A COMPARISON OF THREE SEQUENTIAL SAMPLING SYSTEMS FOR COTTON FLEAHOPPER (*Pseudatomoscelus seriatus* Reuter)

By

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Thesis Approved:

Thesis Adviser

Dean of the Graduate College

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ABREVIATIONS USED

ASN	Average Sample Number
ET	Economic Threshold
IPM	Integrated Pest Management
NBD	Negative Binomial Distribution
SZ	Safety Zone
SPRT	Sequential Probability Ratio Test
2-SPRT	Two simultaneously conducted one sided SPRT's
LI	Lower intercept for the boundary of a 2-SPRT
UP	Upper intercept for the boundary of a 2-SPRT
LS	Lower slope for the boundary of a 2-SPRT
US	Upper slope for the boundary of a 2-SPRT
XBAR	Density
LSD	Least Squares Difference

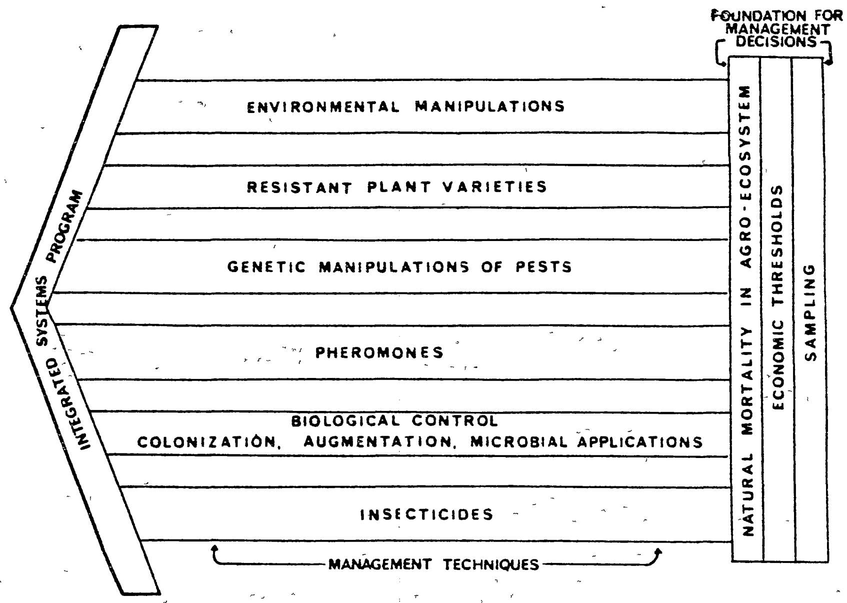
CHAPTER I

INTRODUCTION

Sequential Sampling has been a subject of tremendous interest in the scientific community for the past 20 years. As it is normally difficult to count invertebrates in a habitat, an efficient sampling system to estimate the population is desirable (Southwood, 1987). Sampling procedure, according to Gonzalez (1970), is the foundation for management decisions in an integrated systems program (Fig. 1). Since the sequential analysis was developed in 1943 (Wald, 1943), the study and application of sequential analysis to biological problems has increased year by year.

In the early 1950's the first publications about biological applications of sampling were written by forest entomologists, Stark (1952), Ives (1954), Morris (1954), and Waters (1955). LeRoux and Reimer (1959) reported sampling recommendations for immature stages of apple pests. The first uses of sequential sampling in agricultural entomology were published by Sylvester and Cox (1961), Wolfenbarger and Darroch (1965), and Harcourt (1966, 1967). However, most of the information about insect sampling appeared after Gonzalez (1970). Recent publications include those by

Figure 1. A Schematic Diagram Depicting Development of a Pest Management Program Analagous to Building a House. (Gonzalez, 1971)


FOUNDATION FOR MANAGEMENT DECISIONS
INTEGRATED SYSTEMS PROGRAM
ENVIRONMENTAL MANIPULATIONS
RESISTANT PLANT VARIETIES
GENETIC MANIPULATIONS OF PESTS
PHEROMONES
BIOLOGICAL CONTROL
COLONIZATION, AUGMENTATION, MICROBIAL APPLICATIONS
INSECTICIDES
MANAGEMENT TECHNIQUES
NATURAL MORTALITY IN AGRO-ECOSYSTEM
ECONOMIC THRESHOLDS
SAMPLING

Sevacherian and Stern (1972), who studied sequential sampling plans for determining the need for chemical control for Lygus hesperus Knight and L. elisus Van Duzee in cotton; Pieters and Sterling (1974), who presented a sequential sampling plan based upon the negative binomial distribution of the cotton fleahopper, Pseudatomoscelis seriatus Reuter; Waddill et al. (1974), who studied a sequential sampling plan for Nabis spp. and Geocoris spp. on soybeans; and Hammond and Pedigo (1976), who, also working with soybeans, developed sequential sampling plans for larvae of Plathypena scabra F. Other important research about sequential sampling is described by Luna et al. (1983), Zehnder and Trumble (1985), and Sparks and Boethel (1987).

Hammond and Pedigo (1976) state that despite the large amount of knowledge in this area, farmers continue to apply unnecessary pesticides to control pests. Even with the use of sequential sampling techniques for pest species, a pest management scout may desire additional information before making a decision, particularly when treatment is only narrowly justified (Waddill et al., 1974).

For Integrated Pest Management (IPM), which has dominated the practice of agriculture pest control in the last few years, it is desirable to have an accurate methodology for sampling (Young et al. 1976). In addition, management of insect pests of crops through biological and integrated control methods requires a working knowledge of the complex interaction between population of pests and beneficial insects, their hosts, and the environment (Smith et al., 1976). For these reasons, there is still a need for a sampling procedure that is inexpensive, and practical for the farmer (Hammond and Pedigo, 1976).

Calculation of the sampling plans for the sequential procedures is time-consuming when performed manually. Initially, this was a disadvantage of sequential sampling procedures. However, with the increased use and availability of PCs, computer programs written to generate sampling plans for sequential procedures have significantly reduced the time required to conduct the sequential procedures.

Sequential sampling plans are important in the implementation of IPM programs. These plans save much time for the scout. Studies have shown that the use of sequential sampling plans have resulted in significant time saving over the fixed sample procedures. Waters (1955) reports that sequential sampling may reduce sampling time by more than 50%. A time saving of 76% over conventional sampling technique was obtained by Sterling (1975) and Rothroch et al. (1982) for cotton arthropods. According to Young et al. (1977) sequential sampling is the fastest and most reliable method of making decision ('treat-nontreat`) in insect scouting.

Among the sequential sampling plans, there are differences in time saving. The Sequential Probability Ratio Test (SPRT) (Wald, 1943) and Willson's Sequential Sampling (Young and Willson, 1989) are widely used among researchers and producers. In this study, these plans and the 2-SPRT (Lorden, 1976) are used. They are based on the negative binomial distribution and show desirable characteristics which should be considered by researchers, scouts and farmers.

On certain occasions, the SPRT sampling method has some difficulties in its application, such as the tendency for the sample size to become too large when the mean is between the hypothesized values. However, recent studies done by Lorden (1976) show that this problem can be avoided by using the 2-SPRT. Young and Young (1989) support Lorden's conclusions and suggest using 2-SPRT as an alternative to Wald's SPRT. The 2-SPRT is based on two one-sided SPRT's.

Another improvement on sequential sampling techniques has been made in recent years. The Willson's Sequential Sampling Plan (Young and Willson, 1989) is a sequential sampling technique which is used to estimate the number of insects, plants, or fruits on cotton. This system allows the user to choose different risk factors, which is the percent of CV controlled. An additional advantage of this method is that the sampling plans are easy to generate.

The objectives of this study are to:

1. Compare the performance(*) of 2-SPRT Sequential Sampling with Wald's Sequential Sampling Techniques;

2. Compare the performance(*) of 2-SPRT Sequential Sampling with Willson's Sequential Sampling Plan;

3. Validate the sampling plans with computer simulation.

(*) Performance with respect to time required to reach decision.

CHAPTER II

LITERATURE REVIEW

Wald's Sequential Sampling: Sequential Probability Ratio Test

To test statistical hypotheses Wald (1943) developed a sequential procedure called the sequential probability ratio test (SPRT). As one of the most accurate methods avaiable, Wald's SPRT, known among entomologists simply as sequential sampling, is an important and practical tool in agriculture, but it was only after Oakland's publication about whitefish sampling that researchers in the biological sciences started to use this system. Fifteen years after Wald's publication, Jackson (1960) prepared a bibliography with 374 references dealing with the subject of sequential analysis. Since 1943, the use of SPRT has become common among entomologists. Fowler and Lynch (1987) related 65 references about the development of sequential sampling plans in insect pest management (IPM) based on Wald's SPRT, of which 25 are related to forest entomology and 40 to agriculture entomology. Included in this publication are studies by Stark (1952) who elaborated the method for sampling lodgepole needleminer, Recurvaria milleri Bush and by Waters

(1955) who used sequential sampling for forest insect surveys.

Many researchers have developed sequential sampling plans for cotton insects around the world. These include plans from Allen et al. (1972), Sevacherian and Stern (1972), Sterling and Pieters (1973, 1974, 1975), Sterling (1975), and Young et al. (1977a, 1977b), in the United States; Sterling (1976), in Australia; and Sterling et al. (1983), in Brazil. Pieters et al. (1974) gives a specific definition of sequential sampling in relation to cotton as "a technique which permits the cotton scout to make rapid decisions about the level of pest infestations with predetermined accuracy" (p. 102). According to Waters (1955), Wald's sequential sampling method may reduce sampling time by more than 50%. A great time saving of 76% over conventional sampling techniques was obtained by Sterling (1975) and Rothrock et al. (1982) when sequential sampling plans were used for cotton arthropods. This great saving of time in pest management decision is obtained when pest populations are very large or very small (Sterling, 1975).

<u>Wald's Hypotheses</u>

Wald's Hypothesis for Sequential Sampling involves the testing of two hypotheses:

Ho: the population is above an economic threshold (ET) level;

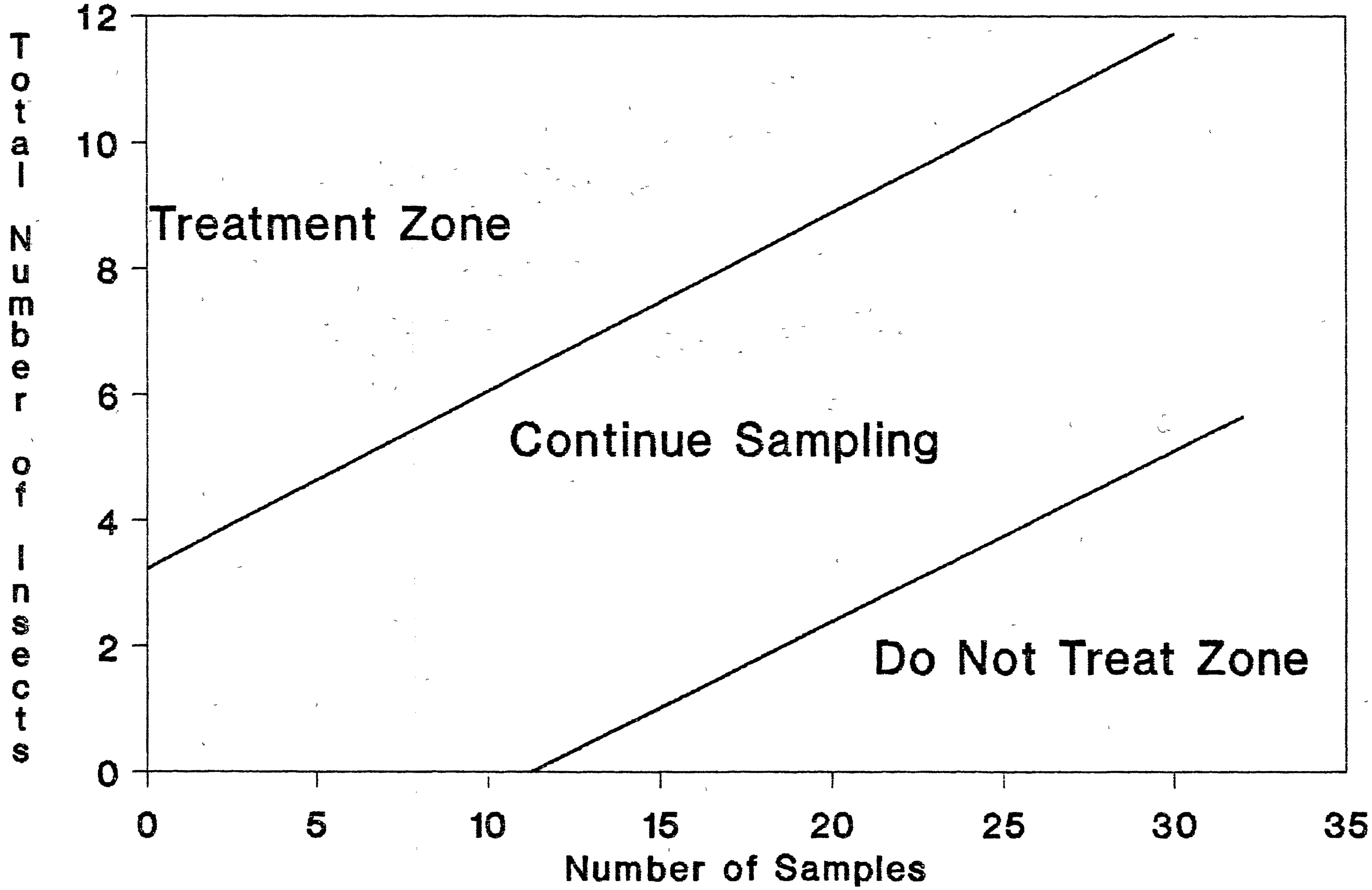
H1: the population is below a safety zone (SZ) level.

Every sequential sampling plan is defined by pairs of parallel lines (Fig. 2), in which three zones are produced: (1) treatment zone, which recommends action control; (2) no treatment zone, which means no control; and (3) indecision zone, which suggests sampling be continued.

The general formulae for construction of parallel lines is: Y = a + b (x), where Y = the accumulated number of organisms; a = the Y - intercept; b = the slope; and x = the sample number.

Figure 2. Decision Boundaries for Wald's SPRT.

