1986

Method Of Sampling Seed Banks In Arable Soils With Special Reference To Chenopodium Spp

Diane Lyse Benoit

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS REÇUE

Canada

METHODS OF SAMPLING SEED BANKS IN ARABLE SOILS WITH SPECIAL REFERENCE TO *Chenopodium* spp.

by

Diane Lyse Benoit

Department of Plant Sciences

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
July 1986

ISBN 0-315-33026-0

The University of Western Ontario
Faculty of Graduate Studies

Certificate of Examination

Chief Advisor

Paul B. Cavers

Examining Board

F.L. Cook

Advisory Committee

F.L. Cook

D.B. Wake

S.M. Smith

The thesis by
Diane Lyse Benoit

entitled
Methods of sampling seed banks in arable soils

is accepted in partial fulfilment of the
requirements for the degree of
Doctor of Philosophy

Date 28th August 1986

W. H. Tam
Chairman of Examining Board

ABSTRACT

Sampling procedures for seed bank studies have long been ignored and my objective was to evolve a procedure which would give an unbiased estimate of the seed bank of a major weed species while minimizing the sampling variance and the sampling effort. 1024 soil cores (1.9 cm in diameter and 15 cm deep) were taken systematically over 1.35 ha in a corn field in Oxford County, Ontario. Intact seeds of Chenopodium spp. (lamb's-quarters) were extracted using a solution of sodium hexametaphosphate and sodium bicarbonate (2:1 w/w). Seed numbers were recorded to create a data-bank from which repeated samplings with replacement were made to compare random, systematic, stratified random and cluster sampling in their capacity to minimize the sampling variance calculated by Monte Carlo technique (MC $S^2_{\bar{x}}$). The MC $S^2_{\bar{x}}$ decreased with increasing sample size regardless of the sampling method used. The MC $S^2_{\bar{x}}$ for systematic and cluster sampling was greatly influenced by the sampling interval and the shape and size of the cluster respectively. This was attributed to the underlying aggregate seed distribution of lamb's-quarters in the soil with its pattern of high and low seed density parallel to corn rows. There were some differences between the MC $S^2_{\bar{x}}$ of random and stratified random sampling but either of these methods could be used to sample seed banks. Of the auger size tested (1.9, 2.7 and 3.3 cm in diameter and 15 cm deep), the smaller sampling unit gave the most precise estimate of seed density of lamb's-quarters on a per volume basis. The minimum sample size needed to estimate the size of seed banks of common species such as lamb's-quarters ranged between 60 and 100 small sampling units. Fields under various crop rotations were found to have

similar sized seed banks of lamb's-quarters (802 to 2912 seeds/m^2). The application of manure was the most noticeable factor in increasing the number of Chenopodium spp. seeds in the soil (11 829 seeds/m^2). A muck soil under cultivation had no lamb's-quarters seed bank while two fallow fields with large populations of lamb's-quarters had similarly large seed banks (16 357 and 21 512 seeds/m^2). The seed banks of lamb's-quarters of all fields surveyed consisted of 92% black seeds and 8% brown seeds. The contribution of the different categories of Chenopodium spp. seeds to the seed population in the soil was constant throughout all fields with approximately 10% whole (viable) seeds, 56% damaged seeds and 34% underdeveloped seeds.

ACKNOWLEDGEMENTS

The author wishes to thank sincerely her thesis advisor, Dr. Paul Cavers for his continuous constructive criticism and his constant support. I also thank Mr. John Tucsok and sons for their permission and their cooperation in letting me work on his farm. Technical assistance from Mr. Steve Cruise and Mr. Tim Ellis as summer help in 1982, Mr. David Hill and Ms. Andrea Patch for cleaning soil samples is acknowledged. Special thanks are extended to Mr. Peter Andreae for designing such a wonderful soil washing machine. Assistance from Mrs Bernier-Cardou, as statistical counsellor, was greatly appreciated.

After fruitful exchanges of ideas and serious discussions with Dr. Norm Kenkel, this project on the application of sampling theory to seed bank studies was born. His active participation in writing the computer programs and his keen sense of criticism ensured the success of this project. Discussion with the "ecology group" - M. Bough, D. Broderick, J. Colosi, S. McCanny and P. Threadgill and from all other Plant Science graduate students, were most helpful.

Many of the figures in this thesis were drafted by Mr. A.A. Benoit and Mr. P. Benoit. Typing of this manuscript was done by Ms. Ghyslaine Brodeur. Their excellent work was most helpful to the author.

Financial support from the Ontario Pesticide Advisory Committee research grant and additional support from an operating grant of the NSERC of Canada to Dr. Paul Cavers were greatly appreciated. The author was sponsored by Agriculture Canada as part of a perfection program. Last but not least, I extend my gratitude to Dr. Claude B. Aubé for allowing time to finish writing this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF PHOTOGRAPHIC PLATES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Seed banks in arable soils

Weed seeds in the soil are an integral but unseen part of the weed flora. Any modification of the visible weed flora by changing cultural practices will result in gradual changes in the potential population of weedy plants as represented by the weed seeds in the soil (Froud-Williams et al., 1983). The visible weed population is often much smaller in numbers than the potential weed flora including buried seeds (Roberts, 1966; Froud-Williams et al., 1983) and may represent as little as 0.5% of the seed bank (Roberts and Feast, 1973a) but usually ranges between 3.0 and 9.0% (Roberts, 1966; Roberts and Dawkins, 1967; Roberts and Feast 1973a; Roberts and Ricketts, 1979).

Most seed bank studies have dealt with the pattern of loss of viable seeds over several years as well as the factors which govern the decrease of seed populations in arable soils. When seed production in a weed population is prevented, the decrease in the seed bank is exponential (Roberts and Dawkins, 1967; Roberts, 1970; Roberts and Feast, 1973a; Cook, 1980; Roberts, 1983) and approximately constant in percentage from year to year (Roberts, 1962, 1963b; Cook, 1980). The rate of decrease of a seed bank is related to its species composition (Roberts, 1962, 1963b, 1968), the degree of natural dormancy of the dominant species (Roberts, 1962) and the cultural practices employed (Roberts, 1962,

1968). The rate of decrease of a mixed-species seed bank ranges between 22 and 70% with a mean of 50% (Roberts, 1962; Roberts and Dawkins, 1967; Roberts and Feast, 1973a; Froud-Williams et al., 1983; Roberts, 1983) depending on the nature of the dominant species (Roberts, 1962).

The species composition of the seed bank of an arable soil is mainly represented by annuals (Kropáč, 1966; Roberts, 1970; Barralis, 1973; Lewandowska and Skapski, 1979; Dvořák and Krejčíř, 1980b; Roberts, 1981; Froud-Williams et al., 1983; Roberts, 1983). Very often a few species can account for most (70 to 80%) of the seeds found in the soil (Roberts, 1970; Barralis, 1973; Roberts, 1981, 1983).

1.2 Methods of sampling seed banks

Descriptions of seed bank populations have been done repeatedly in various studies of agricultural and natural vegetation (Tables I and II of Appendix A). The problem in describing any seed population in the soil is associated with the inherent heterogeneity of the seed bank. The estimation of a seed bank must be based on a sampling procedure which will minimize the sampling effort and feature an element of randomness during sampling. This point has been made repeatedly for sampling of other kinds of community. However, very little work has been done to see how the application of sampling theory to seed bank studies affects the estimates when the underlying population is unknown. A casual inspection of a seed bank furnishes no information on plant abundance or distribution.

Many investigators have been concerned with the efficiency of extraction techniques used to obtain seeds from soil samples (Brenchley and Warington, 1930; Dyer, 1938; Rabotnov, 1958; Kropač, 1966; Malone, 1967; Feast and Roberts, 1973; Thorsen and Crabtree, 1977; Fay and Olson, 1978; Standifer, 1980; Roberts, 1981). Only a few investigators, were concerned with the efficiency of the various sampling methods in estimating the desired statistics. They have concentrated their studies on (i) defining the dimension of the sampling unit (or soil core) used; (ii) defining the sample size (or total number of soil cores) needed and (iii) describing of the seed distribution in the soil.

