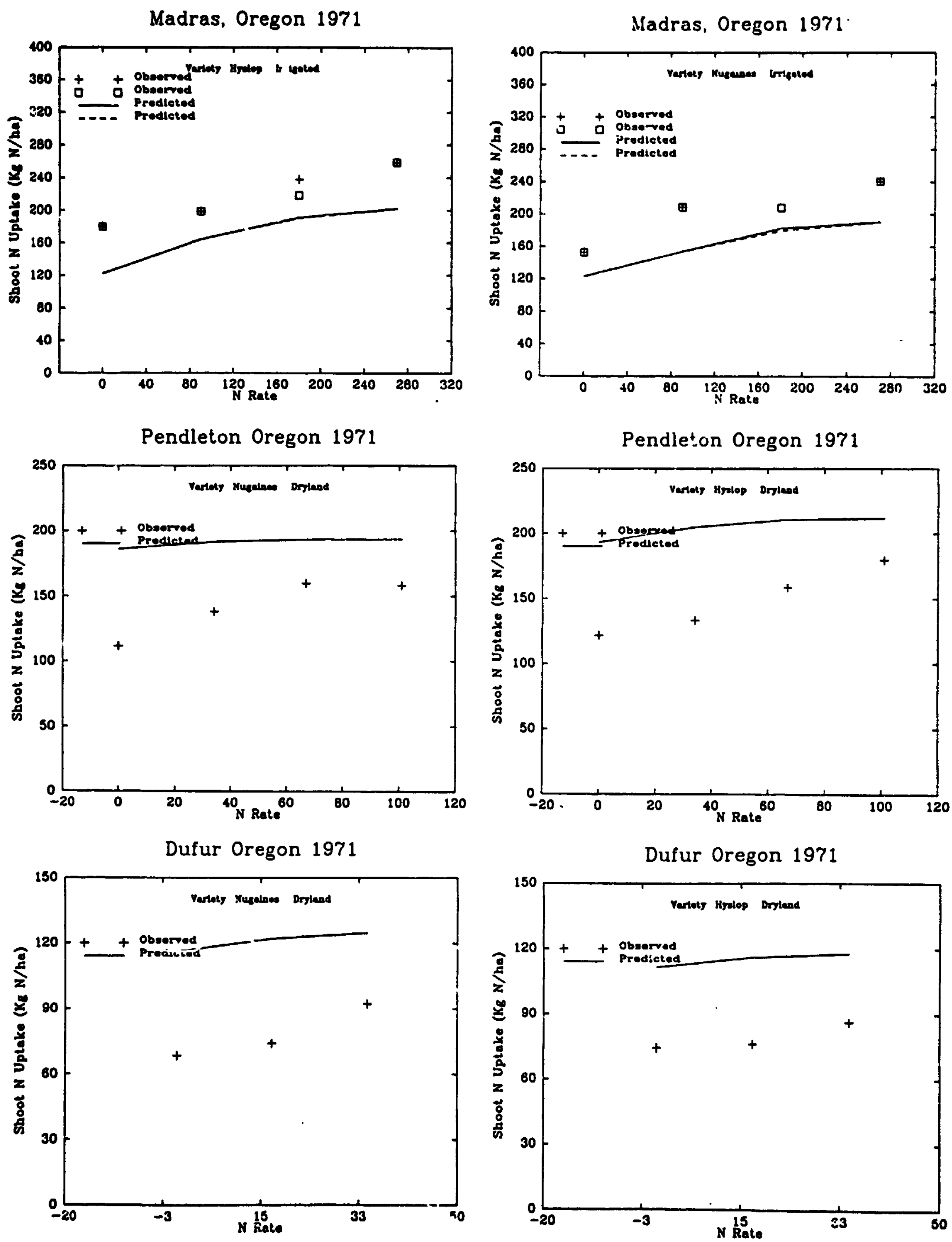
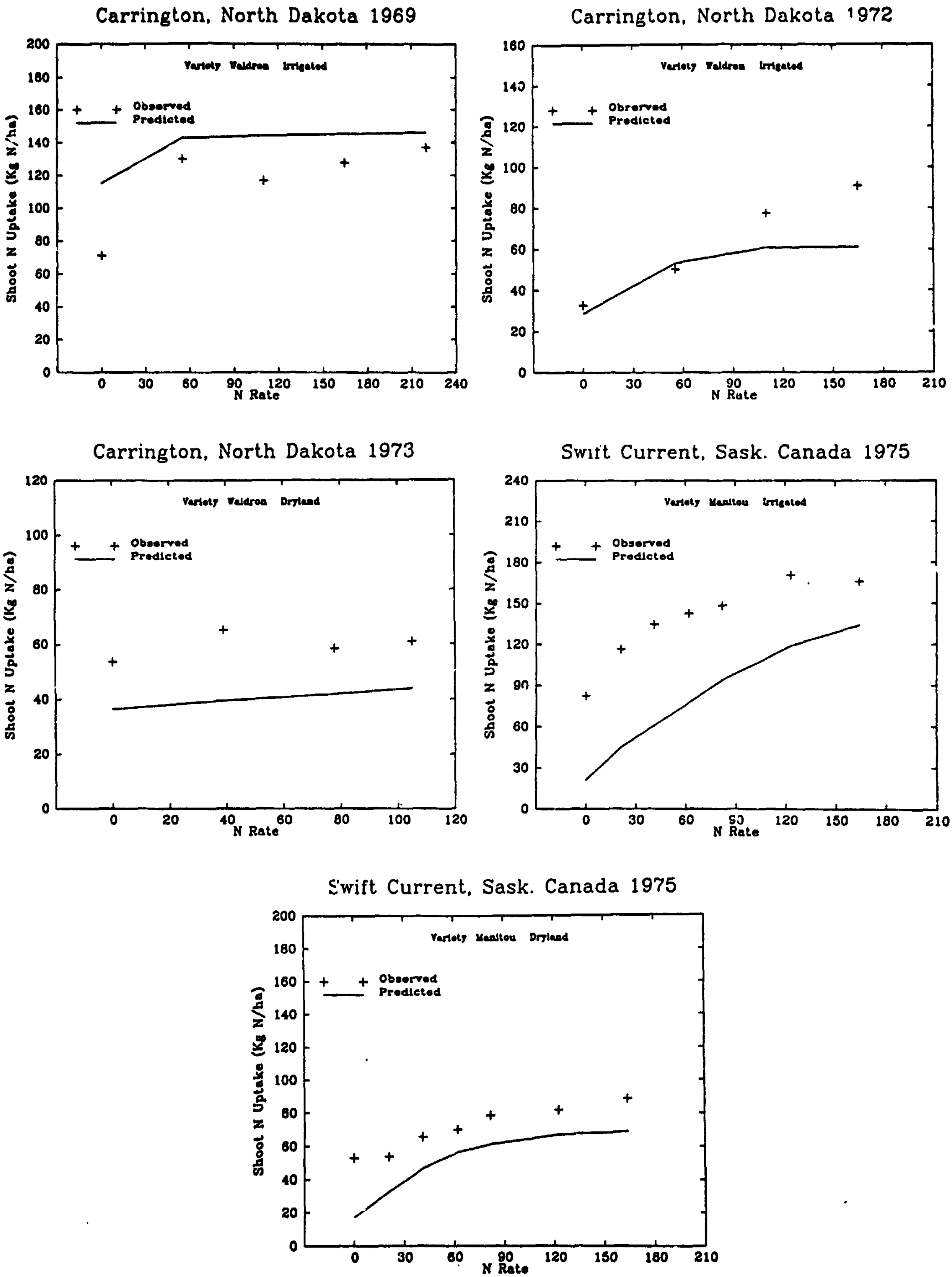


Figure B.6. Continued.