Wald's SPRT


Treatment Zone
Continue Sampling
Do Not Treat Zone
Total Number of Insects
Number of Samples
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35

To construct a Wald's Sequential Sampling Plan, it is necessary to know the follow prerequisites:

1. Distribution. The first step for designing a sequential plan is to know the nature of the distribution of pests because it determines the equations which will be used in the subsequent steps. The negative binomial distribution (NBD) has been shown to be the most common distribution found in insect control studies (Anscombe, 1979; Harcourt, 1960, 1963; Taylor, 1984; Willson et al., 1984; Young and Willson, 1986). The NBD is also called "clumped" or "contagious" (Southwood, 1978), and its pattern can be well visualized in Figure 3. The NBD has two parameters. These parameters, described in terms of insects counts, are:

   1.1 - The mean $(\bar{X})$ - population density, which is the average number of insects per sample, described as:

$$\bar{X} = \frac{\Sigma x_i}{N} \quad (1),$$

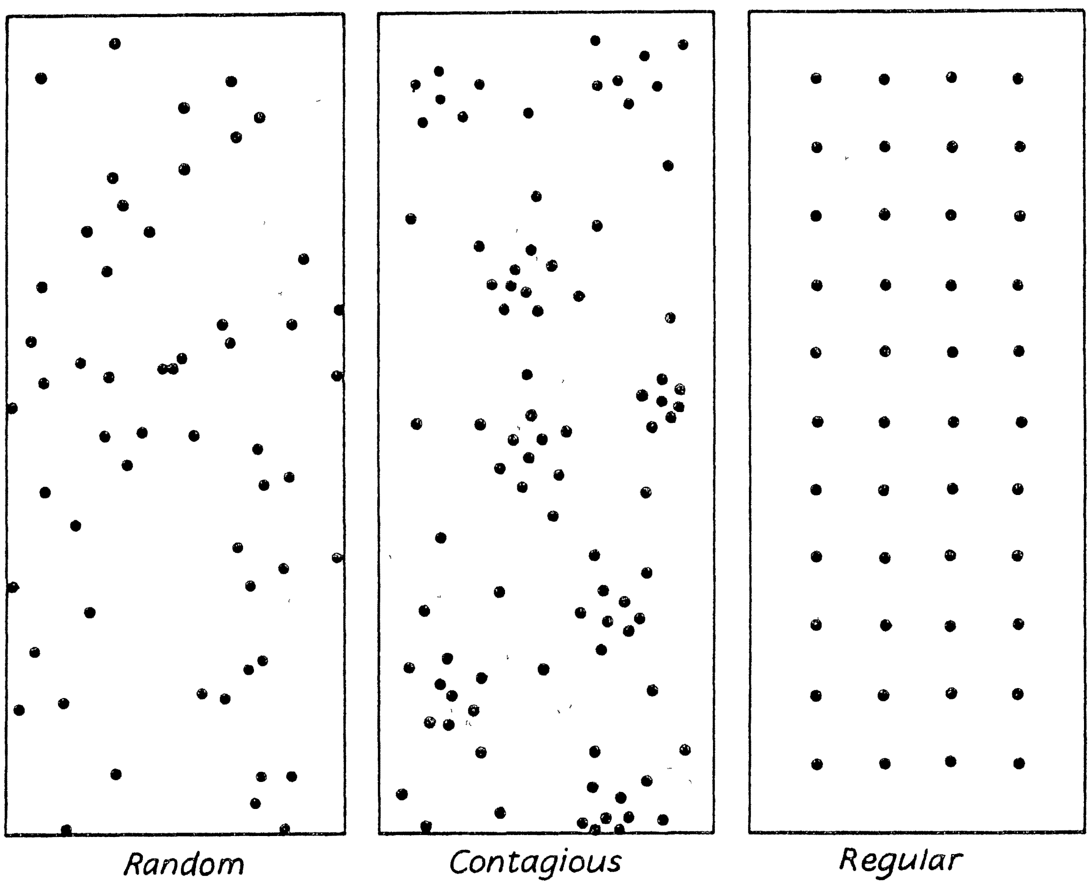
where x_i is the number of insects in sample unit i and N is the number of sample units, and

   1.2 - The index of aggregation (k) - which reflects the degree to which the insects are spatially clumped; k is estimated by method of moments as:

$$k = \frac{\bar{X}^2}{S^2 - \bar{X}}$$

(2) , where the variance (S^2) is larger than the mean ($\bar{X}$): $S^2 > \bar{X}$.

Figure 3. Different Types of Distributions. (Southwood, 1978)


Random
Contagious
Regular

2. <u>Economic Threshold.</u> The Economic Threshold (ET or mu2) is the pest density or injury level at which it is necessary to start control procedures in order to avoid economic loss. Stern (1966) defined ET as "... the pest population density at which control measures should be determined to prevent an increasing population from reaching the economic injury level". In other words, ET is the pest density treatment level. In pest management programs, reliable ET estimates permit greater utilization of the "field insectory" (predators and parasites found in abundance in a crop), which means fewer insecticide treatments (Gonzalez, 1970).

3. <u>Safety Zone.</u> The Safety Zone (SZ or mu1) is the pest density that will insure that economic damage will not occur.

4. <u>Risk Factors.</u> There are two types of errors involved in sequential sampling. There is the risk Type I error (alpha) of rejecting a null hypothesis when it is true, for example, when insecticide is applied when it should not have been; and the risk Type II error (beta) of accepting the null hypothesis when it is not true, as for instance, when "a decision for spraying" is not taken when it should have been. Often these factors, alpha and beta, are set at the same level

(Young and Willson, 1986). Either one should be used with high levels of reliablility. Table I shows the slope and intercept equations for the Wald's SPRT decision boundaries for the negative binomial distribution.

TABLE I

SLOPES AND INTERCEPTS FOR WALD'S SPRT DECISION BOUNDARIES FOR THE NEGATIVE BINOMIAL DISTRIBUTION

LI	UI	S
$\dfrac{b}{\ln \left[\dfrac{P1Q0}{P0Q1}\right]}$	$\dfrac{a}{\ln \left[\dfrac{P1Q0}{P0Q1}\right]}$	$k \dfrac{\ln \left[\dfrac{Q1}{Q0}\right]}{\ln \left[\dfrac{P1Q0}{P0Q1}\right]}$

Where:

LI = Lower Intercept
UI = Upper Intercept
S = Slope
a = log [(1-beta)/alpha]
b = log [beta/(1-alpha)]
P1 = mu1/k
P0 = mu0/k
Q1 = 1 + P1
Q0 = 1 + P0
k = Parameter k
ln = Natural Logarithim

Lorden's 2-SPRT

The 2-SPRT presented by Lorden (1976, 1980) was proposed to solve some difficulties found in the application of the SPRT, such as the tendency of the sample size to become too large when the population density is between mu1 and mu0 and the unbounded number of observations (Nagardeolekar, 1982). The 2-SPRT is based on two one-sided SPRT's. The 2-SPRT has convergent decision boundaries. Figure 4 shows the decision boundaries for Lorden's 2-SPRT. Table II shows the slopes and intercepts for Lorden's 2-SPRT decision boundaries for the negative binomial distribution.

Willson's Sequential Sampling Plan

The Willson's Sequential Sampling Plan (Willson and Young, 1983) is used to estimate the density of insects, plants or fruits on cotton. This sampling plan allows the user to use 4 risk factors: 10, 15, 20 or 25 per cent (Young and Willson, 1989). The risk factor (C) is defined as 1 - % of CV control. Table III shows the equations for contructing the Willson's Sequential Sampling Plan for a negative binomial distribution.

Figure 4. Decision Boundaries for Lorden's 2-SPRT.

Lorden's 2-SPRT

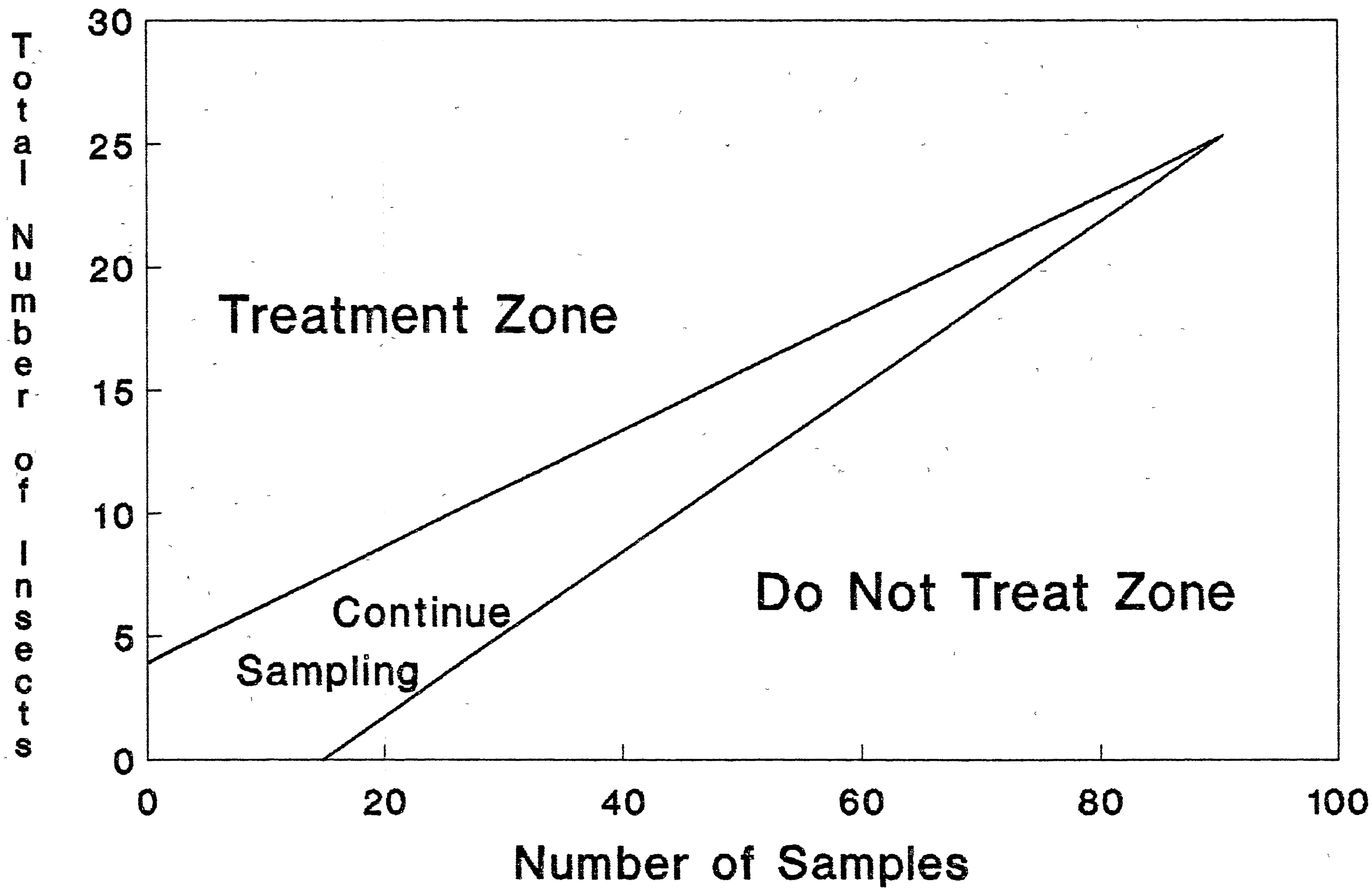


TABLE II

SLOPES AND INTERCEPTS FOR LORDENS'S 2-SPRT DECISION BOUNDARIES FOR THE NEGATIVE BINOMIAL DISTRIBUTION

LI	UI	LS	US
$\frac{\log(A)}{\log(q1/q0)}$	$\frac{\log(1/B)}{\log(qo/q2)}$	$\frac{k \log(p0/p1)}{\log(q1/q0)}$	$\frac{k \log(p2/p0)}{\log(q0/q2)}$

Where:

LI : Lower intercept

UI : Upper intercept

LS : Lower slope

US : Upper slope

k : Parameter of the NDB

p0 : k/(mu0 + k)

p1 : k/(mu1 + k)

q0 : 1 - p0

q1 : 1 - p1

A and B : Constants used to achive desired type I and type II error computed in program developed by Lim (1989)

TABLE III

EQUATIONS FOR CONSTRUCTING THE WILLSON'S SEQUENTIAL SAMPLING PLAN FOR A NEGATIVE BINOMIAL DISTRIBUTION

GENERAL EQUATION	MSN	C
$\text{Sum } x \geq = \dfrac{kn}{C^2(kn + 1) - 1}$	$\dfrac{1}{C^2 K} - \dfrac{1}{K} + 1$	$\sqrt{\dfrac{\left(\dfrac{Kn + 1}{\text{Sum } x}\right)}{Kn + 1}}$

Where:

k = k Parameter of the NBD

C = 1 - Percent of CV Control

n = Sample Number

Sum x = Accumulated Number of Insects Observed

MSN = Minimum Sample Number

CHAPTER III

MATERIALS AND METHODS

This study consists of two components. The first involves the performance of field trials. Field trials were conducted to compare times required for the 3 sampling methods. In addition computer simulations were performed to validate the sampling plans.

Field Trials

During the summer of 1989, cotton (Gossypium hirsutum L.) terminals were sampled for cotton fleahopper (Pseudatomoscelis seriatus Reuter) (Hemiptera:Miridae) in Agricultural Experiment Stations fields at Perkins, Chickasha, Oklahoma State University, and in producers' fields near Purcell and Maysville, Oklahoma (See Fig. 5).

Sampling started on July 17, three weeks after cotton planting. The fields were sampled at least once a week. Sampling was not conducted under rainy or windy conditions. Table IV shows the sampling schedule for this experiment. The model of walking for sampling fleahoppers suggested by EMBRAPA (1985) was used. This model is shown in Fig. 6.

Figure 5. Locations in the State of Oklahoma (USA) Where Sampling Procedures on Cotton (*Gossypium hirsutum* L.) Were Performed.