Many authors have looked also at the effects of either cultivation or vegetation cover on the distribution of seeds in the soil profile. In so doing, a wide variety of sampling methods has been used but frequently many investigators have failed to identify their sampling method clearly (Table IV of Appendix A). To my knowledge, no work has been done (i) to evaluate the efficiency of different sampling methods in estimating seed populations in the soil and (ii) to evaluate the effect of the seed distribution in the soil on the efficiency of different sampling methods.

1.3 Description of Chenopodium album L.

Chenopodium album (Chenopodiaceae) is known by several common names - fat-hen, pigweed, white goosefoot, amarante commune, ansérine, chou gras, farineuse herbes grasses, poulette grasse (Bassett and Crompton, 1978) but in Canada is officially called lamb's-quarters or chénopode

blanc (Alex et al. 1980). This cosmopolitan weed of Eurasian origin is found growing in disturbed waste places, roadsides and cultivated fields all over North America. In Canada, it has been recorded from coast to coast (Fig. 1).

Several life cycle stages of Chenopodium album are illustrated in Plate 1. The following botanical description is taken from Bassett and Crompton (1978, 1982) and Smith (1977):

annual, 1 to 2.5m high. Stem angular, greenish or sparsely farinose with sometimes reddish or purplish lengthwise stripes and ridges, ascending or erect, simple to much branched. Leaves alternate, petioled without stipules, mealy-farinose to nearly glabrous, ovate-lanceolate to rhombic-lanceolate, with sinu-dentate to entire margins, deep to light green, often turning reddish late in the season. Laminal-12cm long, 0.5-8.0cm wide and at least 1.5 times longer than wide. Plant wind pollinated, with small perfect flowers, clustered in elongate spikes of continuous glome-rules. Calyx 2-5 connate sepals, farinose to glabrous. Corolla absent. Perianth basally, united with keeled midrib, clasping or nearly enclosing the the mature fruit (or utricle). Stamens 5-merous, r[illegible] or 4, opposite sepals. Pistil with short style and 2 papil[illegible] stigmas. Gynoecium of 2 (rarely 3-5) united carpels, unilocular, 1-ovuled with superior ovary. Seeds horizontal, almost shiny black, generally circular, 1.1-1.5mm wide by 1.1-1.5mm long. Pericarp smooth, very thin, adherent or nonadherent. Testa smooth or with faint radiating reticulate-regulate ridges. Embryo coiled. Chromosome number, 27 pairs. Flowers from late May to October.

Figure 1 The distribution of three Chenopodium spp. in Canada.

Source: Bassett and Crompton, 1978.

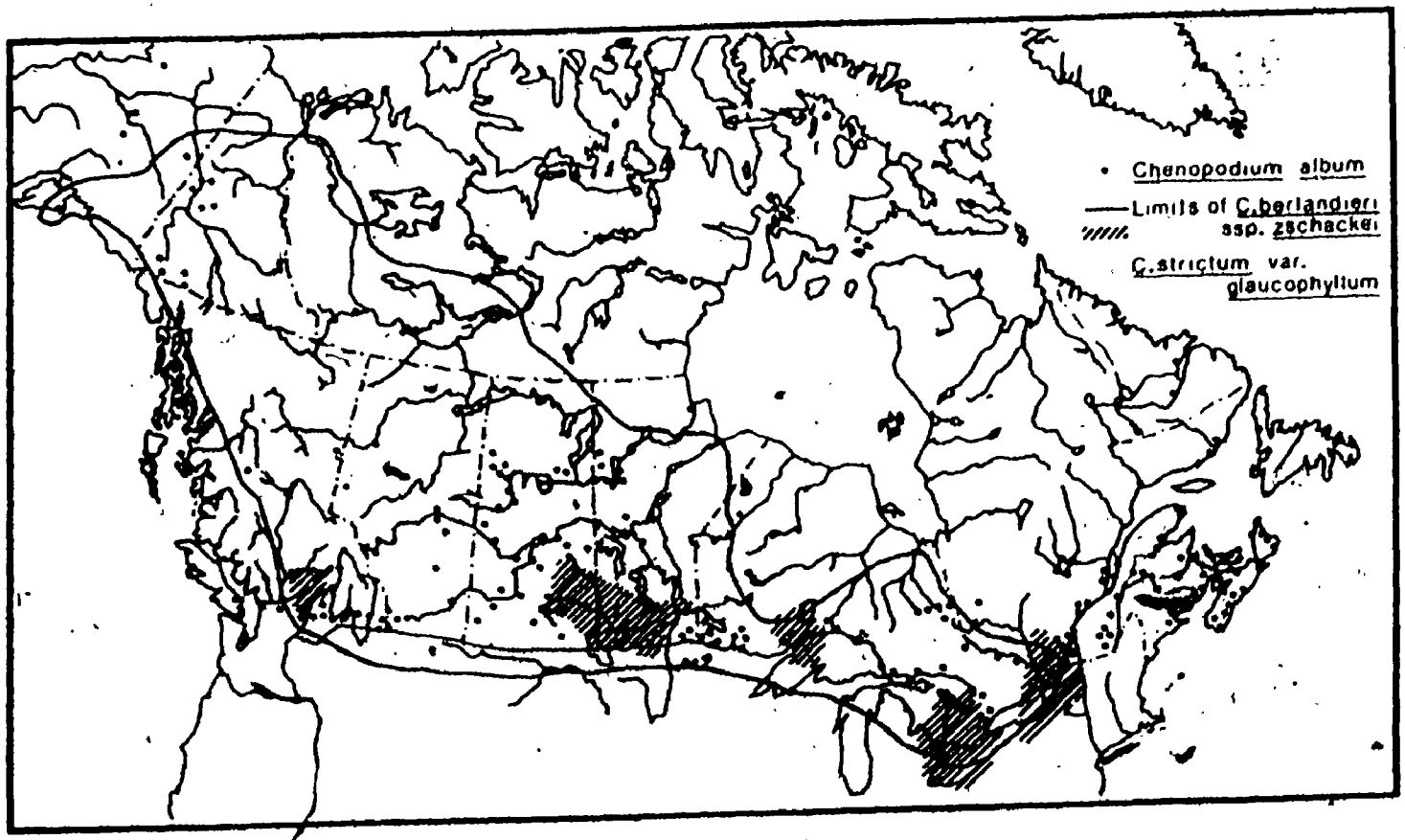
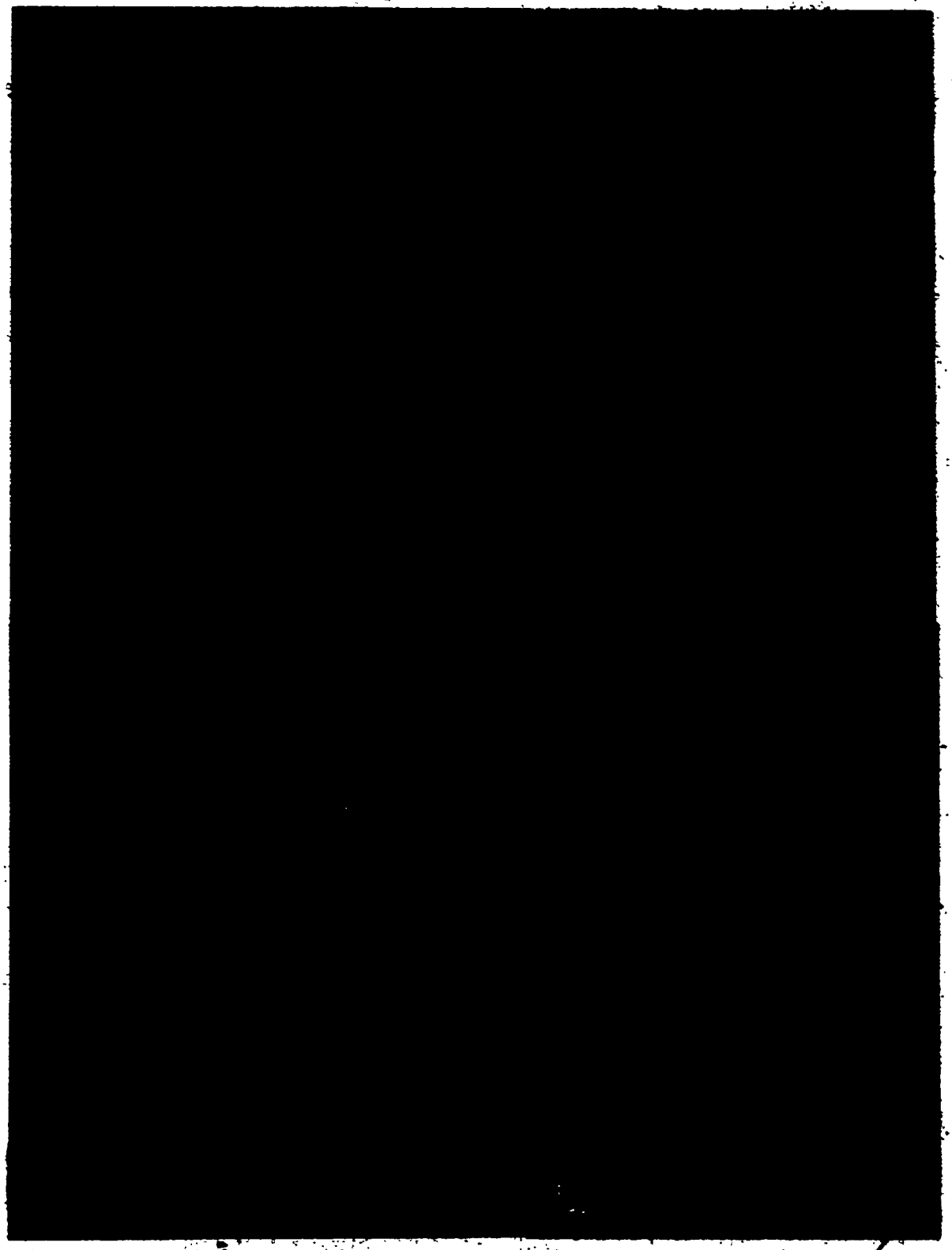