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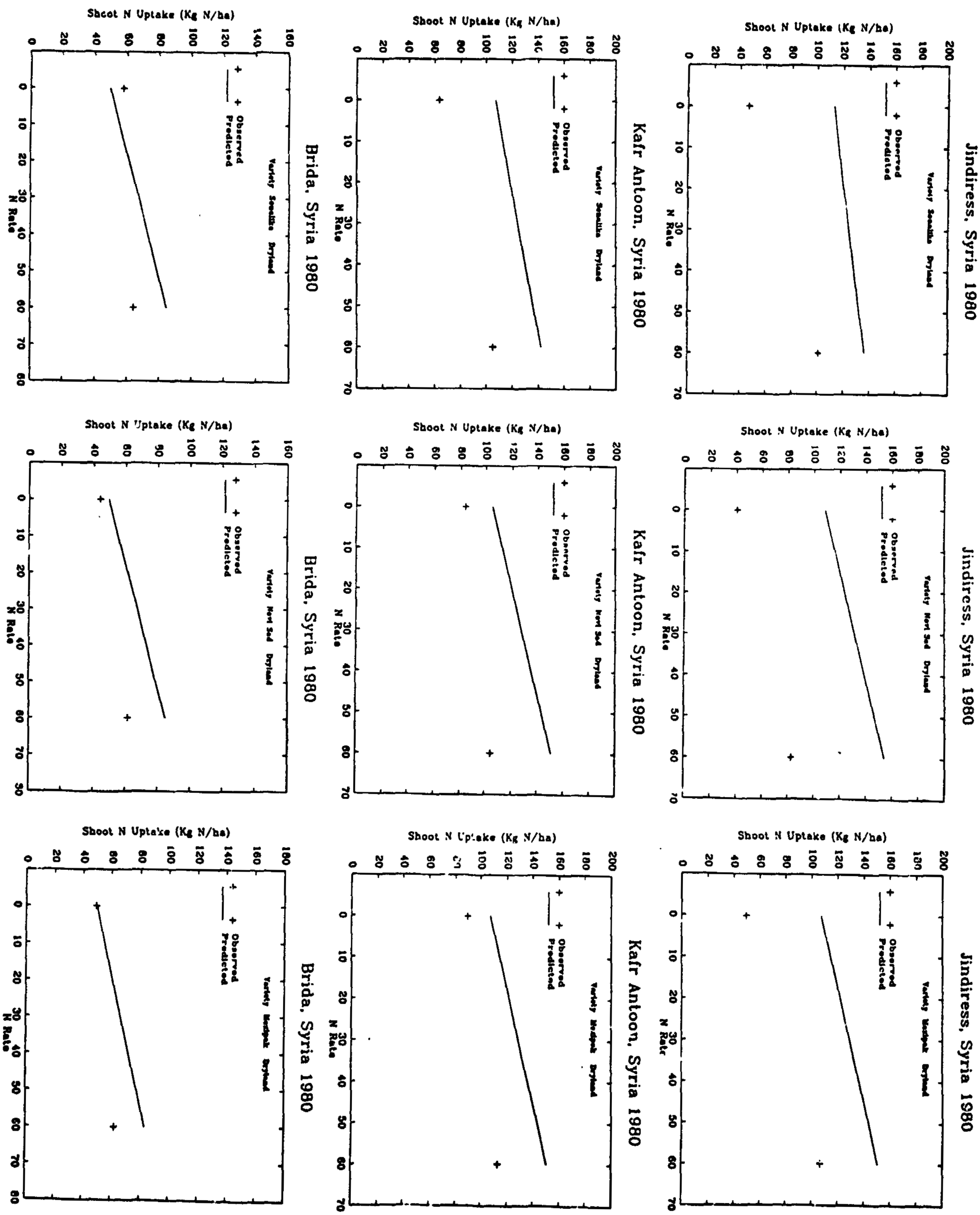
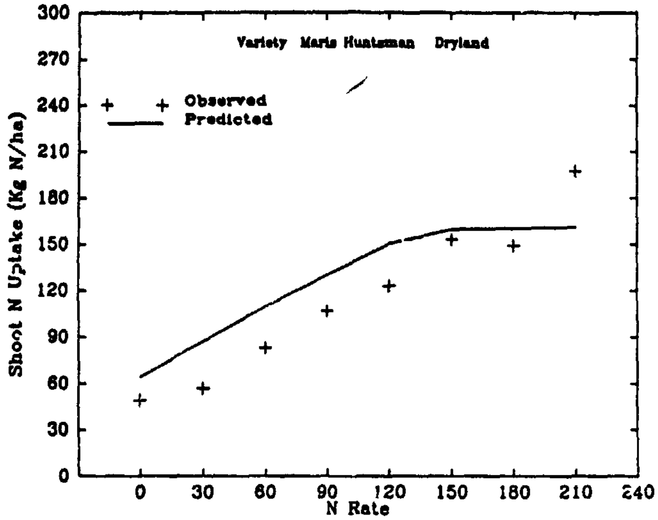
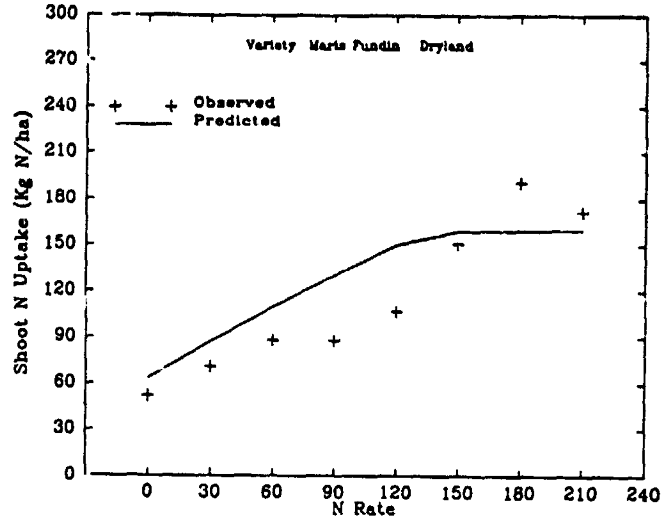


Figure B.6. Continued.