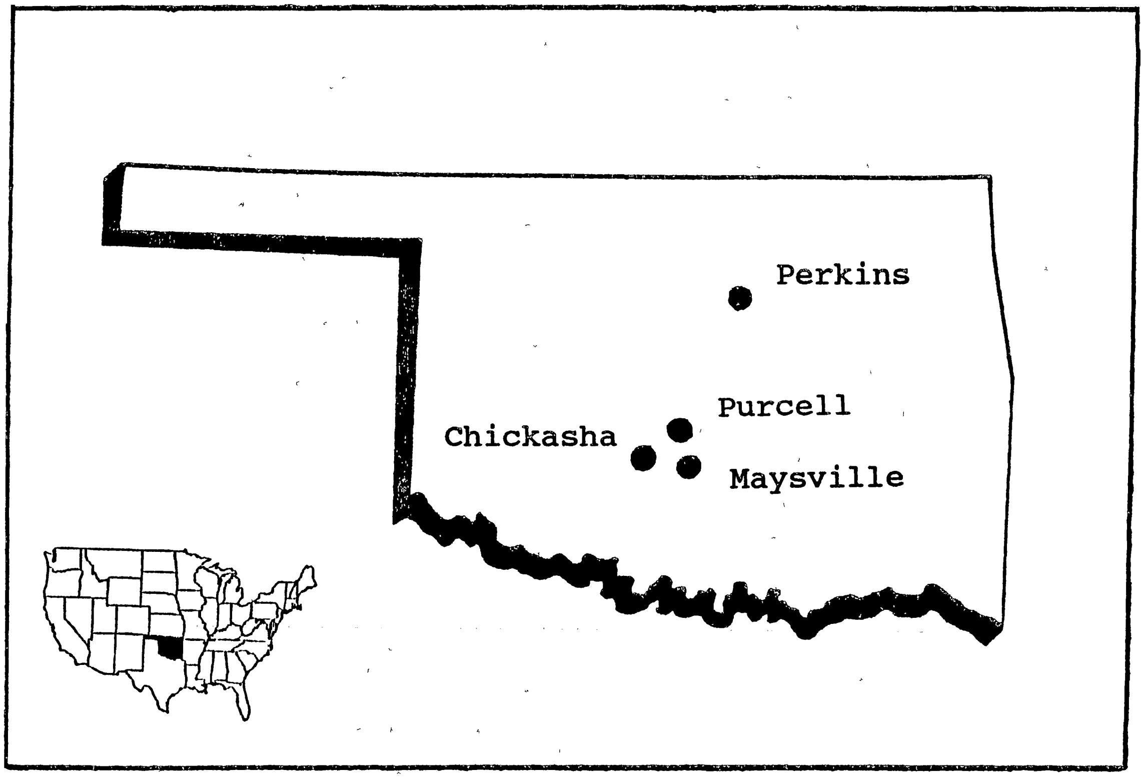
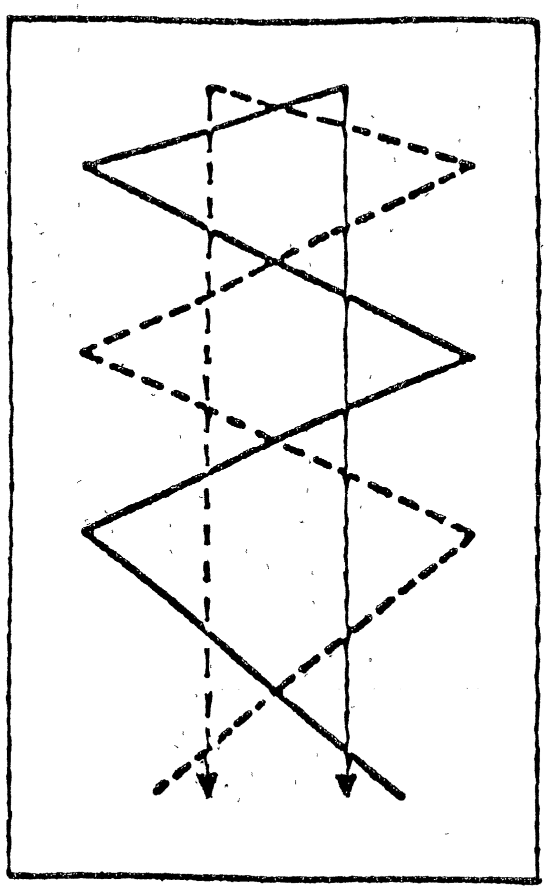

Perkins
Purcell
Chickasha
Maysville

TABLE IV

SAMPLING SCHEDULE FOR COTTON FLEAHOPPER
IN OKLAHOMA, 1989

SAMPLING DATE	NO. FIELDS SAMPLED	LOCATIONS (Number of Fields)
07/17	3	Maysville (1), Purcell (2)
07/24	6	Chickasha (4), Purcell (2)
07/28	4	Chickasha (4)
07/31	6	Chickasha (4), Purcell (2)
08/07	4	Chickasha (4)
08/16	1	Perkins (1)
08/18	3	Chickasha (1), Purcell (2)
08/23	4	Perkins (4)
08/31	4	Perkins (4)
TOTAL	35	4

Figure 6. Model of Walking for Sampling in Cotton Field. (EMBRAPA, 1985)



Preliminary estimates of the fields were determined by the method of Willson and Young (1983). This method utilizes CV Control. Eighty-five percent of the variation was controlled. The SPRT, 2-SPRT and Willson's Sequential Sampling methods were used to sample each field. The length of time until a decision was reached was recorded. Time was measured with a chronometer (Cronus Precision Products Inc., Santa Clara, CA) for the three sampling methods.

Sampling plans were generated using computer programs developed by Seebeck (1989) for SPRT, Lim (1989) for 2-SPRT, and Young and Willson (1989) for Wilson's Sequential Sampling.

Generation of Sampling Plans

Computer programs, written in Quick Basic® by Microsoft, were used for the generation of sampling plans for the three sampling procedures. These programs are described below.

SPRT. The computer program used to generate a sampling plan based on Wald's Sequential Probability Ratio Test was written by Seebeck (1989). For the negative binomial distribution, the user must supply the following information:

1. The null hypotheses (Economic Threshold)
2. The alternative hypotheses (Safety Zone)

3. Type I error rate (alpha)
4. Type II error rate (beta)
5. The k value

The Economic Threshold used was 0.4 (mu2), the Safety Zone = 0.2 (mu1), the risks alpha = beta = 0.15, and the parameter k = 1.

After receiving this information, a computer printout of the SPRT sampling plan was given as shown in TABLE V.

<u>2-SPRT.</u> The computer program used to generate a sampling plan based on Lorden's 2-SPRT was written by Lim (1989). For the negative binomial distribution, the user must supply the following information:

1. The null hypotheses (Economic Threshold)
2. The alternative hypotheses (Safety Zone)
3. Type I error rate (alpha)
4. Type II error rate (beta)
5. The k value

The same values used for the SPRT were given to this program. After receiving this information, a computer printout of the 2-SPRT sampling plan was given as show in TABLE VI.

TABLE V

A COMPUTER PRINTOUT OF THE SPRT DATA SHEET FOR A NEGATIVE BINOMIAL DISTRIBUTION OF COTTON FLEAHOPPER WHEN SZ = 0.2, ET = 0.4, AND ALPHA = BETA = 0.15

1	0	------	3	51	11	------	17
2	0	------	3	52	11	------	18
3	0	------	4	53	11	------	18
4	0	------	4	54	12	------	18
5	0	------	4	55	12	------	18
6	0	------	4	56	12	------	19
7	0	------	5	57	13	------	19
8	0	------	5	58	13	------	19
9	0	------	5	59	13	------	20
10	0	------	6	60	13	------	20
11	0	------	6	61	14	------	20
12	0	------	6	62	14	------	20
13	0	------	6	63	14	------	21
14	0	------	7	64	15	------	21
15	1	------	7	65	15	------	21
16	1	------	7	66	15	------	22
17	1	------	8	67	15	------	22
18	1	------	8	68	16	------	22
19	2	------	8	69	16	------	22
20	2	------	8	70	16	------	23
21	2	------	9	71	17	------	23
22	3	------	9	72	17	------	23
23	3	------	9	73	17	------	24
24	3	------	10	74	17	------	24
25	3	------	10	75	18	------	24
26	4	------	10	76	18	------	24
27	4	------	10	77	18	------	25
28	4	------	11	78	19	------	25
29	5	------	11	79	19	------	25
30	5	------	11	80	19	------	26
31	5	------	12	81	19	------	26
32	5	------	12	82	20	------	26
33	6	------	12	83	20	------	26
34	6	------	12	84	20	------	27
35	6	------	13	85	21	------	27
36	7	------	13	86	21	------	27
37	7	------	13	87	21	------	28
38	7	------	14	88	21	------	28
39	7	------	14	89	22	------	28
40	8	------	14	90	22	------	28
41	8	------	14	91	22	------	29
42	8	------	15	92	23	------	29
43	9	------	15	93	23	------	29
44	9	------	15	94	23	------	30
45	9	------	16	95	23	------	30
46	9	------	16	96	24	------	30
47	10	------	16	97	24	------	30
48	10	------	16	98	24	------	31
49	10	------	17	99	25	------	31
50	11	------	17	100	25	------	31

A COMPUTER PROGRAM DEVELOPED BY THE OKLAHOMA AGRICULTURAL EXPERIMENT STATION

TABLE VI

A COMPUTER PRINTOUT OF THE 2-SPRT DATA SHEET FOR A NEGATIVE BINOMIAL DISTRIBUTION OF COTTON FLEAHOPPER WHEN SZ = 0.2, ET = 0.4, AND ALPHA = BETA = 0.15

SAMPLE NUMBER	LOWER LIMIT	RUNNING TOTAL	UPPER LIMIT	SAMPLE NUMBER	LOWER LIMIT	RUNNING TOTAL	UPPER LIMIT
1	0	-------	4	51	12	-------	16
2	0	-------	5	52	13	-------	16
3	0	-------	5	53	13	-------	17
4	0	-------	5	54	13	-------	17
5	0	-------	5	55	14	-------	17
6	0	-------	5	56	14	-------	17
7	0	-------	6	57	14	-------	18
8	0	-------	6	58	15	-------	18
9	0	-------	6	59	15	-------	18
10	0	-------	6	60	15	-------	18
11	0	-------	7	61	16	-------	19
12	0	-------	7	62	16	-------	19
13	0	-------	7	63	16	-------	19
14	0	-------	7	64	17	-------	19
15	0	-------	8	65	17	-------	20
16	1	-------	8	66	17	-------	20
17	1	-------	8	67	18	-------	20
18	1	-------	8	68	18	-------	20
19	2	-------	9	69	18	-------	21
20	2	-------	9	70	19	-------	21
21	2	-------	9	71	19	-------	21
22	3	-------	9	72	19	-------	21
23	3	-------	10	73	20	-------	22
24	3	-------	10	74	20	-------	22
25	4	-------	10	75	21	-------	22
26	4	-------	10	76	21	-------	22
27	4	-------	11	77	21	-------	22
28	5	-------	11	78	22	-------	23
29	5	-------	11	79	22	-------	23
30	5	-------	11	80	22	-------	23
31	6	-------	11	81	23	-------	23
32	6	-------	12	82	23	-------	24
33	6	-------	12	83	23	-------	24
34	7	-------	12	84	24	-------	24
35	7	-------	12	85	24	-------	24
36	7	-------	13	86	24	-------	25
37	8	-------	13	87	25	-------	25
38	8	-------	13	88	25	-------	25
39	8	-------	13	89	25	-------	25
40	9	-------	14	90	26	-------	26
41	9	-------	14	91	26	-------	26
42	9	-------	14	92	26	-------	26
43	10	-------	14	93	27	-------	26
44	10	-------	15	94	27	-------	27
45	10	-------	15	95	27	-------	27
46	11	-------	15	96	28	-------	27
47	11	-------	15	97	28	-------	27
48	11	-------	16	98	28	-------	27
49	12	-------	16	99	29	-------	28
50	12	-------	16	100	29	-------	28

Willson's. The computer program to generate a sampling plan based on Willson's Sequential Sampling was written by Young and Willson (1989). This program allows the user to use 4 levels of CV control: 90, 85, 80 or 75 per cent. For the negative binomial distribution, the user must supply the k value.

The parameter value used for k was 1. With this information a computer printout was given with the Willson's Sequential Sampling Plan as shown in TABLE VII. The level of CV control used was 0.15.

TABLE VII

A COMPUTER PRINTOUT OF THE WILLSON'S SEQUENTIAL SAMPLING FOR A NEGATIVE BINOMIAL DISTRIBUTION OF COTTON FLEAHOPPER WHEN K = 1

Sample Number	Total Count Needed 0.1	0.15	0.2	0.25	Sum X	Sample Number	Total Count Needed 0.1	0.15	0.2	0.25	Sum X
1	0	0	0	0	---	51	0	299	47	22	---
2	0	0	0	0	---	52	0	270	46	22	---
3	0	0	0	0	---	53	0	246	45	22	---
4	0	0	0	0	---	54	0	227	45	22	---
5	0	0	0	0	---	55	0	211	44	22	---
6	0	0	0	0	---	56	0	198	43	21	---
7	0	0	0	0	---	57	0	186	43	21	---
8	0	0	0	0	---	58	0	177	42	21	---
9	0	0	0	0	---	59	0	168	42	21	---
10	0	0	0	0	---	60	0	161	41	21	---
11	0	0	0	0	---	61	0	154	41	21	---
12	0	0	0	0	---	62	0	148	40	21	---
13	0	0	0	0	---	63	0	143	40	21	---
14	0	0	0	0	---	64	0	138	40	20	---
15	0	0	0	0	---	65	0	134	39	20	---
16	0	0	0	256	---	66	0	130	39	20	---
17	0	0	0	136	---	67	0	126	38	20	---
18	0	0	0	96	---	68	0	122	38	20	---
19	0	0	0	76	---	69	0	119	38	20	---
20	0	0	0	64	---	70	0	117	38	20	---
21	0	0	0	56	---	71	0	114	37	20	---
22	0	0	0	50	---	72	0	112	37	20	---
23	0	0	0	46	---	73	0	109	37	20	---
24	0	0	0	42	---	74	0	107	37	20	---
25	0	0	625	40	---	75	0	105	36	20	---
26	0	0	325	37	---	76	0	103	36	19	---
27	0	0	224	36	---	77	0	101	36	19	---
28	0	0	175	34	---	78	0	100	36	19	---
29	0	0	145	33	---	79	0	98	35	19	---
30	0	0	124	32	---	80	0	97	35	19	---
31	0	0	110	31	---	81	0	95	35	19	---
32	0	0	100	30	---	82	0	94	35	19	---
33	0	0	91	29	---	83	0	93	35	19	---
34	0	0	85	28	---	84	0	92	35	19	---
35	0	0	79	28	---	85	0	90	34	19	---
36	0	0	75	27	---	86	0	89	34	19	---
37	0	0	71	26	---	87	0	88	34	19	---
38	0	0	67	26	---	88	0	87	34	19	---
39	0	0	65	26	---	89	0	86	34	19	---
40	0	0	62	25	---	90	0	85	34	19	---
41	0	0	60	25	---	91	0	85	33	19	---
42	0	0	58	24	---	92	0	84	33	19	---
43	0	0	56	24	---	93	0	83	33	19	---
44	0	0	55	24	---	94	0	82	33	19	---
45	0	0	53	24	---	95	0	81	33	19	---
46	0	799	52	23	---	96	0	81	33	18	---
47	0	587	51	23	---	97	0	80	33	18	---
48	0	468	50	23	---	98	0	79	33	18	---
49	0	392	49	23	---	99	0	79	33	18	---
50	0	338	48	22	---	100	0	78	32	18	---