• Chenopodium album
——Limits of C.berlandieri ssp. zschackei
C.striçtum var. glaucophyllum

Plate 1 *Chenopodium album* L. 1) 28 day old seedlings; 2) adult plant; 3) top = black seeds, middle = brown seeds, bottom = underdeveloped seeds.

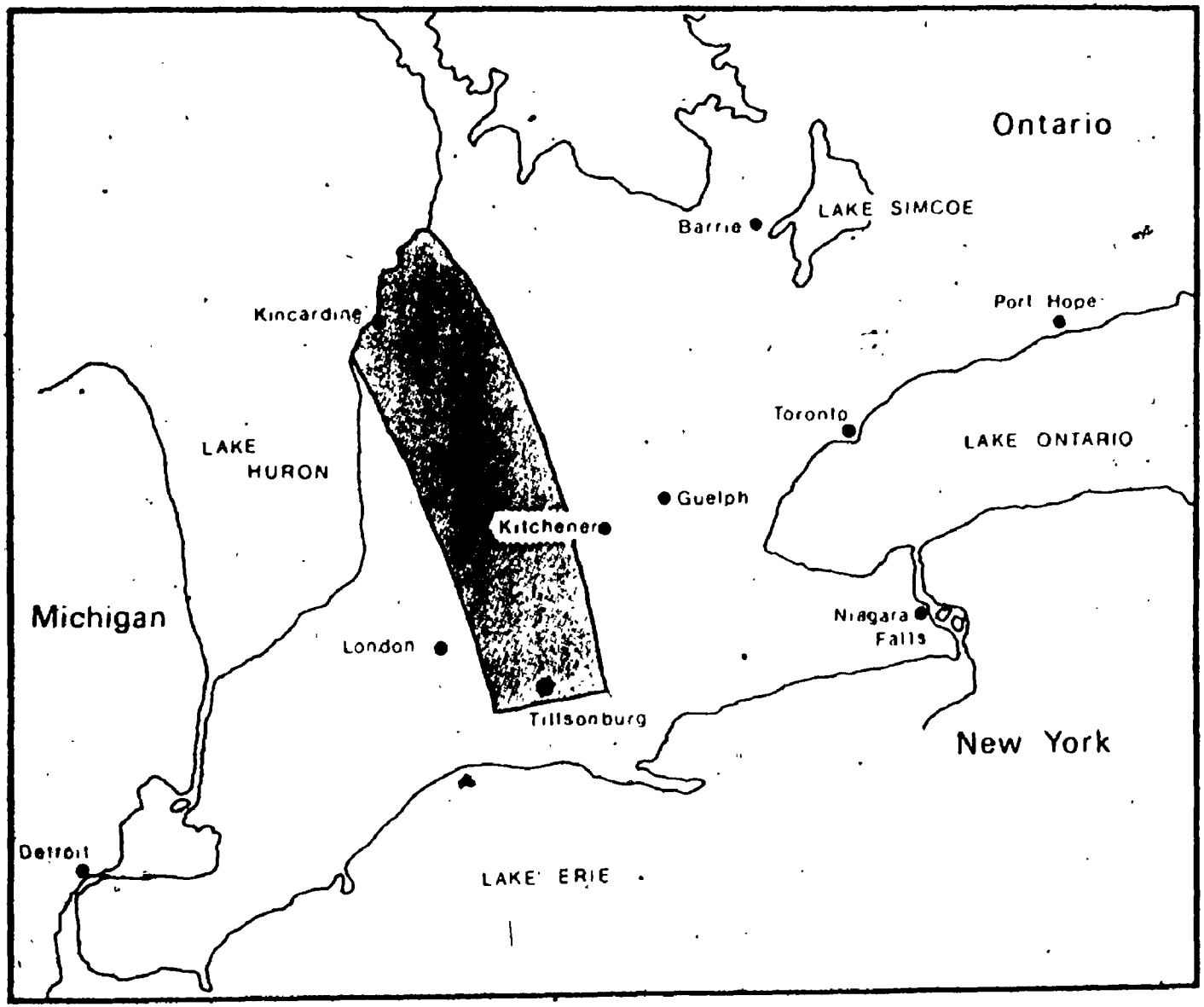


Within the genus Chenopodium, the botanical description of many species is difficult because of the plasticity of the macroscopic morphological characters of the genus (Bassett and Crompton, 1982). A comparison of the various North American floras indicates that there are differences in the nomenclature of many taxa (Bassett and Crompton, 1982). It is very difficult to identify plants to the species level unless they are flowering and fruiting. To identity a plant by only its seed can become impossible since many features of the seeds are no longer visible after a prolonged stay in the soil. For this reason, I will often refer to Chenopodium species rather than Chenopodium album.

Seeds of Chenopodium species can remain in the soil for many years. They have been found in archeological sites both in Europa (Ødum, 1965) and in North America (Yarnell, 1964 cited in Erichsen-Brown, 1979). Chenopodium album seeds were found at the Juntunen site (800 A.D. - 1320 A.D.) in Michigan and this finding tends to indicate that it was probable native to the region and was not introduced from Europe as previously believed (Yarnell, 1974 cited in Erichsen-Brown, 1979).

Triazine resistance in certain populations of Chenopodium album was first reported in Washington State in 1973 (Anonymous 1973; Peabody 1974). Presently, triazine-resistant lamb's-quarters are found in 29 counties in Ontario (Alex and McLaren, 1983) (Fig 2). Populations of resistant and susceptible biotypes of Chenopodium album in southern Ontario exhibited variation in growth characteristics and these variations were correlated with geographical location and climatic differences between these locations (Warwick and Black, 1981; Warwick and

Figure 2. Distribution of triazine-resistant Chenopodium album in southwestern Ontario, according to Bandeen et al. (1982).


Ontario
LAKE SIMCOE
Barrie
Kincardine
Port Hope
Toronto
LAKE ONTARIO
LAKE
HURON
Guelph
Kitchener
Michigan
London
Niagara
Falls
Tillsonburg
New York
Detroit
LAKE ERIE

Marriage, 1982a,b). My work is centered on a farm which had had large populations of triazine-resistant Chenopodium album for several years.