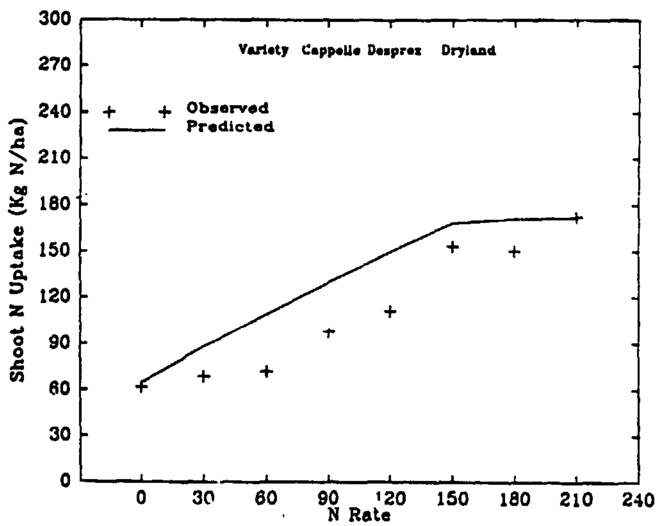
Rothamsted, United Kingdom 1975



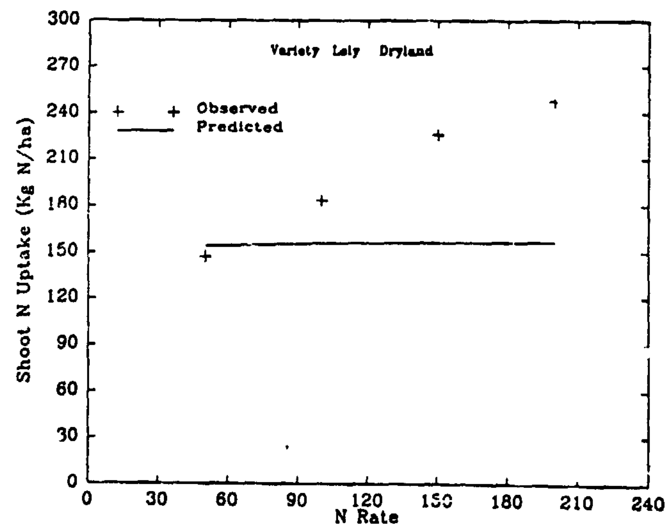
Rothamsted, United Kingdom 1975



Rothamsted, United Kingdom 1975



Flevopolder, Netherlands 1975



Bozeman, Montana 1971

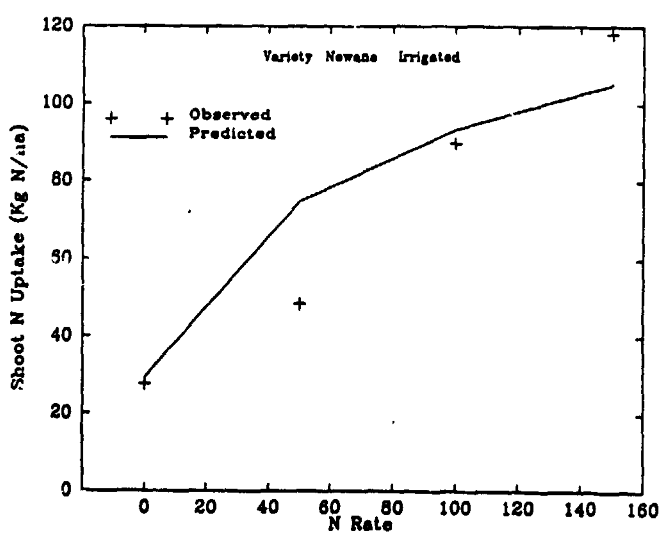
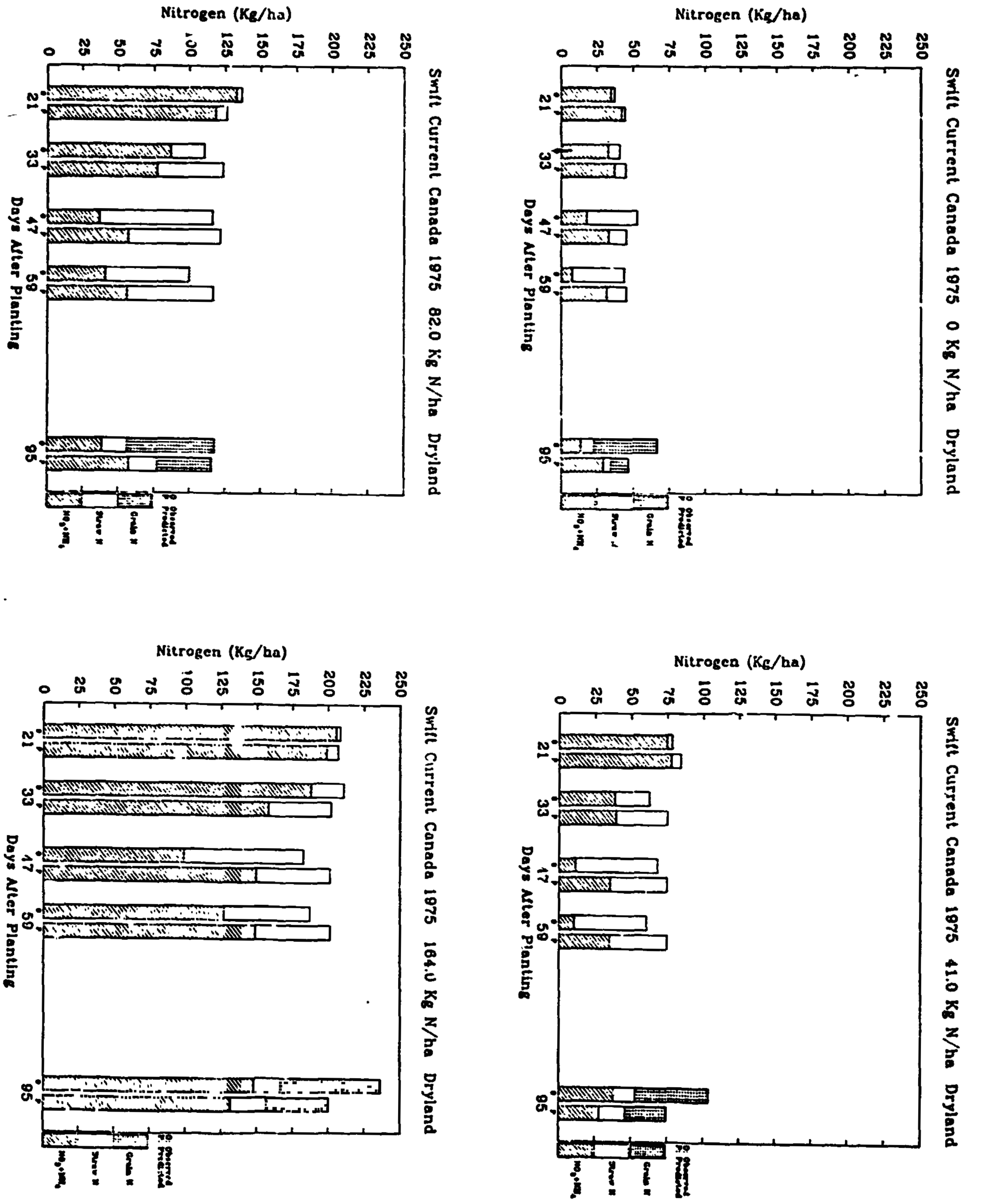


Figure B.7. Comparison of predicted and observed patterns in :easonal N balance for individual data sets.