TABLE VII

A COMPUTER PRINTOUT OF THE WILLSON'S SEQUENTIAL SAMPLING FOR A NEGATIVE BINOMIAL DISTRIBUTION OF COTTON FLEAHOPPER WHEN K = 1 (Continuation)

Sample Number	Total Count Needed 0.1	0.15	0.2	0.25	Sum X
101	0	77	32	18	___
102	0	77	32	18	___
103	0	76	32	18	___
104	0	76	32	18	___
105	0	75	32	18	___
106	0	75	32	18	___
107	0	74	32	18	___
108	0	74	32	18	___
109	0	73	32	18	___
110	999	73	31	18	___
111	924	73	31	18	___
112	861	72	31	18	___
113	807	72	31	18	___
114	760	71	31	18	
115	718	71	31	18	___
116	682	71	31	18	___
117	650	70	31	18	___
118	621	70	31	18	___
119	595	70	31	18	___
120	571	69	31	18	___
121	549	69	31	18	___
122	530	69	31	18	___
123	512	68	31	18	___
124	496	68	31	18	___
125	480	68	30	18	___
126	466	67	30	18	___
127	453	67	30	18	___
128	441	67	30	18	___
129	430	67	30	18	___
130	419	66	30	18	___
131	409	66	30	18	___
132	400	66	30	18	___
133	391	66	30	18	___
134	382	65	30	18	___
135	375	65	30	18	___
136	367	65	30	17	___
137	360	65	30	17	___
138	353	64	30	17	___
139	347	64	30	17	___
140	341	64	30	17	___
141	335	64	30	17	___
142	330	64	30	17	___
143	325	63	30	17	___
144	320	63	30	17	___
145	315	63	29	17	___
146	310	63	29	17	___
147	306	63	29	17	___
148	302	62	29	17	
149	298	62	29	17	___
150	294	62	29	17	___
151	290	62	29	17	___
152	286	62	29	17	___
153	283	62	29	17	___
154	280	61	29	17	___
155	276	61	29	17	___
156	273	61	29	17	___
157	270	61	29	17	___
158	267	61	29	17	___
159	265	61	29	17	___
160	262	61	29	17	___
161	259	60	29	17	___
162	257	60	29	17	___
163	254	60	29	17	___
164	252	60	29	17	___
165	250	60	29	17	___
166	247	60	29	17	___
167	245	60	29	17	___
168	243	59	29	17	___
169	241	59	29	17	___
170	239	59	29	17	___
171	237	59	29	17	___
172	235	59	29	17	___
173	233	59	29	17	___
174	232	59	29	17	___
175	230	59	28	17	___
176	228	59	28	17	___
177	226	58	28	17	___
178	225	58	28	17	___
179	223	58	28	17	___
180	222	58	28	17	___
181	220	58	28	17	___
182	219	58	28	17	___
183	217	58	28	17	___
184	216	58	28	17	___
185	215	58	28	17	___
186	213	57	28	17	___
187	212	57	28	17	___
188	211	57	28	17	___
189	210	57	28	17	___
190	208	57	28	17	___
191	207	57	28	17	___
192	206	57	28	17	___
193	205	57	28	17	___
194	204	57	28	17	___
195	203	57	28	17	___
196	202	57	28	17	___
197	201	57	28	17	___
198	200	56	28	17	___
199	199	56	28	17	___
200	198	56	28	17	___

How The Cotton Fleahopper Was Sequentially Sampled Using SPRT And 2-SPRT Methods. According to Sterling and Pieters (1974), sampling for the cotton fleahopper should start about the 7-node stage and continue until the first bloom. During this study, terminals were sampled following the steps given below:

1. The terminal (top 2-4 inches) of a randomly selected plant was checked;

2. Finding infestation of one cotton fleahopper (adult or nymph) we marked a '1` (one) in the blank column (called "running total column"); finding 2 cotton fleahoppers, we marked a '2`, and so on; If the plant was uninfested, we marked a '0` (zero).

3. Suppose that in our first plant we found 1 (one) adult. So, we marked a '1` (one) in the running total column by plant 1.

4. Now, suppose a second terminal was randomly selected and on it we found another fleahopper. We add a '1` to the running total. In this case a, '2` will be placed in the running total column by plant two.

5. We continue this process until we get a number below the lower limit or above the upper limit, respectively. In

case the running total is smaller than the lower limit, it indicates that no treatment is needed. However, if the running total is greater than the upper limit, it indicates that treatment is needed.

6. A minimum of 10 plants per field sampled is recommended (Pieters and Sterling, 1974) before making any decision so even if 10 cotton fleahoppers are found on the first plant, which is above the Economic Threshold for this pest, no decision should be taken at this time.

How the Cotton Fleahopper Was Sequentially Sampled by Willson's Technique. The same terminals sampled for the SPRT and 2-SPRT systems were also sampled using Willson's method. This method had the following steps:

1. 85 percent of the risk factor was controlled, which means the CV was 15 percent.

2. The process of counting the cotton fleahopper (adult or nymph) described above was used. However, in this technique, there is only one column for decision. When the running total is equal to or greater than the total count needed for 85 % control of CV, it indicates that the CV has been controlled at the level indicated.

3. It is necessary to keep sampling until the running total value reaches the total count needed for 85% CV control.

Design And Analysis of Field Trials

The experimental design was randomized complete block where blocks are sample date by field combinations, since each sampling method (treatment) was applied once to a field on a given sample date. The data from the field trials were analyzed using analysis of variance (SAS Institute, 1985). Two analyses of variance were performed using 1)time until a decision and 2)number of samples until a decision as the dependent variables. The LSD test was used to compare means of the data for the different sampling techniques.

Computer Simulation

In order to validate the sampling plans used in this experiment for cotton fleahopper, a computer simulation was used. This simulation, developed by Dr. Linda Young (Statistics Dept., OSU) uses a method by Norman and Cannon (1972), is a computer program for generation of random variables (insect population) using a desired discrete distribution. This computer simulation started running in October 20, 1989, in the Entomology Department, Oklahoma State University. It took approximately 545 hours on an IBM® PC to run 110 simulations.

A description of the basic steps of this program is given below:

1. An insect population is generated using a pseudo random

number generator of discrete distributions;

2. Then the program applies the SPRT, fixed and 2-SPRT sampling procedures to the population;

3. The process is repeated 10,000 times for each combination of population mean, alpha, and beta;

4. The number of decisions to spray and not to spray out of the 10,000 trials is recorded for each sampling technique.

The geometric distribution which is a special case of the negative binomial distribution was used. The population mean values were (0.1, 0.2, ..., 1.0), and the values for alpha were set equal to value of beta and were (0.10, 0.11, ..., 0.2).

To run this simulation, it was necessary to calculate the slopes and intercepts of the sequential sampling plans. The computer program written by Lim (1989) was used for this.

Tables I and II provide formulas for the slopes and intercepts of the Wald's SPRT and Lorden's 2-SPRT decision boundaries, respectively. Tables XII through XXII (See Appendix) give the output for the geometric distribution with p1 = 0.714 (SZ = 0.2), p2 = 0.833 (ET = 0.4), and values of alpha and beta ranging from 0.10 to 0.20 where alpha = beta. Table values were obtained using computer programs developed by Seebeck (1989) and Lim (1989), which evaluate the SPRT and 2-SPRT systems.

Graphs were made of the results from the computer simulation in order to compare results and validate the sequential sampling used.

CHAPTER IV

RESULTS AND DISCUSSION

Field Observations

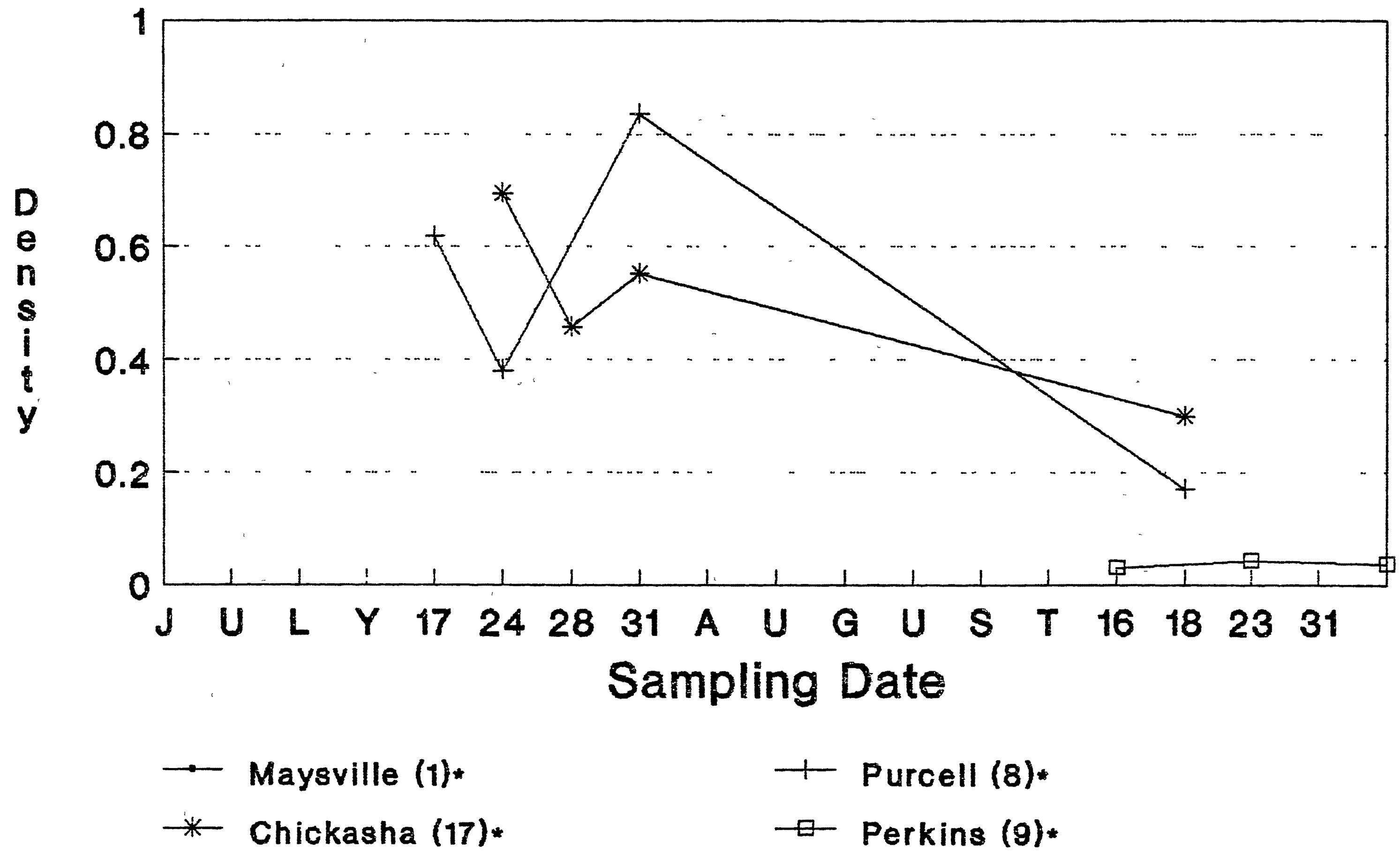
The density of cotton fleahopper populations varied from July 15th to August 31st. Fig. 7 shows the fluctuations of cotton fleahopper in different locations in Oklahoma.

The number of samples until a decision for the SPRT and 2-SPRT methods were not significantly different. However, the number of samples to reach a decision for both the SPRT and 2-SPRT methods were significantly fewer than Willson's (Table VIII). In addition, the same table indicates that the SPRT and 2-SPRT were not significantly different in terms of time until decision. However, the time to reach decision for both the SPRT and 2-SPRT methods were significantly less than Willson's (See Table VIII).

The number of samples necessary to make a decision for the three sampling methods is shown in a graph in Fig. 8. The SPRT and 2-SPRT showed approximately the same behavior during this study. However, for the Willson's sequential sampling, it was necessary to take more samples in order to

Figure 7. Population Trends of Cotton Fleahopper in Different Cotton Fields in Oklahoma. Summer 1989