1.4 The importance of Chenopodium album as an agricultural weed

Chenopodium album is listed as the tenth worst weed in the world and is reported in 40 crops in 47 countries (Holm et al., 1977). It is considered an important weed of cultivated fields, grain crops and gardens (Muenscher, 1980). It has been also reported as a problem in plantings of nursery stock (Fletcher, 1983).

In Canada, Alex (1964) reported Chenopodium album as ranking second in abundance of weeds in tomato fields surveyed in three Ontario counties. It was ranked among the ten most important weeds in cropland in Saskatchewan by Thomas (1977). Doyon and Bouchard (1981) recorded Chenopodium album in 36% of the corn fields surveyed in St-Hyacinthe County, Quebec. However, in cereal crops, it was reported in 74 to 93% of the fields surveyed in different regions of Quebec (Doyon, 1984).

Since Chenopodium album is such an important weed, efforts have been made to control it by the timely use of cultural and chemical methods. Lamb's-quarters can be controlled effectively by several herbicides applied either as a pre-emergence (PRE), a post-emergence (POST) or a pre-plant incorporated (PPI) spray (Bandeen and McLaren, 1976).

A major factor in the success of lamb's-quarters as an important arable weed is the persistence of its seed bank. The longevity of

dormant lamb's-quarters seeds in the soil is documented as 20 years or more (Bassett and Crompton, 1978). Since the plants are prolific seed producers, the escape of a few lamb's-quarters plants can contribute many thousands or even millions of seeds every year to the seed bank. Chenopodium album exhibits "somatic seed polymorphism" (as defined by Harper, 1977) by producing both black and brown seeds (Williams and Harper, 1965). Black seeds show dormancy and are produced in great quantities. The larger brown seeds germinate quickly and are produced early in the season and in much smaller quantities (Williams and Harper, 1965). Because black seeds exhibit dormancy, they form the seed bank of lamb's-quarters. However, the contribution of brown seeds to the seed bank is not documented and may be of some importance if they are present.

I chose to study the seed bank of lamb's-quarters rather than the total seed bank because this species is an economically important weed and a major contributor to the seed bank of arable soils in temperate regions (Roberts 1981, 1983). The presence of large populations of triazine-resistant lamb's-quarters on the farm where my work was carried out, guaranteed the presence of a large seed bank of lamb's-quarters.

1.5 Purpose of this thesis

The aim of seed bank studies is generally to estimate the seed population in the soil. In order to achieve this goal, the sampling procedure must ensure that the samples are representative of the population and devoid of selection bias. Since Chenopodium album is an important agricultural weed and a major contributor to seed banks of arable soils,

this genus was chosen for our investigation.

Because little attention has been paid previously to the efficiency of different sampling procedures in estimating seed populations in the soil, the first objective was to evolve sampling procedures for seed bank studies which would permit an unbiased estimate of the size of the seed bank while minimizing the sampling variance (or increasing the precision) and maximizing the efficiency of the sampling effort. The dimension of the sampling unit (or soil core), the sample size (or total number of soil cores) and the sampling method (random vs systematic vs stratified random vs cluster) were the components of the sampling procedure which were investigated in this study.

The second objective was to describe with precision the seed bank of Chenopodium spp. in several cultivated fields. Attempts were made to determine the proportional contribution of black and brown seeds to the seed bank and to describe their physical state in the soil. Special attention was paid also to the sampling procedure and its effect on the estimate of the size of the seed bank of Chenopodium spp.

CHAPTER 2

SAMPLING METHODS FOR ESTIMATING THE SEED BANKS OF WEEDS IN THE SOIL

2.1 General Principles of Sampling Theory

The purpose of any procedure of sampling from a population is to obtain a sample which within its size limitations, will describe the desired characteristics of that population as closely as possible (Yates, 1960; Zar, 1974). Thus, any sampling procedure consists of two parts: a means of taking the sample (i.e. the sampling method) and a set of rules for making estimates about the population from the results of the sample (Snedecor and Cochran, 1980).

In the first part of the sampling procedure, an element of randomness must be included so that the sample is representative of the population. Randomness will allow one to make valid inferences about the population as well as remove any possibility of selection bias (i.e. unduly favouring selection of any one sample)(Steel and Torrie, 1960). The sample can thus be drawn entirely at random, or at random subject to restrictions which improve the accuracy without introducing bias into the results (Yates, 1960). Absence of selection bias does not automatically imply that estimation bias will be avoided (Stuart, 1976). The second part of the sampling procedure (the rules for making estimates) should exhibit efficiency, computational convenience and absence of bias (Yates, 1960).

Before deciding on a sampling procedure one must always consider a) the information sought, b) the problem under investigation and c) the degree of precision necessary (Greig-Smith, 1964, p. 21). Most studies can be divided into two categories: those restricted to a small number of variables in a large context and those dealing with a large number of variables in a small context (Elliott, 1977). In vegetation studies, variables usually refer to species and the context is the sampling area under investigation. The area must be defined clearly before any further considerations of the sampling procedure can take place (Elliott, 1977). Other considerations entering into the sampling process are: a) the dimensions of the sampling unit, b) the number of sampling units in each sample and c) the location of the sampling units in the sampling area (Elliott, 1977).

2.1.1. Dimensions of the Sampling Unit

Quantitative studies of vegetation have dealt for the most part with the description of plant populations. The most commonly used sampling unit has been the "quadrat". Greig-Smith (1964), p. 20-34, has thoroughly discussed the problems associated with the choice of the size and shape of quadrats.

The choice of a sampling unit for any survey rests on a few general principles. First, the units should be defined clearly so that an adequate sample can be obtained at a reasonable cost (Sampford, 1962). This is an essential requirement. Secondly, the sampling units should be uniform in size and enumeration within each unit should be feasible

(Sampford, 1962). Third, a sampling unit from which data can be recorded cheaply is often preferable to one which is less variable but more costly or less convenient to enumerate (Sampford, 1962). However, provided that the unit is large in comparison to the size of the individual (Sampford, 1962), the final choice in the sampling unit is very often a compromise between the statistical and practical requirements (Elliott, 1977).

If a population is truly random, then all sizes of sampling unit will be equally efficient (i.e. give estimates of equal precision) in estimating population parameters (Kershaw, 1973; Elliott, 1977). However, if the population is clustered, a smaller unit is more efficient than a larger one (Elliott, 1977). A small sampling unit is also more advantageous for the following reasons: 1) More units can be taken and processed with the same amount of labour in a sample (Elliott, 1977). 2) If a fixed volume of soil is to be collected, a sample of small units has a lower statistical error because of its greater degrees of freedom than a sample of larger units (Elliott, 1977). 3) Many small units can cover a larger proportion of the sampling area and thereby become more representative of the area (Elliott, 1977).

2.1.2 Number of Sampling Units (or Sample Size)

One of the fundamental problems in setting up a sampling procedure is to determine the number of sampling units needed to describe the population adequately. As a general rule, an increase in sample size will give a better estimate of the mean of the population, but to reduce

the standard error requires a very large sample size (Kershaw, 1973). Thus, it is recommended that one take as large a sample as time (Kershaw, 1973) and labour will permit (Elliott, 1977). It is also essential to describe fully the sampling method used, and the degree of precision required in all aspects of the investigation (Sampford, 1962). An estimate of the variance of the variable under investigation is needed to determine the minimum sample size (Sampford, 1962). Such estimates may be obtained from a previous survey, a pilot survey or a related study (Sampford, 1962).

The minimum number of sampling units need not be the same for different variables of the same population (Greig-Smith, 1964). Consequently, a compromise may be made on sample size but there is no reason why this number should be the same for different variables (Greig-Smith, 1964).