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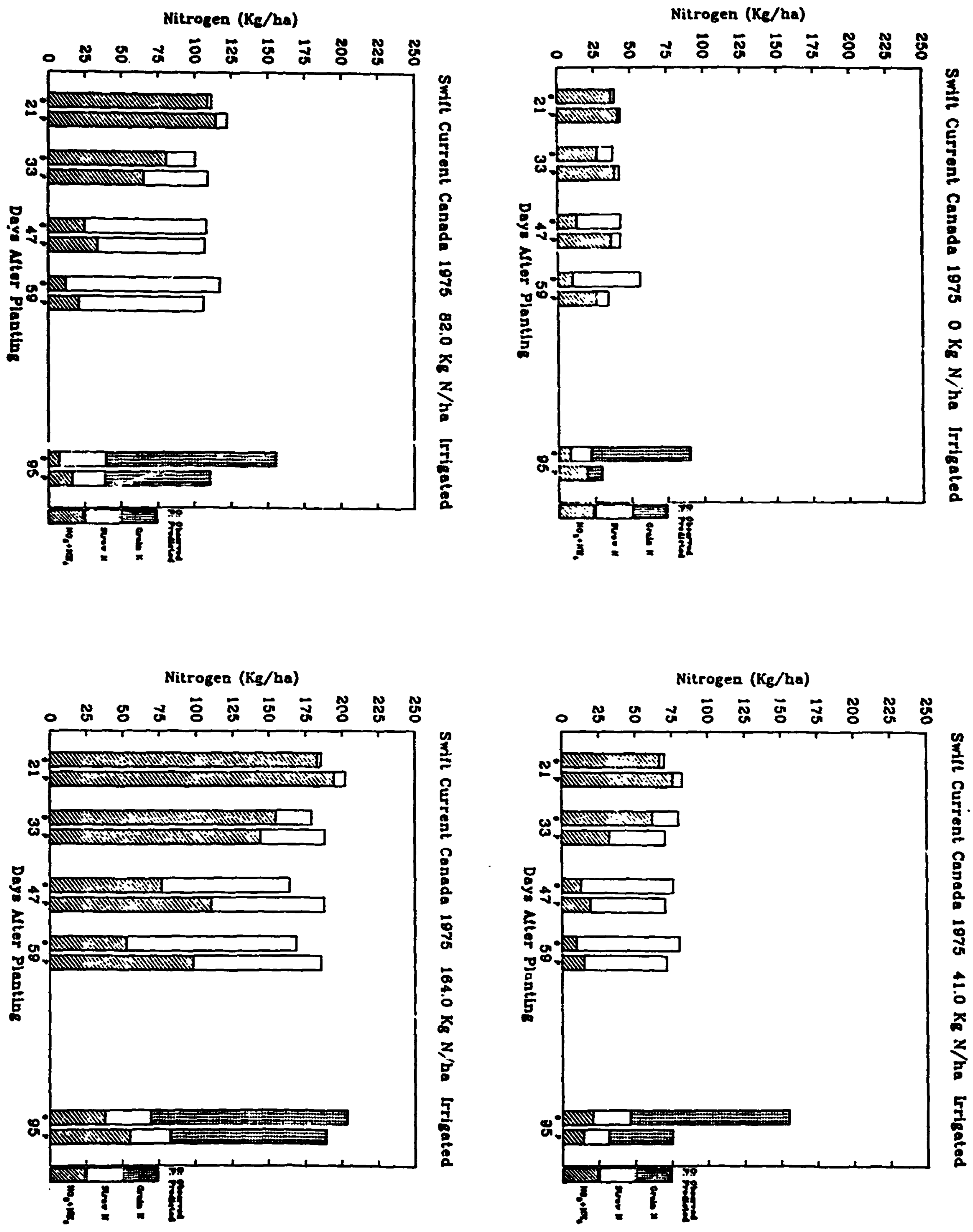