Cotton Fleahopper Density



* Number of Fields

TABLE VIII

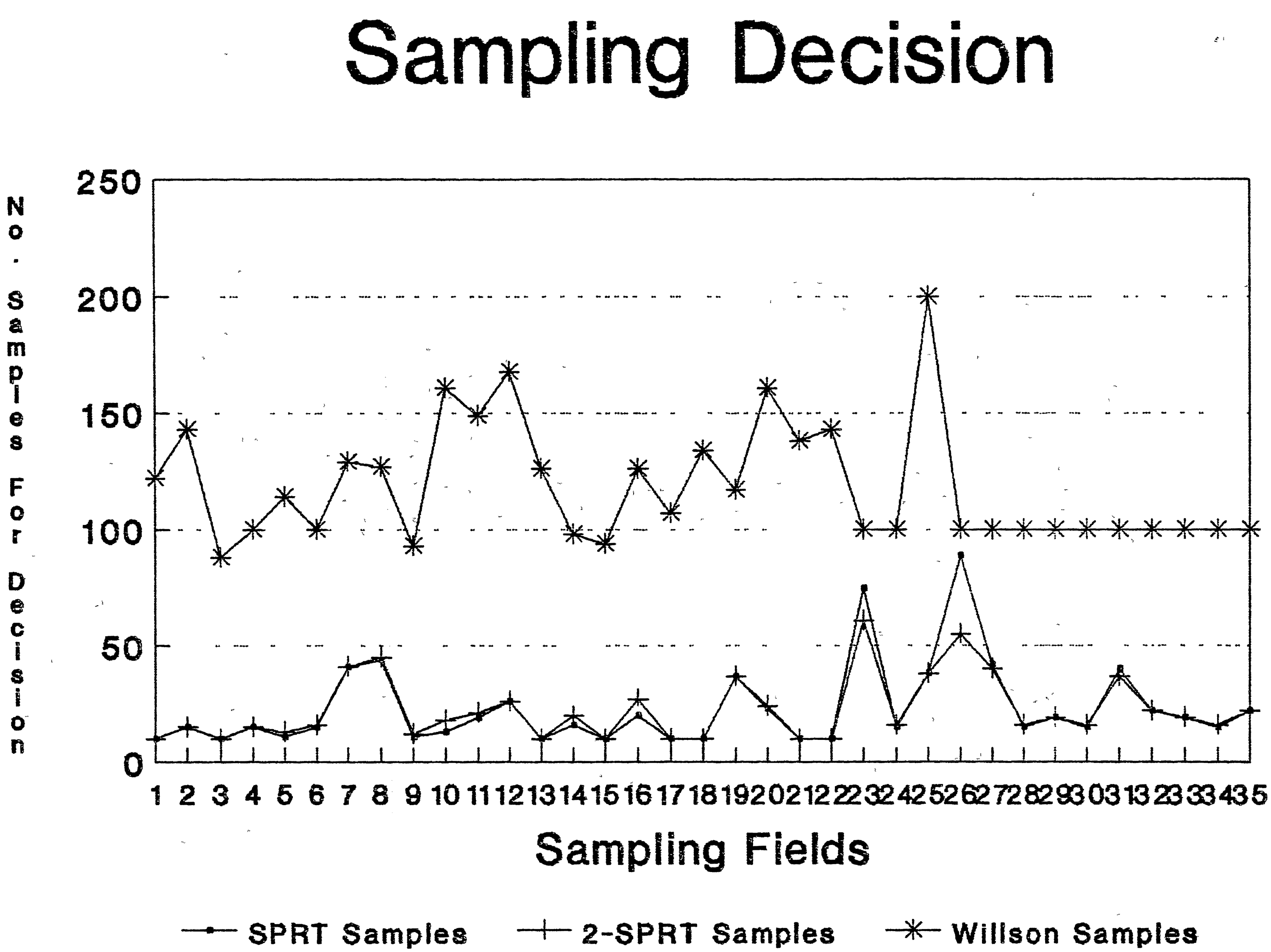
MEANS OF NUMBER OF SAMPLES AND TIME UNTIL DECISION FOR THREE SAMPLING SYSTEMS

Sampling System[1]	Number of Samples Until Decision[2]	Time Until Decision[2]
SPRT	23.229 a	2.494 a
2-SPRT	22.543 a	2.449 a
Willson's	118.343 b	13.411 b

[1] SPRT: Sequential Probability Ratio Test. 2-SPRT: Two simultaneously conducted one-sided SPRT's. Willson's: Willson's Sequential Sampling Plan.

[2] Means with same letter are not significantly different using the LSD test with alpha = .05

Figure 10. Time Necessary to Reach Decision For The SPRT and 2-SPRT.


Sampling Decision
No. Samples For Decision
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Sampling Fields
SPRT Samples
2-SPRT Samples
Willson Samples

to have a decision.

The number of samples for decision is proportional for the time decision. In other words, if the number of samples to reach decision is small, the time to decision will also be small. Fig. 9 shows a graph of the sampling time for the three sampling systems. Here, the behavior of the SPRT and 2-SPRT were similar. Fig. 10 shows a more detailed graph of the sampling time for SPRT and 2-SPRT.

The time saved with this sequential sampling plan not only will save money for the grower, but he will also know that his scout fatigue will be reduced and consequently the sampling error will be decreased.

Eventhough the results show that the SPRT and 2-SPRT performed well, Willson's plan has three unique characteristics that for some cotton growers it may be better, even though it does not save time. First, the computer program for Willson's needs only the parameter k to run. Secondly, when we have a higher k, Willson's plan has a lower sample size when compared with Lorden's 2-SPRT. And thirdly, Willson's plan gives to the user the opportunity to choose, in the field, the risk factor he prefers. With the dynamics of nature, the crop envirionment may indicate, in a given year for example, a good chance for control by natural enemies. In this case, the grower may decide to take a greater risk, considering the influence of natural control factors. This decision would bring enormous benefits for

Figure 9. Time Necessary to Reach Decision For The SPRT, 2-SPRT, And Willson's Sequential Sampling.

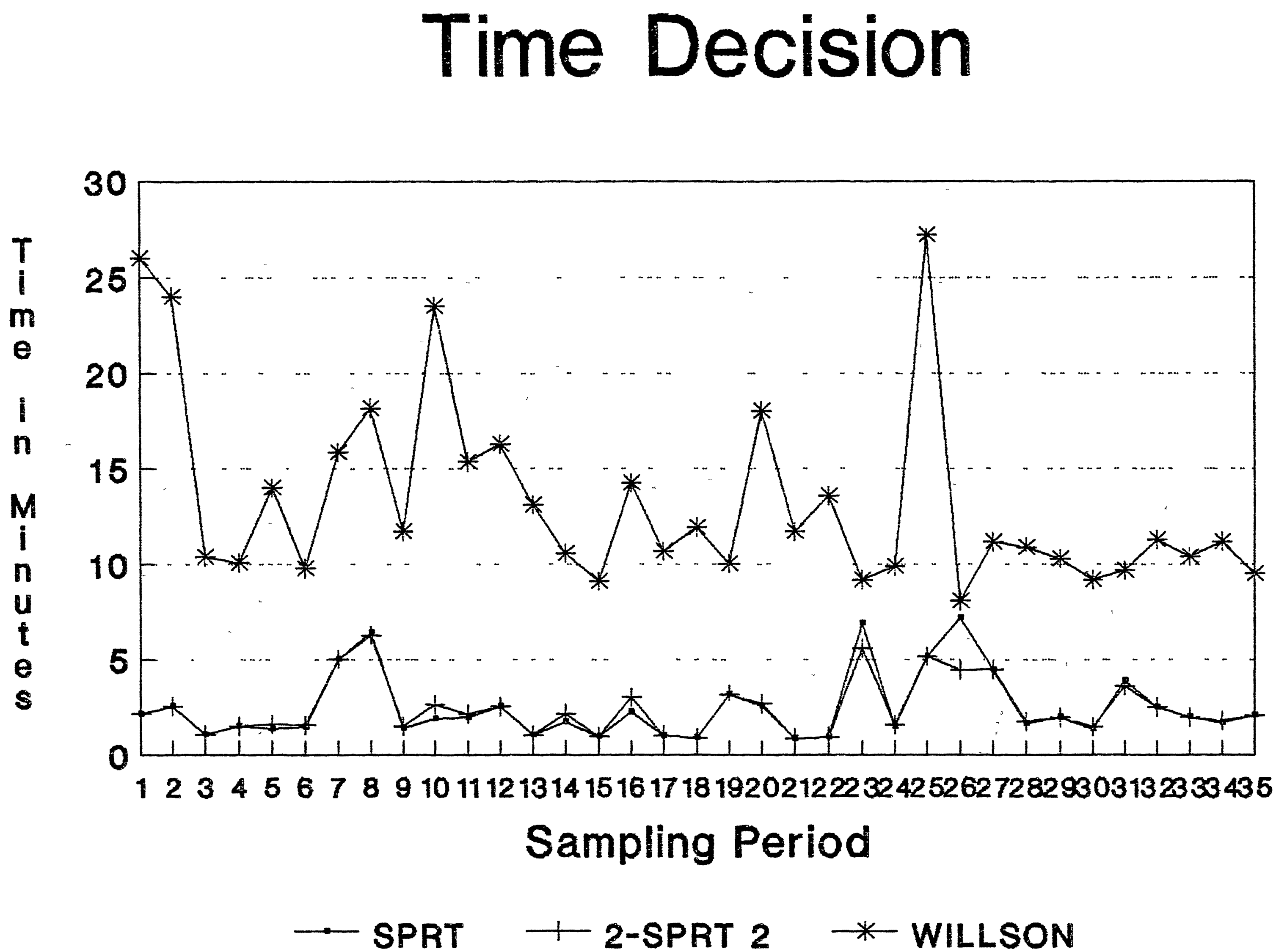
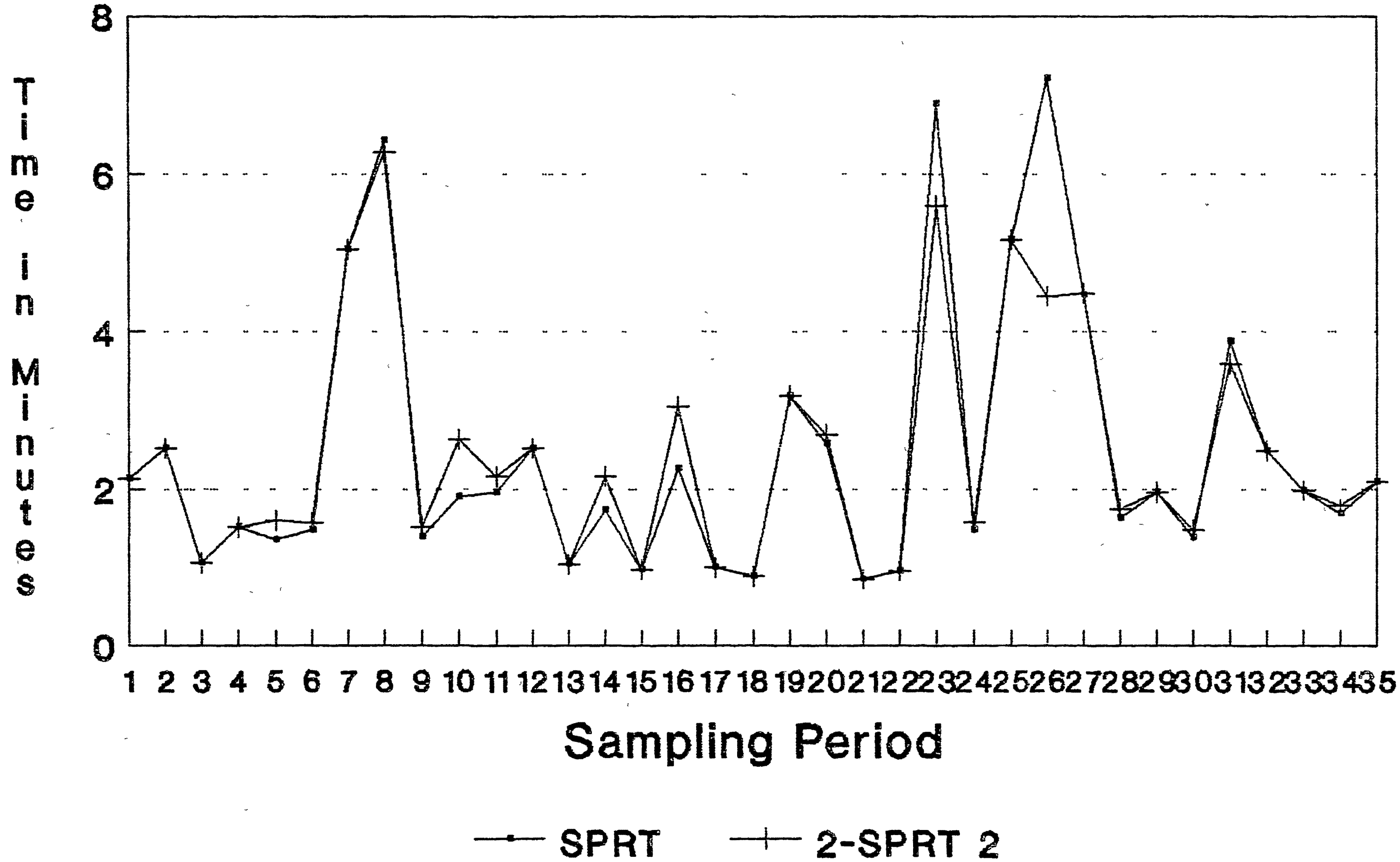

Time Decision
Time in Minutes
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Sampling Period
SPRT
2-SPRT 2
WILLSON

Figure 10. Time Necessary to Reach Decision For The SPRT and 2-SPRT.

Time Decision



the ecological system.

It is true that the environmental equilibrium seems, sometimes, to be too complicated to understand due to the countless interactions among the biotic and abiotic factors. However, one thing is true: the less chemical that is used, the less ambient pollution.

It was found that the sizes of alpha = beta has a great influence on the maximum sample size (M). When alpha = beta increase, M decreases. Table IX shows the response as alpha = beta are changed. Figure 11 shows graphically how M behaves in response to alpha = beta variations for 2-SPRT, under a negative binomial distribution for cotton fleahopper when u1 = 0.2, u2 = 0.4, and k = 1. This result agrees with those presented by Lim (1989). From Fig. 11 it is evident that fewer plants have to be sampled to reach a decision if alpha = beta are increased.

In this study the behavior of M for Willson and 2-SPRT under different k values was analyzed. As we see in Fig. 12, Willson's technique has the great advantage of taking fewer samples when k is high (clumping not severe). For cotton insects in the State of Oklahoma, for instance, most k values are between 2 and 5 when the sample unit is 1/5000 at a foot (Hill et al., 1975).

TABLE IX

THE INFLUENCE OF ALPHA AND BETA ON THE MAXIMUM SAMPLE SIZE (M) FOR A NEGATIVE BINOMIAL DISTRIBUTION WHEN USING 2-SPRT (mu1 = 0.2, mu2 = 0.7, AND k = 1)

alpha = beta	M
0.10	120.563
0.11	113.384
0.12	106.831
0.13	100.802
0.14	95.221
0.15	90.025
0.16	85.165
0.17	80.599
0.18	76.295
0.19	72.224
0.20	68.362

Figure 11. Maximum Sample Size for a Negative Binomial Distribution Using 2-SPRT When mu1 = 0.2, mu2 = 0.4, and k = 1.