2.1.3 Sampling Methods

Randomness can be incorporated in various ways into the sampling procedure. The most common sampling methods are 1) simple random sampling, 2) systematic sampling, 3) stratified random sampling and 4) cluster and multi-stage sampling (Steel and Torrie, 1960; Cochran, 1977; Snedecor and Cochran, 1980). A summary of the properties of each of these sampling methods is given below.

a) Simple random sampling

With this method each possible sample has an equal (or known)

chance or probability of being selected (Zar, 1974; Stuart, 1976; Elliott, 1977; Snedecor and Cochran, 1980). Random selection provides us with unbiased estimates of population means (Cochran, 1977; Kenkel, 1981). An unbiased estimate of the sampling variance can also be calculated (Sampford, 1962; Cochran, 1977). However, this method does not enable the investigator to take account of any known relevant information about the nature of the population (Snedecor and Cochran, 1980). This method is most appropriate for populations with low variability (Steel and Torrie, 1960).

b) Systematic sampling

There is at least one pre-requisite for this sampling method: a complete description of the individual elements and their arrangement in the population. The first sampling unit is drawn at random from the population and every i^{th} unit is selected until the required sample size has been obtained. Provided that the first sample unit is located randomly within the population, then an unbiased estimate of the population mean can be obtained (Sampford, 1962). An advantage of this method is the ease with which samples can be obtained (Sampford, 1962; Elliott, 1977; Snedecor and Cochran, 1980).

Systematic sampling may be more accurate than simple random sampling in certain instances since the sampling units are more evenly distributed throughout the entire population (Poole, 1974). Unfortunately, an unbiased estimate of the standard error of the sample mean (Sampford, 1962; Poole, 1974; Elliott 1977; Snedecor and Cochran, 1980; Kenkel, 1981) cannot be calculated.

c) Stratified random sampling

Stratified random sampling is thought to combine the advantages of both random and systematic sampling (Mueller-Dombois and Ellenberg, 1974). A population is first divided (stratified) into subpopulations or strata, which may or may not be of equal size (Stuart, 1976). Within each stratum a sample is selected randomly and independently. Sampling within each stratum enables the sampling units to be more evenly distributed throughout the whole population (Yates, 1960; Elliott, 1977). For this method to be better than random sampling, these strata should be more homogeneous than the whole population (Elliott, 1977; Snedecor and Cochran, 1980)(i.e. their variances should be minimized while the differences between their means is maximized (Stuart, 1976))and should be of known sizes. An efficient allocation of the physical resources (labour and fixed costs) is usually associated with such stratification (Steel and Torrie, 1960). Very often stratification will be based on arbitrary factors (Stuart, 1976) such as geographical divisions, temperatures, etc.

With stratified sampling, the investigator can choose the sample size within any stratum (Snedecor and Cochran, 1980). The allocation of samples within strata can be achieved by two methods: a) proportional allocation or b) optimal allocation. With the former, the sampling fraction is the same for all strata while with the latter, the sampling fraction is proportional to either the size, the standard deviation or the cost per sampling unit of each stratum. In general, each stratum should be sampled by the most efficient method. The choice of a specific means of allocating sampling units for all strata is only used for

convenience in analysis (Sampford, 1962) and in this study proportional allocation was chosen.

One disadvantage of this sampling method is that stratification increases the complexity of the analysis (Sampford, 1962).

d) Cluster and multi-stage sampling

Cluster sampling is similar to simple random sampling whereby groups of units are selected randomly from the population (Stuart, 1976). These groups can also be called clusters or primary units and be composed of secondary units. With cluster sampling all secondary units are sampled (Steel and Torrie, 1960) In situations where a random sample of secondary units is chosen, the process is called multi-stage sampling (Yates, 1960; Sampford, 1962). The clustering method will work best when the individuals within a cluster vary as much as possible while the cluster means are as similar as possible (Sampford, 1962; Stuart, 1976). This leads to a reduction of the variance of the population of cluster means but to an increase in the average within-cluster variance (Sampford, 1962, Stuart, 1976). The occurrence of clusters having these characteristics does not happen often (Stuart, 1976).

The main advantage of cluster sampling is practicality. Clusters or groups are often easier to identify and locate than individuals (Sampford, 1962). The second advantage is the economical use of available resources (Sampford, 1962). However, this is achieved at the expense of a greater complexity in the selection process as well as in the analysis of the results (Stuart, 1976).

2.2. Sampling Principles for Seed Bank Studies

The principles of sampling theory discussed in the previous section have been applied extensively in quantitative and qualitative studies of vegetation. However, very little work has been done to see how the application of sampling theory to seed bank studies affects the estimates when the underlying population is unknown. Those investigators that have looked at this problem, have concentrated their efforts in three different areas: the dimension of sampling units, the sample size and the seed distribution in the soil.

2.2.1 Dimensions of Sampling Units in Seed Bank Studies

The ramifications of the dimensions of the sampling unit have been investigated by Rabotnov (1958), Kropáč (1966), Cavers and O'Toole (1981, and unpublished) and Tulikov et al. (1981). An important aspect of soil sampling for seed content is the time and labour needed to identify and quantify seeds from soil samples regardless of the techniques used (soil washing or seedling emergence). Ultimately the total soil volume sampled is the limiting factor in seed bank studies. The depth to which sampling units are taken will depend on the purpose of the investigation, the type of vegetation and the volume of soil which can be processed.

Numata et al. (1964a), Hayashi and Numata (1971) and Forcella (1984) estimated species-soil volume curves for the plant communities they investigated. Hayashi and Numata (1971) determined the minimum

soil volume needed to characterize Miscanthus- and Zoysia-type grasslands as 0.5-0.6 liters. In fact Hayashi (1975 cited in Roberts, 1981) suggested that enough samples should be taken to double the minimum soil volume recommended. More recently, Forcella (1984) demonstrated that individual soil samples of 50-200 cm^2 (10 cm deep) were adequate to record the species diversity in the seed banks of pasture. He also indicated that the estimation of seed density did not change as a function of the size of the sampling unit.

Dospekhov and Chekryzhov (1972) and Tulikov et al. (1981) used soil weight to describe their sampling unit. The latter authors recommended 0.5-1.0 kg soil samples to estimate the number of weed seeds and samples $\geq$1 kg to determine the species composition of weed seeds in the soil.

Most investigators have arbitrarily chosen a sampling unit based on the availability and practicality of the sampling tool. Soil texture and compactness often influence the choice. The tools may range from knife, trowel, home-made steel frame, golf cup-cutter and bulb planter to brass pipe, 'ID' soil probe, 'SS Shine's' auger, 'Nekravov's' auger and 'Ekman' dredge. Regardless of the auger or cylindrical borer chosen, compaction occurs so that the volume of undisturbed soil in a core is not constant and can change with soil depth and texture (Böhm, 1979). A summary of the different dimensions of sampling units used in seed bank studies is given in Tables V to VII of Appendix A. It may be concluded that not only has there been no standard sampling unit used in seed bank studies but in fact there has been more variability in types of samplers than has been used with other vegetation.

2.2.2. Sample Size in Seed Bank Studies

The determination of sample size in seed bank studies has been investigated specifically by Champness (1949a), Rabotnov (1958), Goyeau and Fablet (1982) and Forcella (1984). The consensus among investigators working on the description of seed banks in the soil is that a large number of small sampling units is more appropriate than a small number of large units (eg. Roberts, 1958; Kropáč, 1966; Roberts, 1970; Dospekhov and Chekryzhov, 1972) However, in most studies the sampling cost, the available resources (time, space and labour) and the sampling tool available have influenced the choice of sample size and a "reasonable" number of sampling units is usually chosen (Table III of Appendix A).

The number of sampling units needed to estimate the number of seeds in the soil (either of specific species or for the total seed number) increase as the requirement for precision increases (Table I). Fewer sampling units will be needed if estimates are required for the total seed number, the most abundant species and those species evenly distributed in the soil (Rabotnov, 1958). Champness (1949b, cited in Major and Pyott, 1966) suggested 300 sampling units of 250 cm^2 each if the mean number of seeds of individual species per sampling unit is to be estimated within 10% of the mean. For sampling units with total seed numbers ranging from three to ten, 70 sampling units would be required to ensure a result within 10% of the mean and 200 sampling units would be needed to estimate the most abondant species. However, most investigators have collected too few sampling units to make reliable

Table 1 The number of sampling units (10 x 10 cm) needed to estimate the number of seeds in a meadow*.