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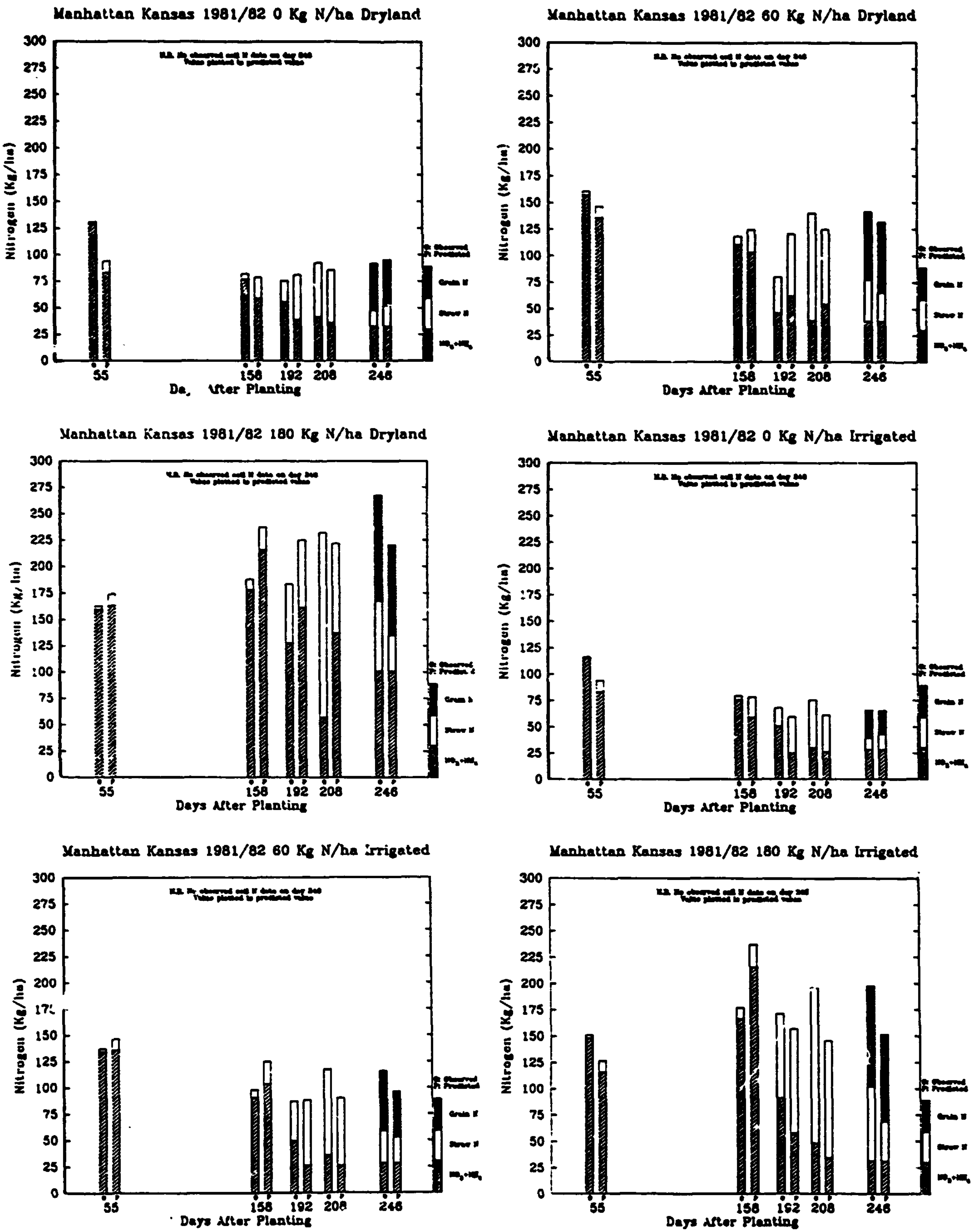
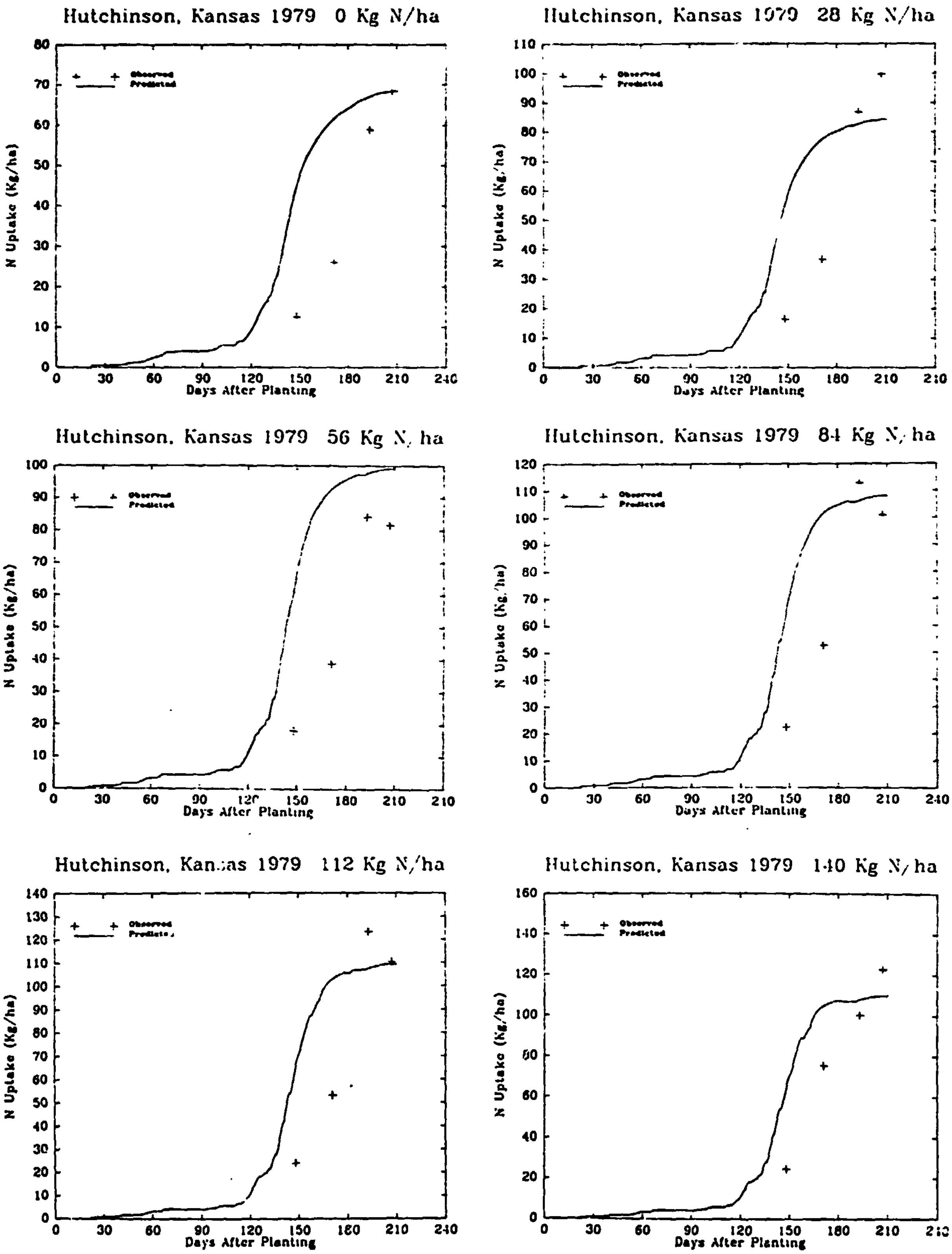


Figure B.8. Comparison of predicted and observed seasonal pattern of N uptake for individual data sets.