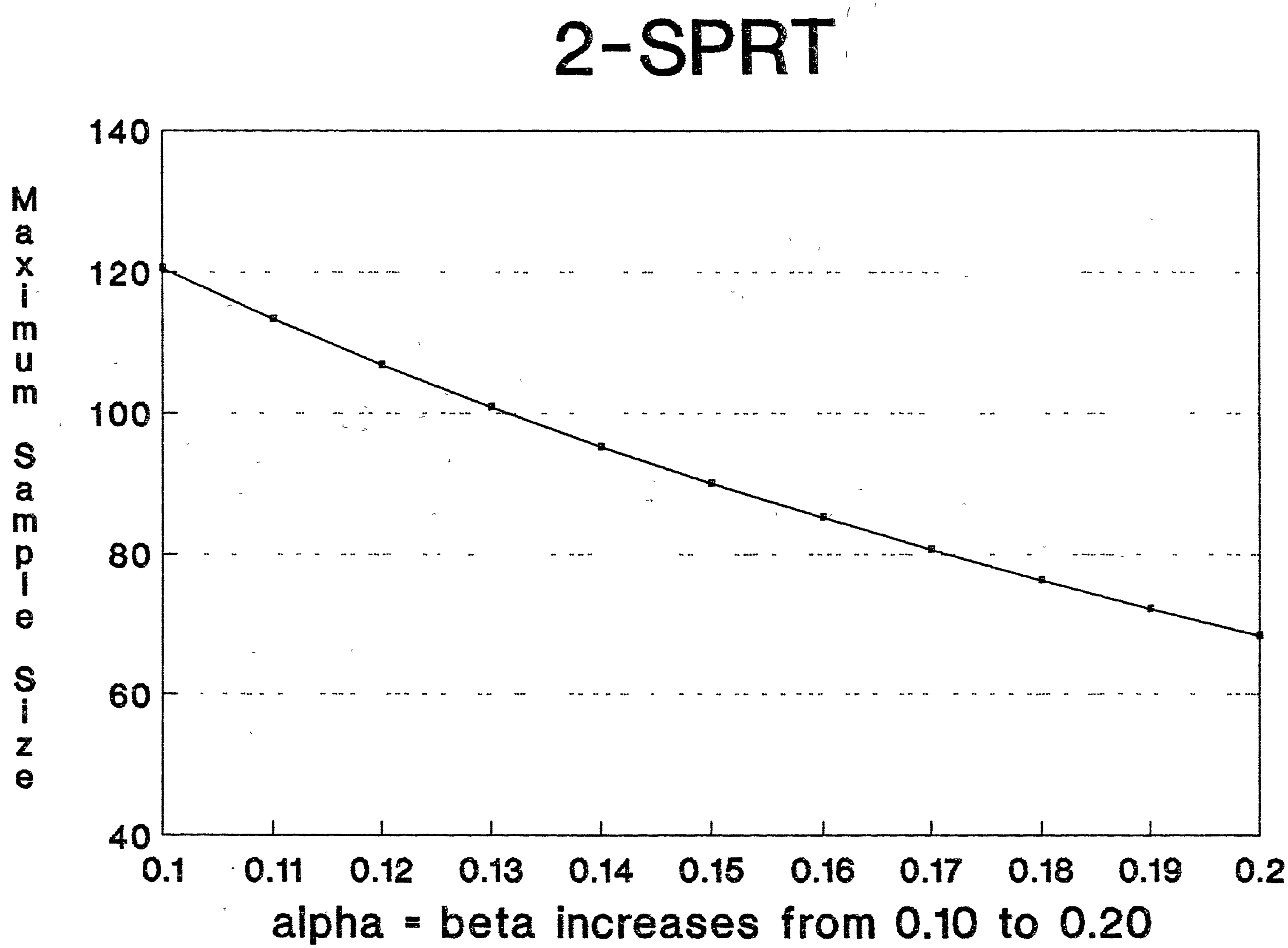
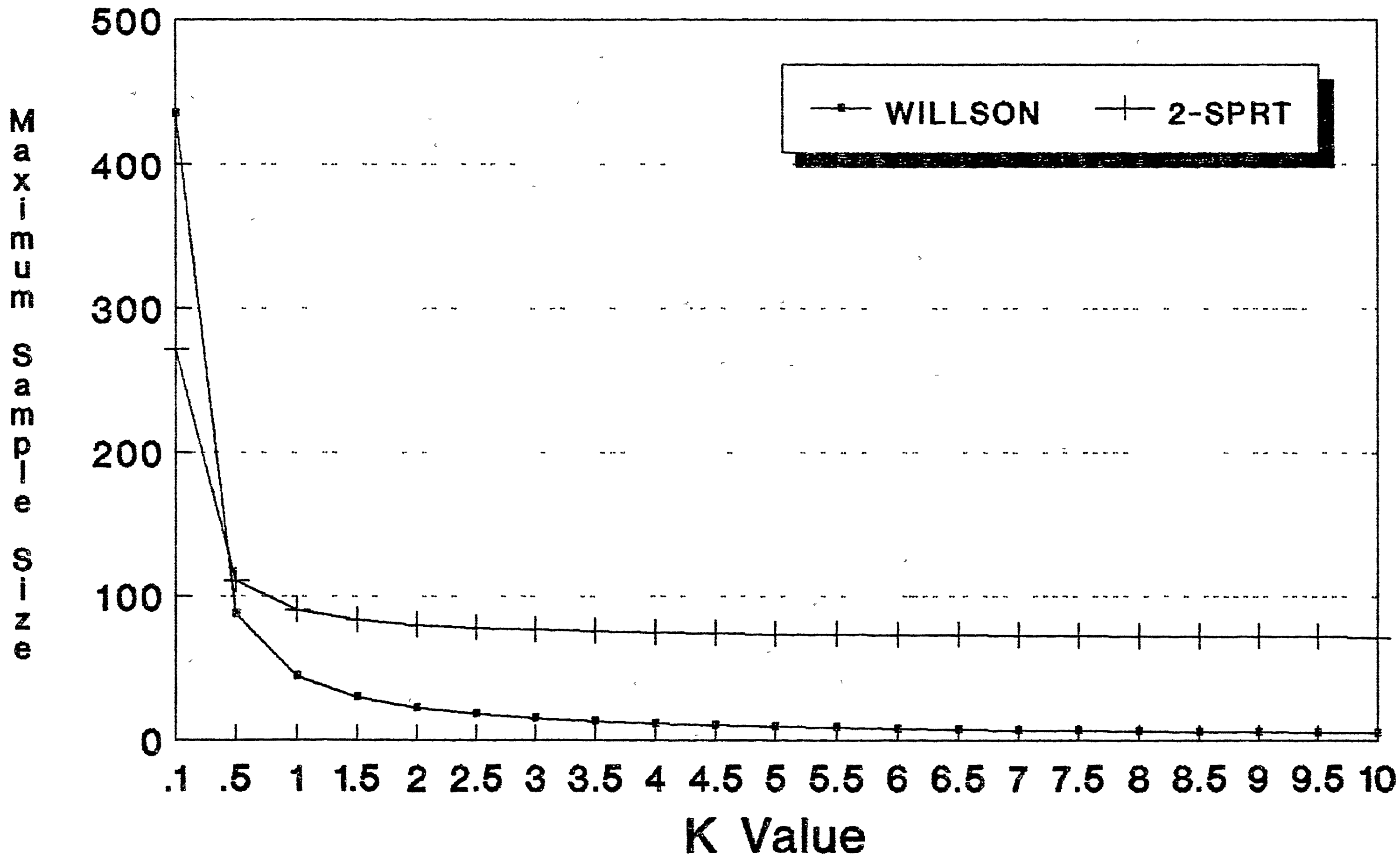

2-SPRT
Maximum Sample Size
140
120
100
80
60
40
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
alpha = beta increases from 0.10 to 0.20

Figure 12 - Maximum Sample Size (M) for Willson and 2-SPRT under different k values.

Maximum Sample Size (M)

For Willson and 2-SPRT



There is a tradeoff between risk level and maximum sample size. In other words, there is a tradeoff between sampling costs and costs of making wrong decision. However, consideration of other factors (such as natural parasites, predators, etc...) may allow the scout to increase risk levels alpha and beta without greatly increasing the cost of making a wrong decision. It is very important for the scout to have a wide knowledge of the ecological potential of the field that would help controlling the pest before deciding to manipulate alpha and beta values.

According to Lim (1989), two other factors could influence the value of M. The first factor is the distance between the two hypothesized parameter values, mu1 and mu2, which decrease M when they are increased. The second factor is the k value, which increases as M decreases.

Simulations

Computer programs to develop and evaluate SPRT and 2-SPRT for discrete distributions such as those developed by Seebeck (1989) and Lim (1989) respectively, are remarkable tools for researchers. These two programs give the decision boundaries for the SPRT and 2-SPRT testing procedure very quickly. Also, a data sheet for field sampling may be printed out immediately.

Tables X and XI give the results of the simulations for the SPRT and 2-SPRT plans. For both plans the increase in observed error is smaller than the corresponding increase in preset values of alpha and beta for a given value of xbar.

Graphically, it was noticed for the SPRT simulation (See Fig. 13) that as the mean (xbar) increases the probability of spraying also increases. It is observed, also, that the error rate affects the decision. As alpha and beta increase the distance between 'treat` and 'non-treat` becomes smaller when the population mean is equal to the economic threshold. Fig. 14 shows that the increase in alpha and beta does not affect significantly the 'treat-nontreat` decision when the population mean is extreme from the economic threshold, such as values of 0.1 and 1.0. However, when the population means are close to the economic threshold, alpha and beta affect the decisions 'treat` and 'non-treat` (See Fig. 15).

For the 2-SPRT simulation as population mean increases the probability of spraying also increases (See Fig. 16). This result is similar to the SPRT simulation at the same conditions (alpha = beta = 0.10, 0.15, and 0.20). Another similar behavior occurred when alpha = beta was increased and the distance between 'treat` and 'nontreat` decisions became smaller when the population mean is equal to the economic threshold (See Fig. 17 and 18).

TABLE X

SPRT SIMULATION

$\alpha=\beta$ \ $\bar{X}$		.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
.10	*	663	1577	3391	5924	8235	9394	9865	9963	9992	10000
	**	9337	8423	6609	4076	1765	606	135	37	8	0
.11	*	610	1599	3449	5852	8171	9358	9846	9966	9995	9999
	**	9390	8401	6551	4148	1829	642	154	34	5	1
.12	*	651	1683	3428	5751	8015	9280	9805	9956	9988	10000
	**	9349	8317	6572	4249	1985	720	195	44	12	0
.13	*	676	1686	3366	5671	7807	9258	9762	9931	9994	10000
	**	9324	8314	6634	4329	2193	742	238	69	6	0
.14	*	709	1713	3335	5529	7840	9160	9757	9934	9990	9999
	**	9291	8287	6665	4471	2160	840	243	66	10	1
.15	*	687	1636	3213	5433	7683	9052	9707	9917	9980	9996
	**	9313	8364	6787	4567	2317	948	293	83	20	4
.16	*	662	1616	3252	5358	7546	9120	9692	9911	9978	9999
	**	9338	8384	6748	4642	2454	880	308	89	22	1
.17	*	670	1611	3188	5421	7512	8942	9708	9886	9985	9998
	**	9330	8389	6812	4579	2488	1058	292	114	15	2
.18	*	615	1635	3040	5249	7439	8955	9590	9900	9987	9998
	**	9385	8365	6960	4751	2561	1045	410	100	13	2
.19	*	661	1813	3292	5372	7345	8901	9588	9860	9974	9995
	**	9339	8187	6708	4628	2655	1099	412	140	26	5
.20	*	701	1783	3282	5238	7370	8801	9523	9836	9969	9996
	**	9299	8217	6718	4762	2630	1199	477	164	31	4

* Treat
** Non-treat

TABLE XI

2-SPRT SIMULATION

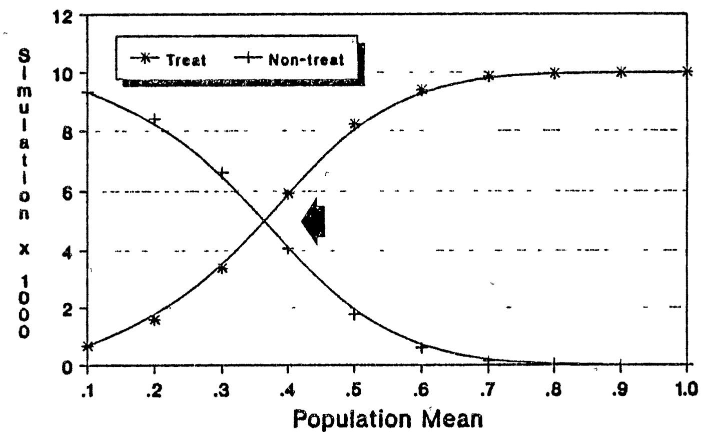
$\alpha=\beta$ \ $\bar{X}$		.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
.10	*	709	1647	3482	5989	8273	9422	9912	9982	9999	10000
	**	9291	8353	6518	4011	1727	578	88	18	1	0
.11	*	632	1647	3456	5849	8148	9395	9855	9979	9999	10000
	**	9368	8353	6544	4151	1852	605	145	21	1	0
.12	*	627	1614	3376	5701	7980	9270	9851	9977	9995	10000
	**	9373	8386	6624	4299	2020	730	149	23	5	0
.13	*	617	1580	3240	5547	7732	9238	9777	9946	9995	10000
	**	9383	8420	6760	4453	2268	762	223	54	5	0
.14	*	653	1590	3156	5301	7695	9088	9749	9938	9994	9999
	**	9347	8410	6844	4699	2305	912	251	62	6	1
.15	*	624	1536	3012	5202	7466	8917	9698	9920	9982	9996
	**	9376	8464	6988	4798	2534	1083	302	80	18	4
.16	*	655	1605	3188	5204	7316	8993	9649	9903	9974	9999
	**	9345	8395	6812	4796	2684	1007	351	97	26	1
.17	*	667	1572	3107	5254	7261	8757	9639	9873	9982	9998
	**	9333	8428	6893	4746	2739	1243	361	127	18	2
.18	*	610	1592	2894	4968	7160	8742	9502	9862	9977	9997
	**	9390	8408	7106	5032	2840	1258	498	138	23	3
.19	*	586	1602	2990	4988	6977	8615	9464	9832	9970	9992
	**	9414	8398	7010	5012	3023	1385	536	168	30	8
.20	*	635	1598	3016	4902	7020	8551	9382	9793	9960	9993
	**	9365	8402	6984	5098	2980	1449	618	207	40	7

* Treat
** Non-treat

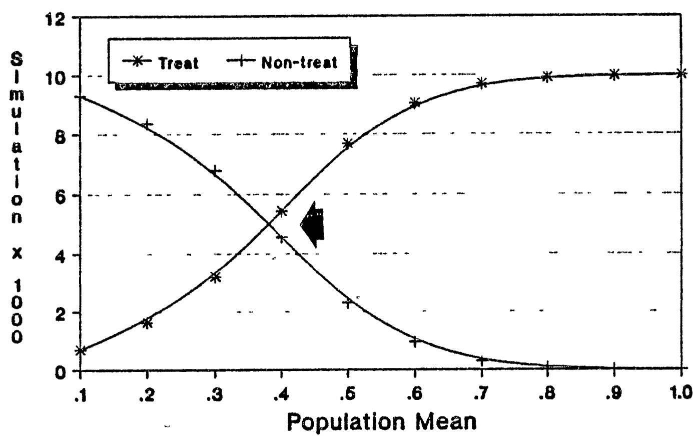
Figure 13 - Results of the SPRT Simulations for Different Means and for Alpha = Beta = 0.10, 0.15, and 0.20. The 'treat' curve describes number of times a decision to <u>treat</u> was reached out of ten thousand SPRT procedures performed. The 'non-treat' curve describes number of times a decision to <u>not treat</u> was reached out of ten thousand SPRT procedures performed.