Variables	Precision (%)†		
	± 10	± 15	± 20
Total seed bank	15	7	4
Seed bank of individual species	29-1587	13-705	7-397

* Summarized from Table 1 of Rabotnov (1958)
Estimates were made for individual species and for the entire seed bank.

† Precision is defined as the half-width of the confidence limits

estimations of the total number of seeds in the seed bank (Table III of Appendix A).

If the seed distribution is expected to be aggregated, the sample size should also be greater than one hundred (Goyeau and Fablet, 1982). Studies by Goyeau and Fablet (1982) and Pratt et al. (1984) seem to indicate that the number of sampling units needed to describe a seed bank depends on the expected seed density and not on the size of the surveyed area (Table 2). Since plant species differ in their seed distributions in the soil (Goyeau and Fablet, 1982), the sample size needed to describe the seed bank may vary from species to species.

Efforts should be made to record data for separate sampling units, rather than for bulked samples. Estimates of variation of the mean values (SD, SE, $S_{\bar{x}}^2$ or CV) can then be calculated (Roberts, 1981). Unfortunately, this has not always been done. Many investigators have either subsampled their individual sampling units, bulked all of their sampling units or subsampled their bulked sampling units. In some cases several cores made up each sampling unit, which was in turn subsampled after thorough mixing (Table VIII of Appendix A).

In situations where all sampling units were bulked, dry weight as well as volume has been used to measure subsamples (Table 3). Rabotnov (1958) tried to determine the size of the average subsample one should take in order to estimate with some degree of precision the size and the species composition of a seed bank. His results indicated that subsamples 1/20 and 1/10 of the total bulked sample underestimated the species

Table 2 The number of sampling units of 5 cm diameter (19.6 cm^2) needed to estimate with 20% precision ($\alpha = 0.01$) the average seed density in the soil*.

Seed density ($\bar{X}$ / sampling unit)	Required sample size
$\bar{X} > 40$	10 - 20
$5 \leq \bar{X} \leq 40$	~ 50
$1 \leq \bar{X} \leq 5$	100 - 200
$\bar{X} < 1$	> 200

* From Goyeau & Fablet (1982)

° Precision is defined as the half-width of the confidence limits.

Table 3 Comparison of the size of subsamples extracted from bulked sampling units used to describe seed banks. Only studies where the size of the subsamples were given, are included in this table.

Reference	Number of sampling units	Dimension of sampling units (cm)*	Depth of sampling units(cm)	Number of subsamples†	Size of individual subsamples	% of total volume of soil subsampled
Hurle, 1974	5	20 x 20	25	5	2.1 kg	-
Roberts and Ricketts, 1979	20	2.5	10	5	200 g	-
	16	2.5	10	3	200 g	-
Johnston et al., 1969	75	10	2.5	3	250 cc	5.1
Livingston and Allesio, 1968	20	10	11	2	4630 cc	25.0

* A single value refers to the diameter of the sampling unit.

† Measures of weight refer to dry weight of soil.

composition. They did not reflect the seed number of individual species with enough precision. Marginally, subsampling could be used to determine the total number of seeds and the number of seeds of the most abundant species (Rabotnov, 1958).

In summary, the total number of seeds and the number of seeds of an abundant species in the soil can be estimated with precision if a large number of small sampling units is collected. These should preferably be processed individually to permit the estimation of the sampling variance.

2.2.3 Seed Distribution in the Soil

The depth of the sampling unit varies with the purpose of the study and the type of vegetation surveyed (Tables V to VII of Appendix A). Arable soils are often sampled to the depth of the plough layer (15-25 cm), while sampling the upper 10 cm of meadows and pastures may be sufficient (Rabotnov, 1958).

Many authors have looked either at the effects of cultivation or of the vegetation cover on the distribution of seeds in the soil profile. Such factors as zero tillage in conjunction with good weed control (Froud-Williams et al., 1983), good vegetation cover in pasture (Rabotnov, 1958; Kropáč, 1966) and certain cultural practices such as ploughing (Roberts and Stokes, 1965), all result in a small number of seeds in the upper soil layer (0-5 cm). However, if seed shedding occurs either in a natural environment (Roach, 1983) or as a result of inadequate weed

control in an agricultural environment (Kropáč, 1966; Froud-Williams et al., 1983), the upper soil layer (0-5 cm) will contain a large number of seeds.

High seed density is also observed in the uppermost soil layer described by the 0-1 cm soil layer (Hodgkinson et al., 1980) or by the 0-2 cm soil layer of several kinds of natural vegetation (Major and Pyott, 1966; Hayashi and Numata, 1971; Leck and Graveline, 1979; Zimmergren, 1980). The number of seeds and the species diversity in the uppermost soil layer (0-2 cm), however, may not necessarily reflect the size of the seed bank. For example, the number of seeds in the uppermost layer of riverbank meadows can exhibit great yearly fluctuations and be more reflective of the seed input and germination conditions in a given year than the total size of the seed bank (Rabotnov, 1958).

The problem of describing the seed distribution in the soil (both horizontal and vertical) is associated with its inherent heterogeneity. Seeds often are shed close to the parent plant with the result that the seed population in the soil exhibits an aggregated distribution rather than a normal one (Major and Pyott, 1966). The most abundant species often have a normal seed distribution, while the less abundant ones usually have a Poisson or aggregated distribution (Goyeau and Fablet, 1982).

Seed populations in the soil are frequently and erroneously assumed to be homogeneous and normally distributed. The sampling methods used to sample these populations can lead to biased estimates. A wide

variety of sampling methods has been used in previous studies (Table IV of Appendix A). However, no work has been done to evaluate the efficiency of different sampling methods in estimating seed populations in the soil.

2.3 Objectives of the Present Study

The purpose of this study was to compare sampling methods in their estimation of the size of the seed bank of a major species and their efficiency in minimizing the sampling variance. The species under investigation was Chenopodium album. However, since the extraction method did not permit the identification of the seeds to the species level, they were grouped as Chenopodium spp.

Five objectives were defined for this study and these are listed below:

1) to determine the most appropriate diameter of sampler to estimate the density of seeds in the soil.
2) to determine the homogeneity of variance of the sampling units used to estimate the seed distribution in the soil over a small area (0.25 m^2).
3) to determine the homogeneity of variance of the sampling units used to estimate the seed distribution in the soil over a large area (1.35 ha).
4) to determine the minimum number of sampling units needed to provide an acceptable estimate of the mean density and the sampling variance of a population.

5) to determine which sampling method minimizes the sampling variance.