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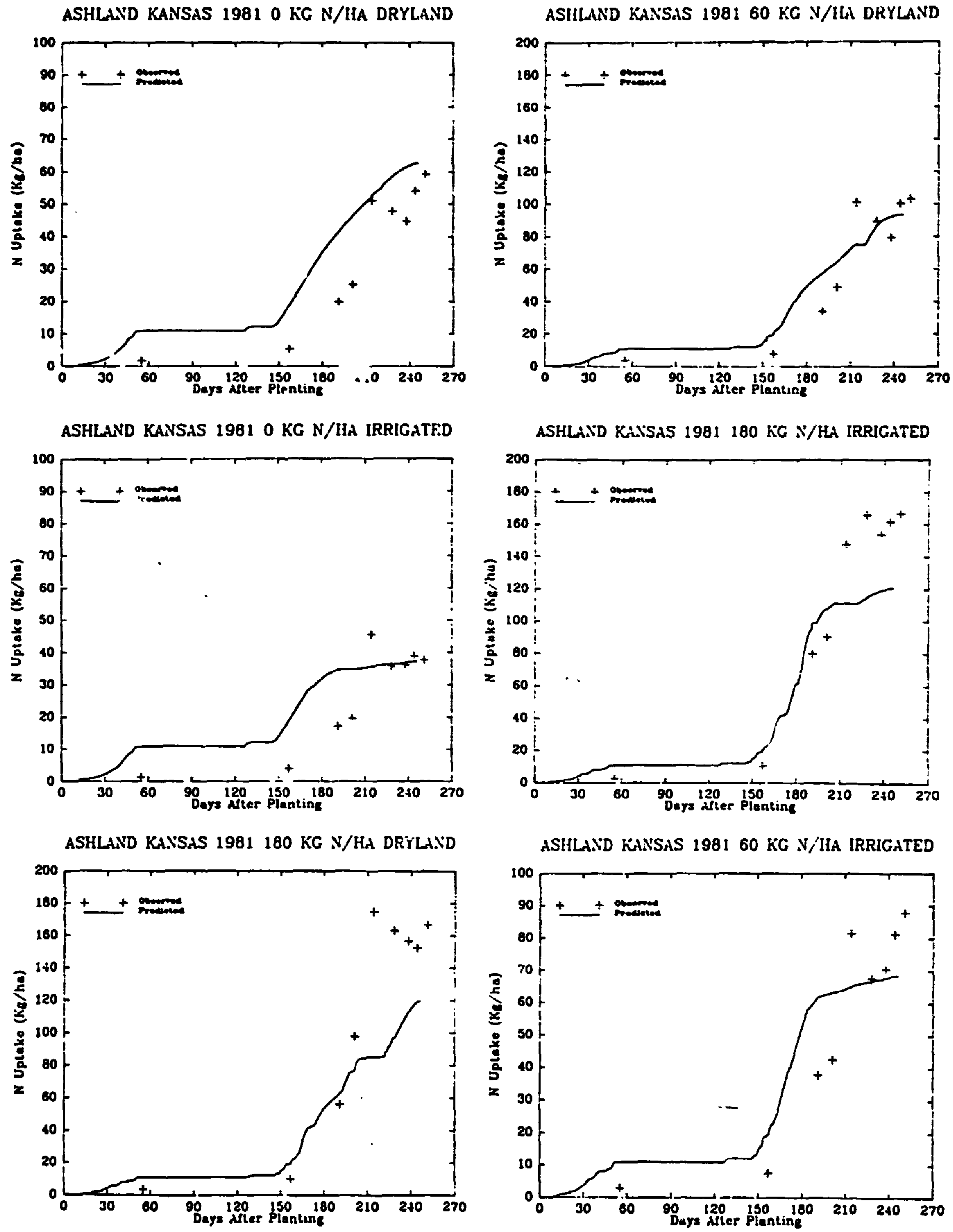

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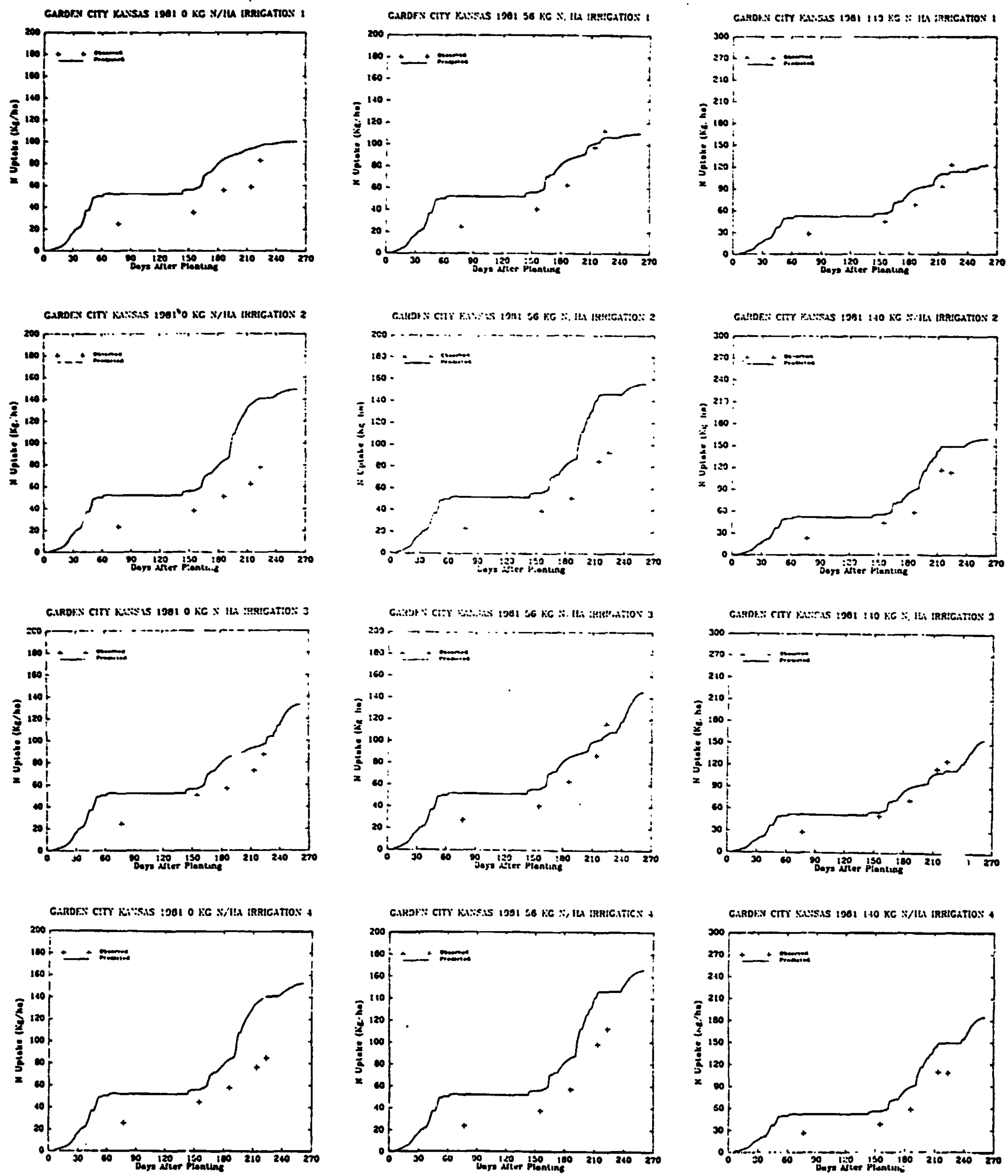
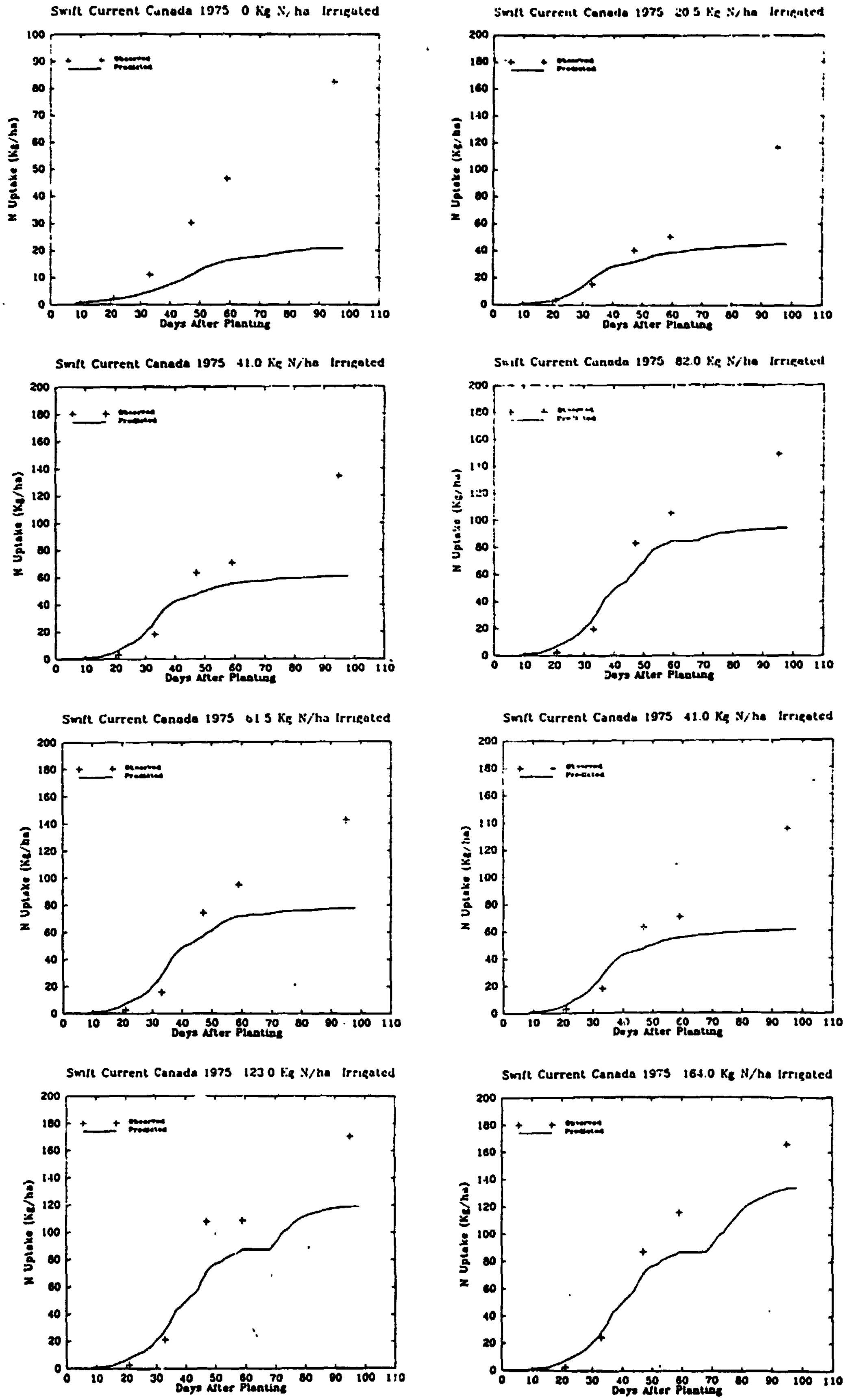