SPRT Simulation

Type I and II Error Rate = .10



Type I and II Error Rate = .15



Type I and II Error Rate = .20

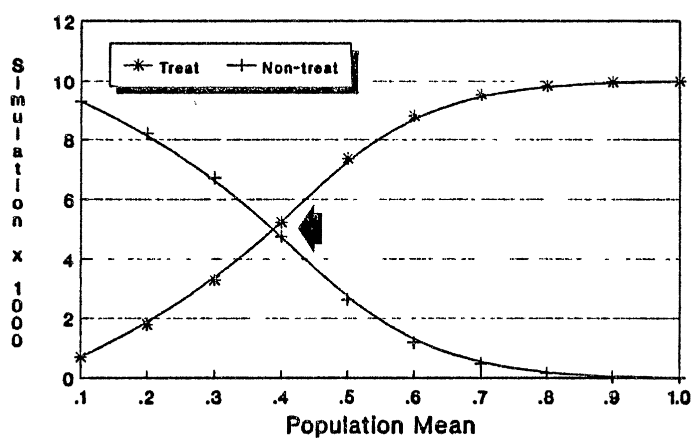
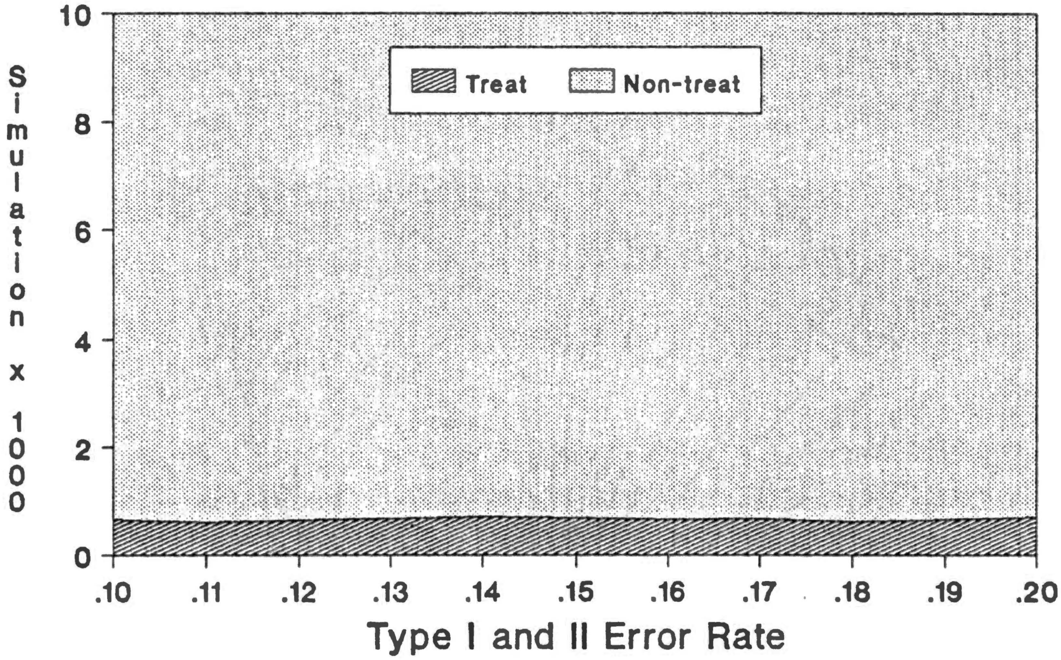


Figure 14. Results of the SPRT Simulations for Different Error Rates (Alpha = Beta) and for xbar = 0.1 and 1.0. The 'treat` curve describes number of times a decision to treat was reached out of ten thousand SPRT procedures performed. The 'non-treat` curve describes number of times a decision to not treat was reached out of ten thousand SPRT performed.

SPRT Simulation

Population Mean = .1



Population Mean = 1

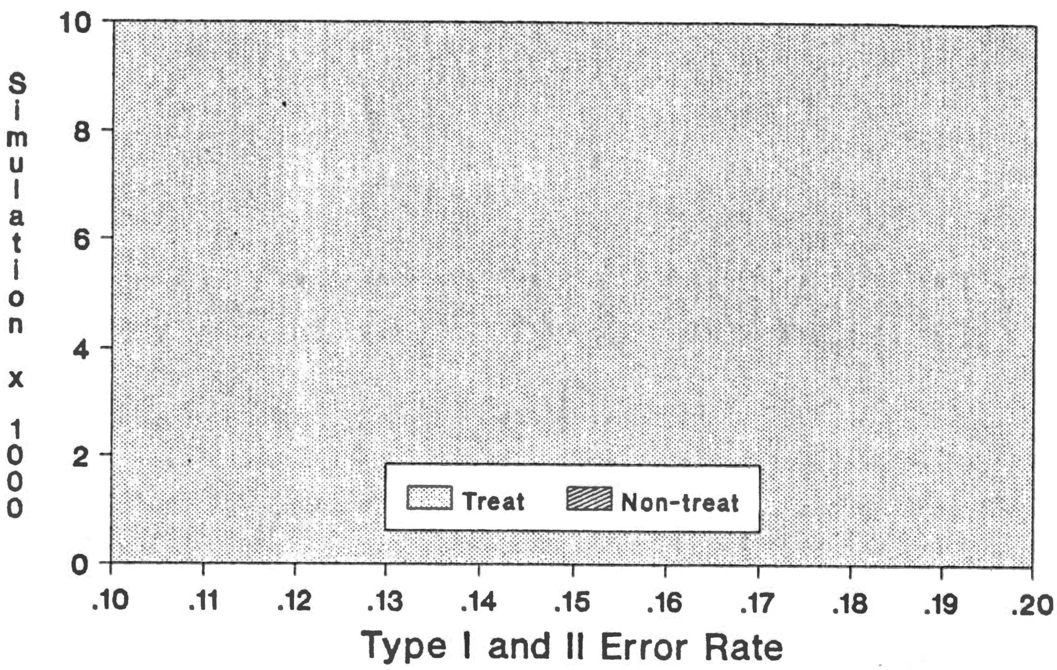
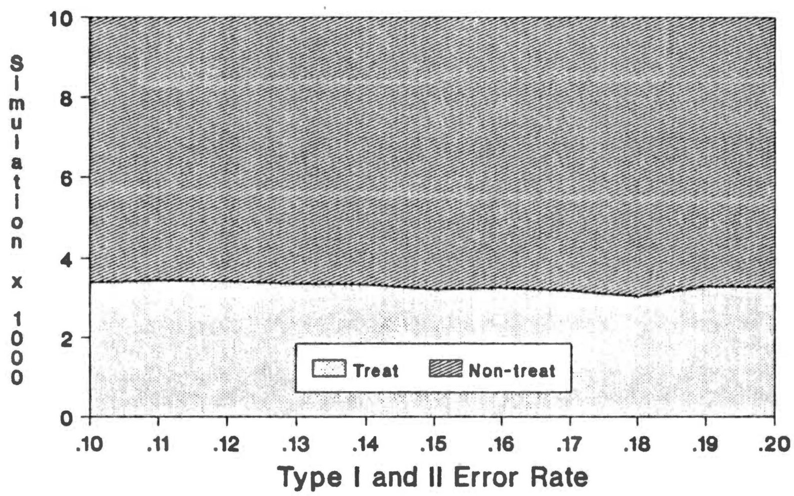


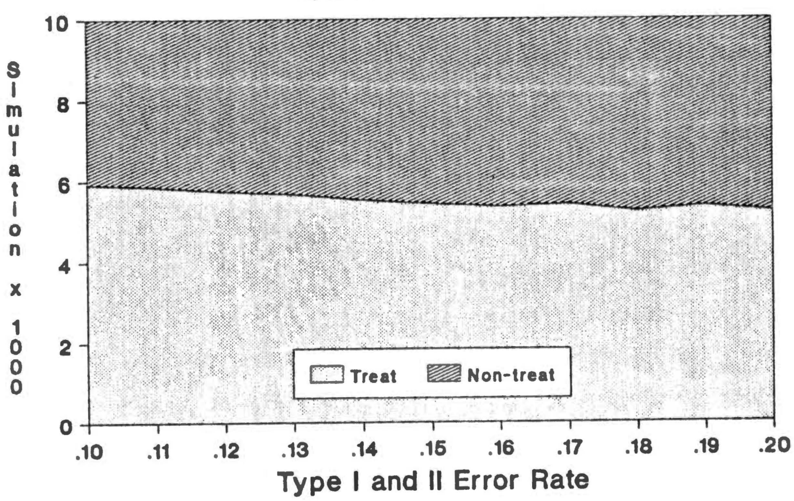
Figure 15. Results of the SPRT Simulations for Different Error Rates (Alpha = Beta) and for xbar = 0.3, 0.4, and 0.5. The 'treat' curve describes number of times a decision to <u>treat</u> was reached out of ten thousand SPRT procedures performed. The 'non-treat' curve describes number of times a decision to <u>not treat</u> was reached out of ten thousand SPRT performed.

SPRT Simulation

Population Mean = .3



Population Mean = .4



Population Mean = .5

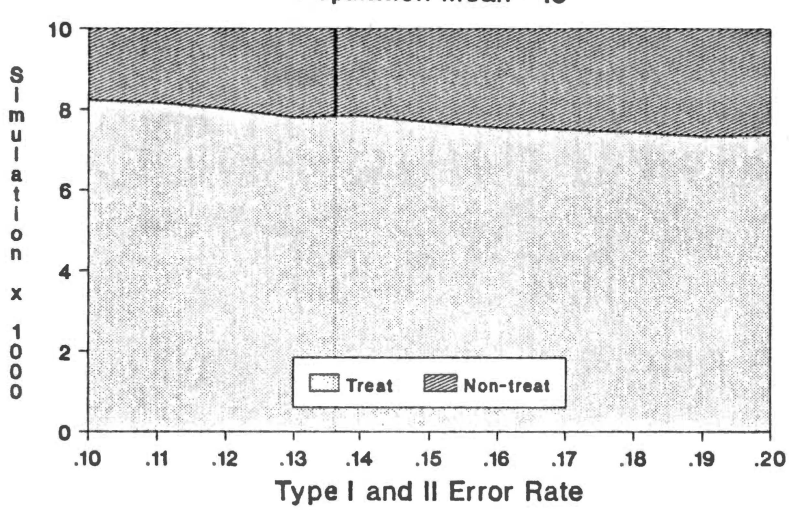
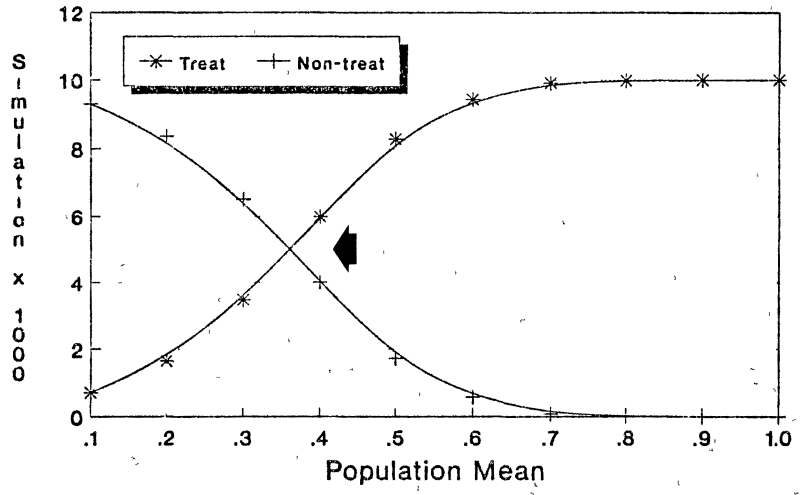


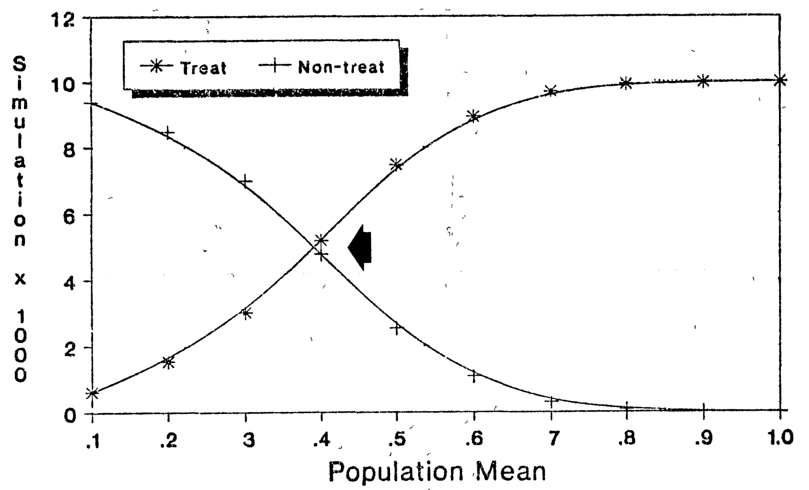
Figure 16 - Results of the 2-SPRT Simulations for Different Means and for Alpha = Beta = 0.10, 0.15, and 0.20. The 'treat` curve describes number of times a decision to treat was reached out of ten thousand 2-SPRT procedures performed. The 'non-treat` curve describes number of times a decision to not treat was reached out of ten thousand SPRT procedures performed.