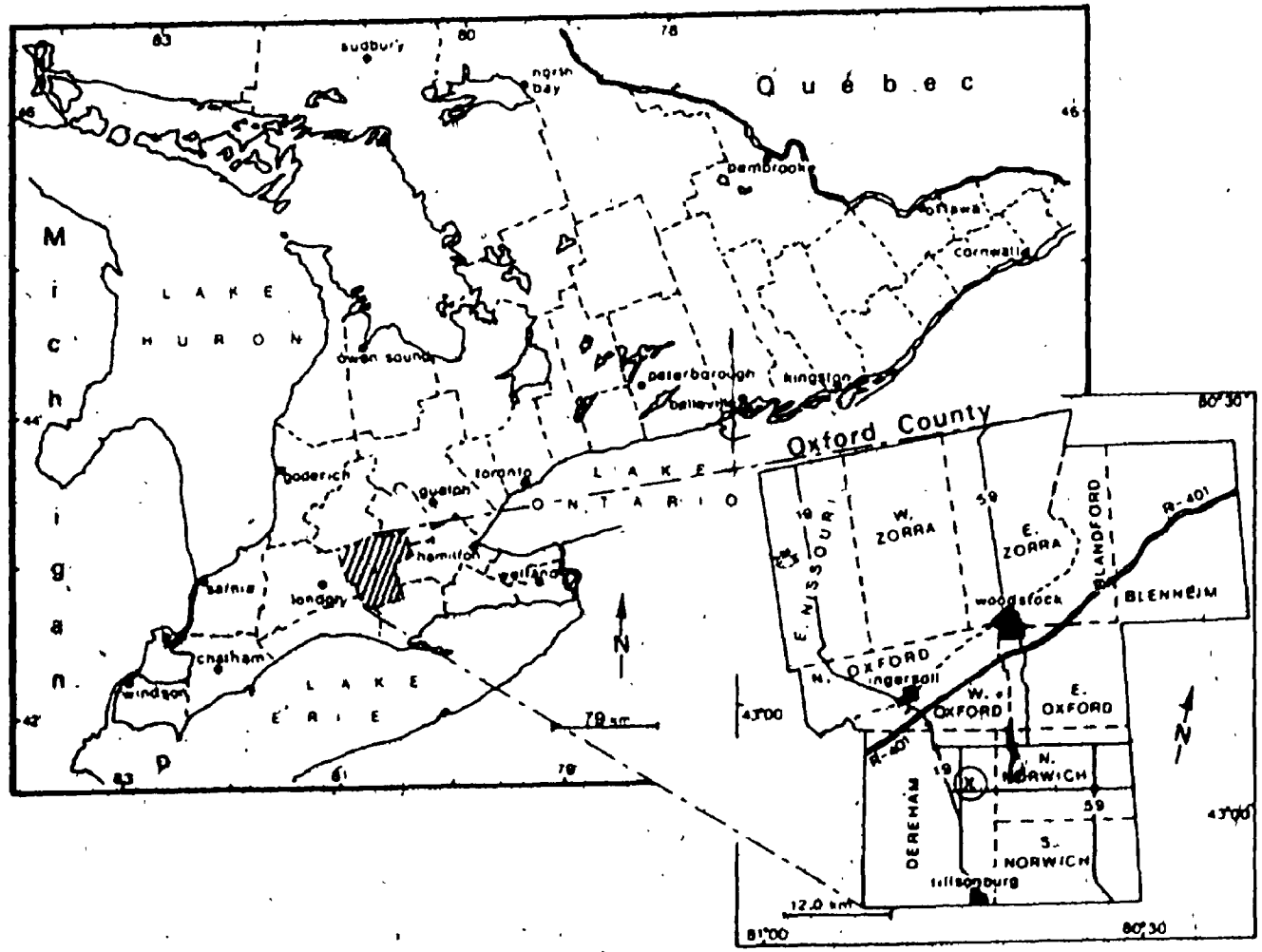
Separate experiments were conducted to test each of the above objectives. Several assumptions were retained throughout the study. A sampler, circular in shape, was chosen and the sampling depth was 15 cm. The recommended depth of ploughing on this region is 6 in. (15 cm) so that soil from a sampling unit represented the ploughed layer of the field. A seed bank was defined as the viable seed population in the soil (Roberts, 1981). In this study, whole seeds which appeared intact, were presumed to be viable. The assessment of these apparently viable seeds can be adequate (Roberts and Ricketts, 1979; Roberts, 1981) but will tend to overestimate the seed bank (Roberts, 1981).

2.4. Description of the Sampling Site

In Dereham Township, Oxford County, Ontario where triazine-resistant Chenopodium album had been reported to occur (H. Wright, personal communication), Mr. John Tucsok's farm was identified as having a large population of triazine-resistant lamb's-quarters. This farm was located 4.0 km S.E. of the village of Mount Elgin and 2.1 km east of Highway No. 19 on Dereham road #5 (42° 56' N, 80° 46' W) (Fig. 3).

A field 9.7 ha in area was selected for the study. It was favored over other available ones because of its good drainage and level topography and the presence of a corn crop in 1982. A corn field was chosen because corn is the crop with the largest acreage in southwestern

Figure 3 Map of southwestern Ontario with Oxford County delineated in black and shown in expanded form in the inset. The location of the study area (X) in Dereham Township, Oxford County is marked in the inset.


Québec
Michigan
LAKE HURON
LAKE ONTARIO
LAKE ERIE
sudbury
north bay
pembroke
ottawa
cornwall
owen sound
peterborough
kingston
belleville
goderich
guelph
toronto
hamilton
st. catharines
sarnia
london
chatham
windsor
79 km
Oxford County
E. NISSOURI
W. ZORRA
E. ZORRA
BLANDFORD
BLENNEIM
woodstock
OXFORD N.
ingersoll
W. OXFORD
E. OXFORD
N. NORWICH
S. NORWICH
DEREHAM
tillsonburg
401
59
19
12.0 km
43°00
81°00
80°30

Ontario and large populations of Chenopodium spp. are present in corn fields. The soil profiles in the field were primarily those of the Perth series with a small area recognized as the Crombie series (Wicklund and Richards, 1961). For my purpose, a field was defined as a cultivated area excluding the border rows (or headlands) around it. A random area of 1.35 ha (155 paces x 155 paces) was marked permanently in the field and became identified as the sampling site (Fig. 4). A pace as measured by the field assistant was 0.7 m long.

2.5 Objective 1

To determine the most appropriate diameter of sampler to estimate the density of seeds in the soil.

2.5.1. Description of Samplers

Each sampler consisted of a 40-44 cm long metal cylinder of the desired diameter welded at right angles to a handle or fitted with a wooden handle. The other extremity of the cylinder was ground to a sharp edge. A 20-38 cm lengthwise cut was made 2.5-3.5 cm from this edge and a portion of the cylinder was removed (Fig. 5). This feature facilitated the cutting of a soil sample to the proper depth and also permitted easy removal of the core.

Three sizes of sampler, described in Table 4, were compared for efficiency in seed sampling and for the relative ease of processing of their samples. The small sampler was available commercially while the other two samplers were built to sample the required volume of soil. In

Figure 4 Schematic description of Mr. J. Tuesok's farm, Oxford County with the location of sampling site marked  . Numbers refer to field identification codes.