Figure B.8. Continued.



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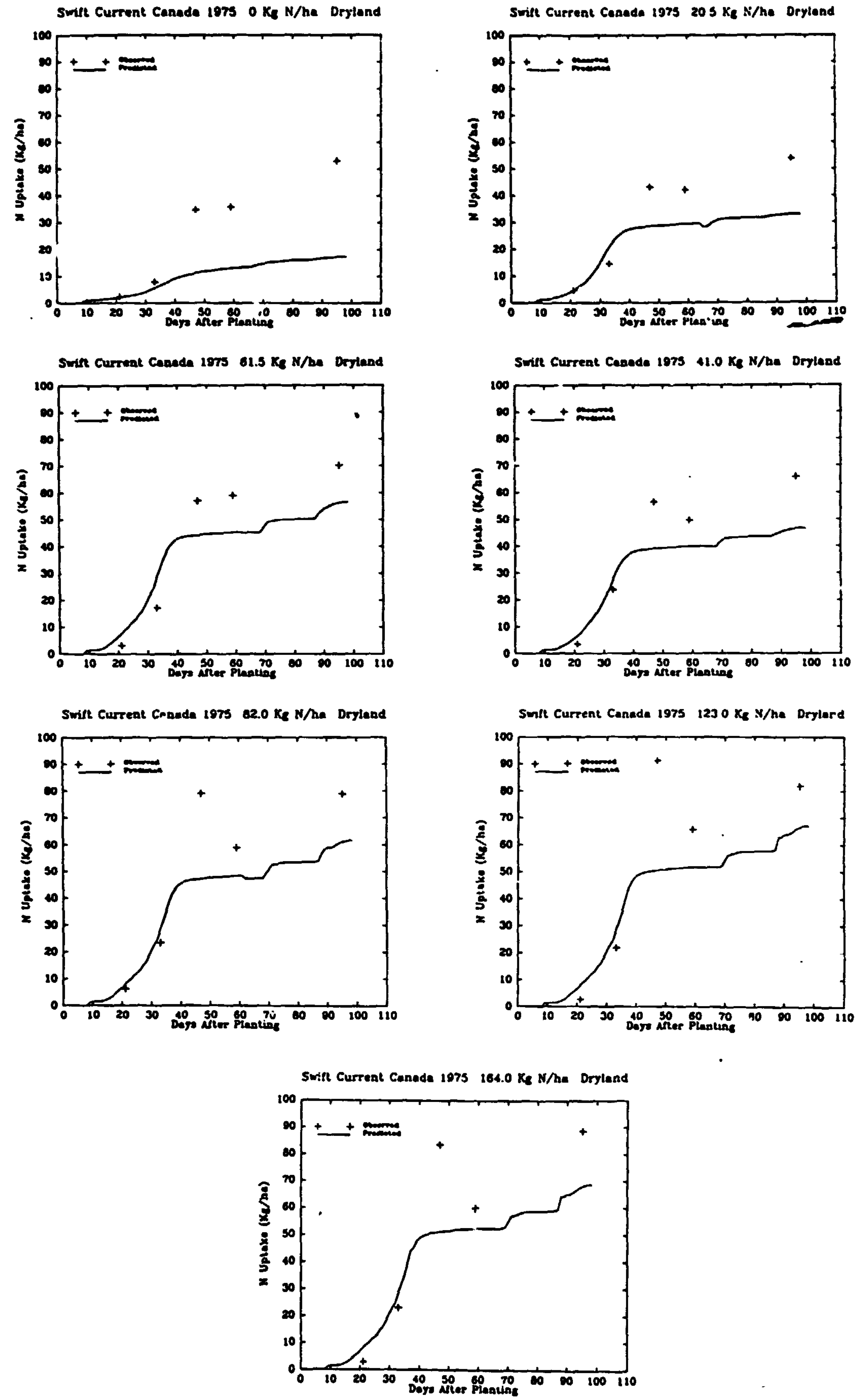

BIBILIOGRAPHY

Aase, J.K. 1978. Relationship between leaf area and dry matter in winter wheat. Agron. J. 70:563-565.