2-SPRT Simulation

Type I and II Error Rate = .10



Type I and II Error Rate = .15



Type I and II Error Rate = .20

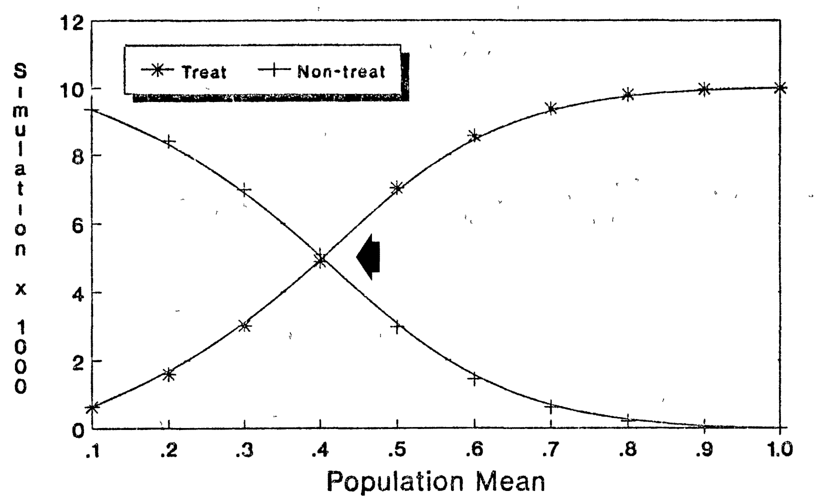
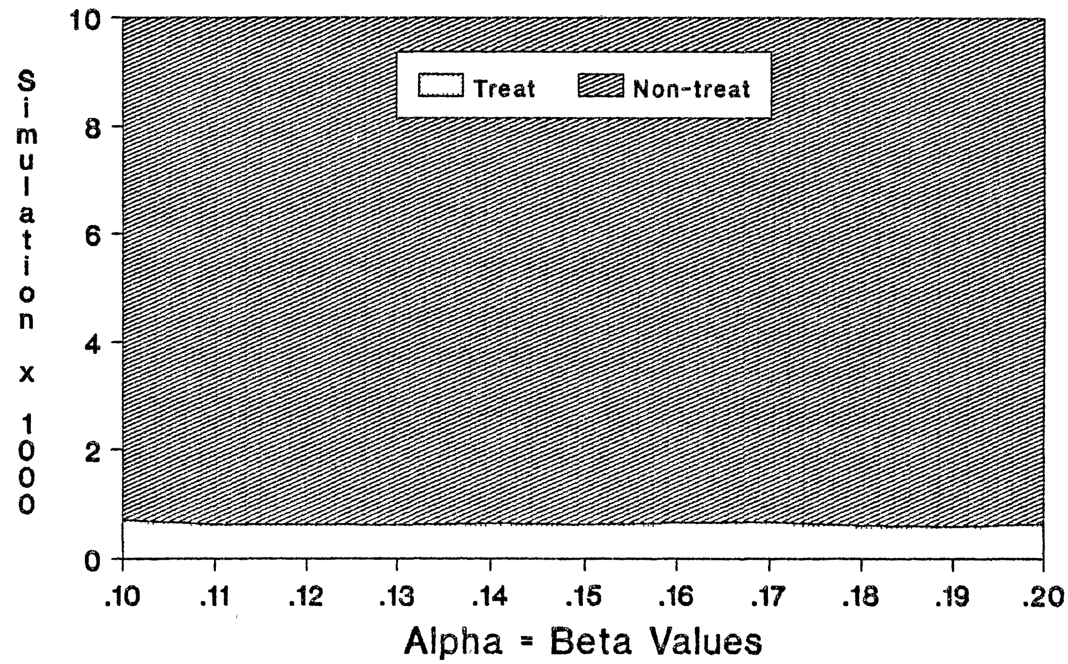


Figure 17. Results of the 2-SPRT Simulations for Different Error Rates (Alpha = Beta) and for xbar = 0.1 and 1.0. The 'treat` curve describes number of times a decision to treat was reached out of ten thousand 2-SPRT procedures performed. The 'non-treat` curve describes number of times a decision to not treat was reached out of ten thousand 2-SPRT performed.

2-SPRT Simulation

Population Mean = .1



Population Mean = 1

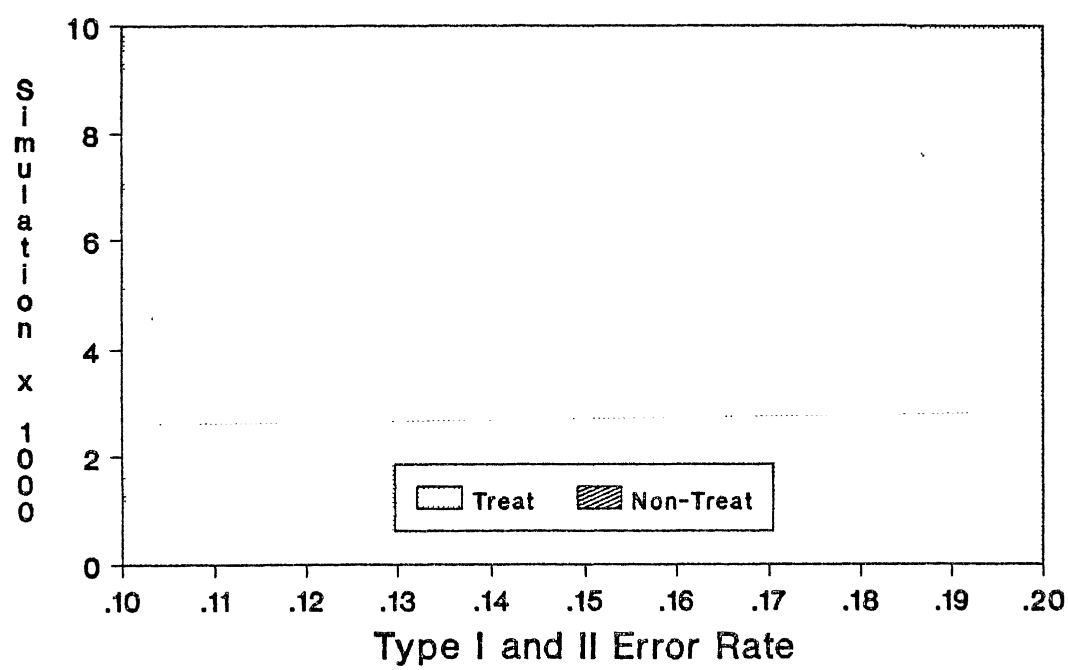
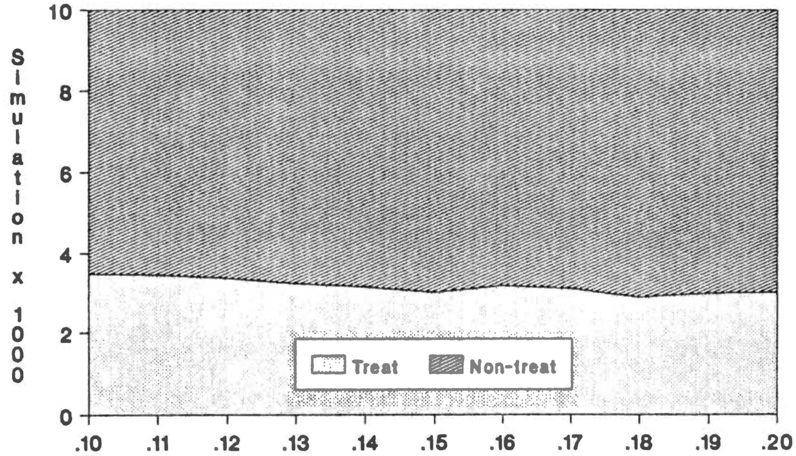


Figure 18. Results of the 2-SPRT Simulations for Different Error Rates (Alpha = Beta) and for xbar = 0.3, 0.4, and 0.5. The 'treat` column describes number of times a decision to treat was reached out of ten thousand 2-SPRT procedures performed. The 'non-treat` column describes number of times a decision to not treat was reached out of ten thousand 2-SPRT performed.

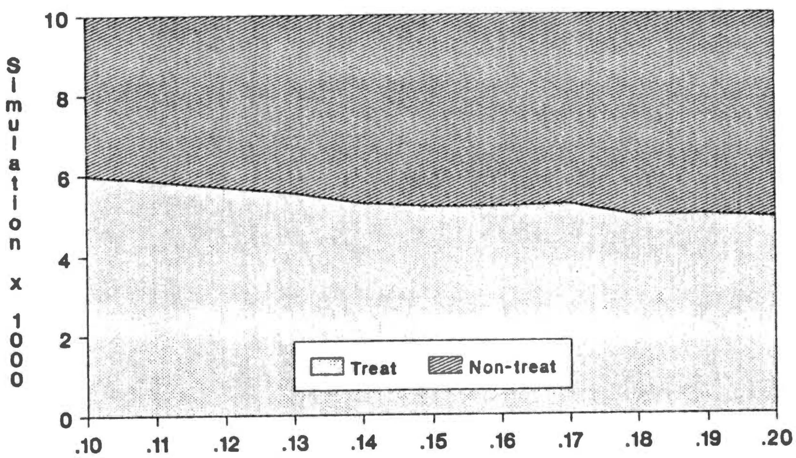
2-SPRT Simulation

Population Mean = .3



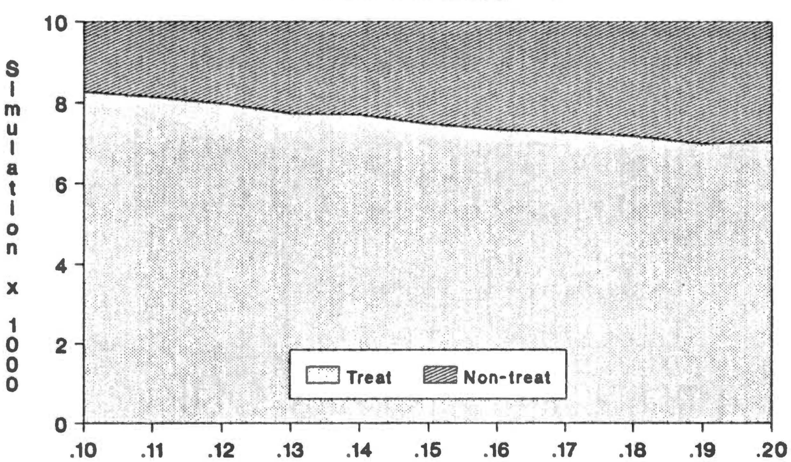
Type I and II Error Rate

Population Mean = .4



Type I and II Error Rate

Population Mean = .5



Type I and II Error Rate

CHAPTER V

SUMMARY

The results show that the 2-SPRT and SPRT techniques were not significantly different with respect to time until a decision was made or the number of samples needed to reach a decision.

In this study we have seen that the 2-SPRT technique performed better in terms of saving time when compared with Willson's Sampling Plan. Also, the 2-SPRT gives a better performance in terms of number of samples needed to reach a decision whether or not to spray for cotton fleahopper when compared with Willson's method. However, Willson's technique has the great advantage of taking fewer samples when k is high (clumping not severe). The saving time of this sequential sampling plan will not only save money for the grower, but will also reduce scout fatigue; consequently, the sampler error will be decreased.

The computer programs used during this study to print a data sheet for field use are easy and practical to use.

The computer simulation program was useful to detect the effects of alpha and beta for the SPRT and 2-SPRT programs. Both the SPRT and 2-SPRT are affected by type I and II error rates in terms of decision. As alpha and beta increases the distance between 'treat` and 'non-treat` become smaller when the population mean is equal to the economic threshold. When we have population mean extremes, such as 0.1 and 1.0, the increase of alpha and beta does not affect significantly the 'treat-nontreat` decision.

Our data demonstrated that each of the sequential sampling plans have unique features. The results indicate that different sampling plans should be utilized depending upon the nature of the distribution of the insects. The differences among sequential sampling plans concerning saving time and number of samples until a decision is reached are good indicators about the dynamics of this study. We can confidently say that even though the graphics and tables used in this study were obtained in a single season, and in a limited area, they may provide a basis for other comparisons of the three methods in other areas. For further studies, for instance, researchers could combine saving time and number of samples to reach a decision with other reliable parameters, such as efficiency, facility, etc.

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APPENDIX

TABLE XII

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.10

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.10
BETA  = 0.10
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -5.909
UPPER INTERVAL FOR THE TRIANGLE : uint =  6.000
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =  120.563
```

TABLE XIII

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES FOR A NEGATIVE BINOMIAL DISTRIBUTION WHEN ALPHA = BETA = 0.11

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.11
BETA  = 0.11
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -5.542
UPPER INTERVAL FOR THE TRIANGLE : uint =  5.658
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =  113.384
```

TABLE XIV

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.12

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.12
BETA  = 0.12
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -5.203
UPPER INTERVAL FOR THE TRIANGLE : uint =  5.350
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =  106.831
```

TABLE XV

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.13

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.13
BETA  = 0.13
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -4.896
UPPER INTERVAL FOR THE TRIANGLE : uint =  5.063
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =  100.802
```

TABLE XVI

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.14

```
NULL HYPOTHESIS : MU1 =  0.200
                 OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                 OR P2 =  0.833
ALPHA = 0.14
BETA  = 0.14
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -4.609
UPPER INTERVAL FOR THE TRIANGLE : uint =  4.799
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   95.221
```

TABLE XVII

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.15

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.15
BETA  = 0.15
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -4.344
UPPER INTERVAL FOR THE TRIANGLE : uint =  4.550
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   90.025
```

TABLE XVIII

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.16

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.16
BETA  = 0.16
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -4.090
UPPER INTERVAL FOR THE TRIANGLE : uint =  4.324
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   85.165
```

TABLE XIX

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.17

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.17
BETA  = 0.17
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -3.855
UPPER INTERVAL FOR THE TRIANGLE : uint =  4.108
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   80.599
```

TABLE XX

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES FOR A NEGATIVE BINOMIAL DISTRIBUTION WHEN ALPHA = BETA = 0.18

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.18
BETA  = 0.18
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -3.636
UPPER INTERVAL FOR THE TRIANGLE : uint =  3.903
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   76.295
```

TABLE XXI

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES FOR A NEGATIVE BINOMIAL DISTRIBUTION WHEN ALPHA = BETA = 0.19

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.19
BETA  = 0.19
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -3.429
UPPER INTERVAL FOR THE TRIANGLE : uint =  3.708
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   72.224
```

TABLE XXII

A COMPUTER PRINTOUT OF THE DECISION BOUNDARIES
FOR A NEGATIVE BINOMIAL DISTRIBUTION
WHEN ALPHA = BETA = 0.20

```
NULL HYPOTHESIS : MU1 =  0.200
                OR P1 =  0.714
ALTERNATIVE HYPOTHESIS : MU2 =  0.400
                OR P2 =  0.833
ALPHA = 0.20
BETA  = 0.20
NUMBER OF SUCCESSES BEFORE X FAILURE : k = 1.00
THIRD HYPOTHESIS : PO =   0.779
LOWER INTERVAL FOR THE TRIANGLE : lint = -3.233
UPPER INTERVAL FOR THE TRIANGLE : uint =  3.523
LOWER SLOPE FOR THE TRIANGLE : lslope =   0.338
UPPER SLOPE FOR THE TRIANGLE : uslope =   0.239
MAXIMUM SAMPLE SIZE FOR A DECISION : capm =   68.362
```

VITA

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