Baker, C.K. 1979. The environmental control of development in winter wheat. Ph.D. Thesis, University of Nottingham, England.

Bauer, A. 1980. Responses of tall and semidwarf hard red spring wheats to fertilizer N rates and water supply in North Dakota 1969-74. North Dakota Agr. Exp. Station Bull. 510, Fargo, ND.

Black, A.L., and J.K. Aase. 1982. Yield comparisons between USA and USSR winter wheat cultivars. Agron. J. 74:436-441.

Brooking, I.R., and E.J.M. Kirby. 1981. Interrelationships between stem and ear development in winter wheat: the effects of a Norin 10 dwarfing gene, Gai/Rht_2. J. Agr. Sci. Camb. 97:373-381.

Campbell, C.A., H.R. Davidson, and F.G. Warder. 1977a. Effects of fertilizer N and soil moisture on yield, yield components, protein content and N accumulation on the above-ground parts of spring wheat. Can. J. Soil Sci. 57:311-327.

Campbell, C.A., D.R. Cameron, W. Nicholaichuk, and H.R. Davidson. 1977b. Effects of fertilizer N and soil moisture on growth, N content, and moisture used by spring wheat. Can. J. Soil Sci. 57:289-310.

Corre, M.N., and R. Delecolle. 1983. Relationships between climatic factors and early wheat development. Report No. M/8314. INRA Avignon, France.

Darwinkel, A. 1978. Patterns of tillering and grain production of winter wheat at a wide range of plant densities. Neth. J. Agr. Sci. 26:383-398.

Dent, J.B., and M.J. Blackie. 1979. Systems simulation in agriculture. Applied Science Publishers, London.

Ellen, J., and J.H.J. Spiertz. 1980. Effects of rate and timing of nitrogen dressings on grain yield formation of winter wheat. Fertilizer Res. 1:177-190.

Freese, F. 1960. Testing accuracy. Forest Sci. 6:139-145.

Gallagher, J.N., P.V. Biscoe, and B. Hunter. 1976. Effects of drought on grain growth. Nature 264:541-542.

Hochman, Z. 1979. Wheat in semi-arid environments: a field and simulation study of the effects of water stress on yield. M.S. Thesis, University of Sidney, N.S.W., Australia.

Johnson, R.C. 1978. Apparent photosynthesis and evapotranspiration of winter wheat in a field environment. M.S. Thesis, Washington State University, Pullman, WA.

Jones, C.A. and J.R. Kiniry. 1986. eds. Ceres-Maize, A simulation model of maize growth and development. Texas A&M University Press, College Station, TX.

Klepper, B., T.W. Tucker, and B.D. Dunbar. 1983. A numerical index to assess early inflorescence development in wheat. Crop Sci. 23:206-208.

Kornher, A., and B.W.R. Torsell. 1983. Estimation of parameters in a yield prediction model for temporary grassland using regional experimental data. Swed. J. Agr. Res. 13:127-144.

Mason, M.G., and A.M. Rowley. 1969. The fate of anhydrous ammonia and urea applied to a wheat crop on a loamy sand in the wheat belt of Western Australia. Aust. J. Exp. Agric. Anim. Husb. 9:630.

Mason, M.G., A.M. Rowley, and D.J. Qualye. 1972. The fate of urea applied at various intervals after the sowing of a wheat crop on a sandy soil in Western Australia, Aust. J. Exp. Agric. Anim. Husb. 12:171.

McMahon, T.A. (ed.). 1983. A general wheat crop model for Australia. Agr. Eng. Report No. 67/83. University of Melbourne, Australia.

Meyer, W.S. 1978. Wheat experiment 1978. Pretoria, RSA.

Monk, R.L., G.F. Arkin, S.J. Maas, and J.T. Ritchie. 1979. Environmental effects on the phenological and morphological development of wheat. Unpublished data.

Musick, J.T., and D.A. Dusek. 1978. Development and yield of irrigated winter wheat in relation to planting date and water deficit in the southern high plains. Manuscript.

Paltridge, G.W., A.C. Dilley, J.R. Garratt, G.I. Pearman, W. Shepherd, and D.J. Connor. 1972. The Rutherglen experiment on Sherpa wheat: Environmental and biological data. Div. of Atmospheric Physics Tech. Paper No. 22. CSIRO, Australia.

Pearman, I., S.M. Thomas, and G.N. Thorne. 1978. Effect of nitrogen fertilizer on growth and yield of semi-dwarf and tall varieties of winter wheat. J. Agr. Sci. Camb. 91:31-43.

Reynolds, Jr., M.R. 1984. Estimating the error in model predictions. Forest Sci. 30:454-469.

Ritchie, J. T. and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat yield model. USDA-ARS. ARS-38. pp. 159-175.

SAS Institute, Inc. 1982. SAS user's guide: Basics. Cary, North Carolina 27511-8000.

Sojka, R.E. 1974. Comparative drought response of selected wheat varieties. Ph.D. Thesis, University of California, Riverside, CA.

Spiertz, J.H.J., and J. Ellen. 1978. Effects of nitrogen on crop development and grain growth of winter wheat in relation to assimilation and utilization of assimilates and nutrients. Neth. J. Agr. Sci. 26:210-231.

Spiertz, J.H.J., and H. van de Haar. 1978. Differences in grain growth, crop photosynthesis and distribution of assimilates between a semi-dwarf and a standard cultivar of winter wheat. Neth. J. Agr. Sci. 26:233-249.

Stapper, M. 1984. Simulations assessing the productivity of wheat maturity types in a Mediterranean climate. Unpublished Ph.D. Thesis, University of New England, Armidale, Australia.

Storrier, R.R. 1965. Excess soil nitrogen and the yield and uptake of nitrogen by wheat in southern New South Wales. Aust. J. Exp. Agric. Anim. Husb. 5:317.

Thill, D.C. 1976. Physiological and environmental effects of yield potential in early- and late-planted winter wheat. M.S. Thesis, Washington State University, Pullman, WA.

Wagger, M.G. 1983. Nitrogen cycling in the plant-soil system. Ph.D. Thesis, Kansas State University, Manhattan, KS.

Watson, D.J., G.N. Thorne, and S.A.W. French. 1963. Analysis of growth and yield of winter and spring wheats. Ann. Bot. 27:1-22.

Willmott, C.J. 1982. Some comments on the evaluation of model performance. Bull. Amer. Met. Soc. 63 (11): 1309-1313.

Wilson, W.W., and J.L. Sebaugh. 1981. Established criteria and selected methods for evaluating crop yield models in the AgRISTARS program. Proc. Am. Stat. Ass., Section on Survey Research Methods, 24-31.