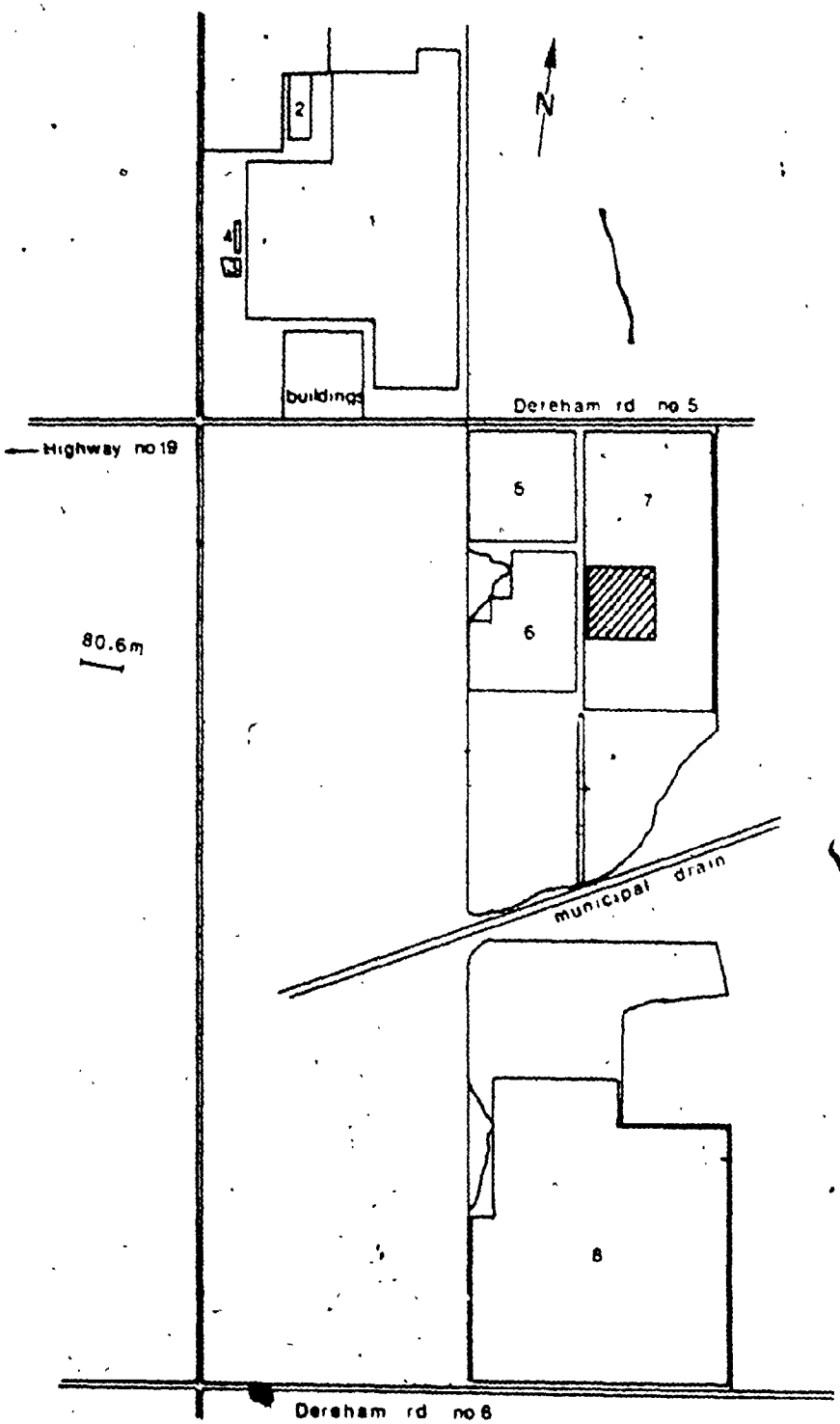
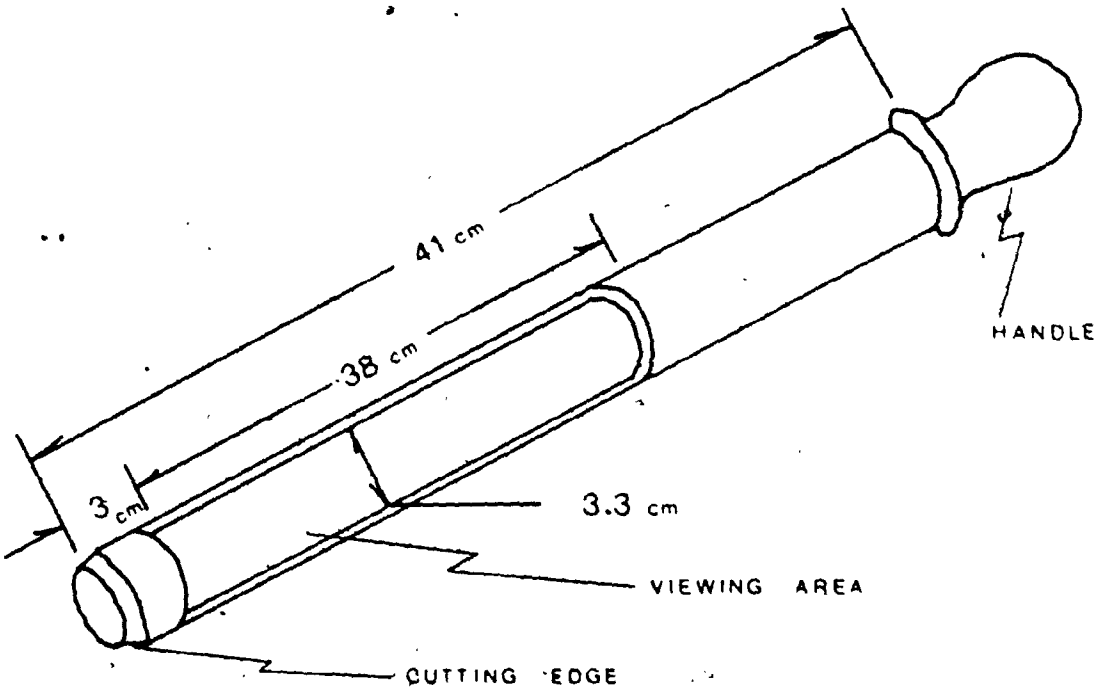

N
2
4
buildings
Dereham rd no 5
Highway no 19
5
7
6
80.6m
municipal drain
1
8
Dereham rd no 6

Figure 5 Schematic diagram of large soil sampler.


41 cm
38 cm
3 cm
3.3 cm
HANDLE
VIEWING AREA
CUTTING EDGE

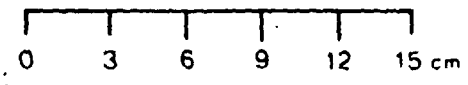

0
3
6
9
12
15 cm

Table 4 Characteristics of the different soil samplers.

Size of sampler	Diameter of sampler (cm)	Expected volume (ml) $V = \pi r^2 h$ *	Total no. of sampling units (n)
Small	1.9	42.5	60
Medium	2.7	85.9	30
Large	3.3	128.3	20

* V. = volume; r = radius; h = height

total, the volume of soil sampled with each type of sampler was equal to that from each other type. Consequently, the total number of soil cores taken with each size of sampler varied.

2.5.2 Sampling Procedure

Soil cores (15 cm deep) were taken at random within the sampling site with the number for each of the different sizes of sampler given in Table 4. Sampling was carried out on 5 November 1982 when most of the corn remained to be harvested. All soil cores were bagged individually in pre-labelled plastic bags. These were stored immediately in a constant temperature room (6.3 ± 0.8°C) until they could be processed.

2.5.3 Seed Extraction Method

Seeds were extracted from the soil cores according to a modification of Malone's (1967) technique (Appendix B). Once dried, all seeds were separated from the debris by hand under a dissecting microscope (6.4 X). The seeds were further separated into 1) Chenopodium spp. and 2) other seeds. For seeds to be placed into either of these categories they had to be recognizable as seeds and be whole with no sign of damage to the testa. These whole seeds were assumed to be viable. When cracks and indentations to the testa were observed, they indicated either an empty or rotten seed and consequently seeds with such characteristics were rejected. The total number of seeds and the number of Chenopodium spp. seeds were determined for every sampling unit.

2.5.4 Statistical Analysis

As both measured variables (the total number of seeds and the number of Chenopodium spp. seeds) were counts and many values were 0's, the values were further transformed by $\sqrt{(X + 0.5)}$ (Zar, 1974, p. 187) and all subsequent analysis was done on the transformed data. Comparison of the sampling units was made on an equal soil volume basis (100 ml) regardless of the sampler size. All results are reported in a retransformed form. The SAS program 'GLM' (general linear models) for unbalanced designs (Anonymous, 1982) was used to perform the analysis of variance.

Some areas of the field had already been harvested while in others, very wet soil conditions prevailed because of impeded drainage. A two-way analysis of variance was used to detect differences between means for comparisons involving the status of the harvest (not harvested vs harvested), the soil conditions (normal vs wet) and their interactions. Subsequently when the effects of these other factors were known, comparison of the means from samplers of different sizes were made.

2.5.5 Results and discussion

Samples obtained from either harvested or non-harvested sections of the field did not affect the number of Chenopodium spp. seeds or the total number of seeds per 100 ml of soil sampled. However, the differences in the number of seeds/100 ml of soil between wet and normal soil conditions was significant ($P \leq 0.05$) but the analysis of variance did not indicate any interaction between the two factors (Table 5 and

Table 5 Summary of an analysis of variance on the effect of the harvest status and soil conditions on the number of Chenopodium spp. seeds and the total number of seeds per 100 ml of soil†.

Source	df	No. seeds of Chenopodium spp. per 100 ml soil		Total number of seeds per 100 ml soil	
		Mean square	F value	Mean square	F value
Model	3	2.17	2.32 NS	2.34	2.28 NS
Harvest	1	0.55	0.58 NS	4×10^{-3}	4×10^{-3} NS
Wetness	1	4.10	4.37*	6.41	6.23* *
Interaction	1	1.87	1.99 NS	0.61	0.60 NS
Error	106	0.94		1.03	

$F_{0.05,1,106} = 3.94$

† The analysis was done on the transformed variables. The transformation was $(x + 0.5)^{1/2}$.

* = significant at the 0.05 level

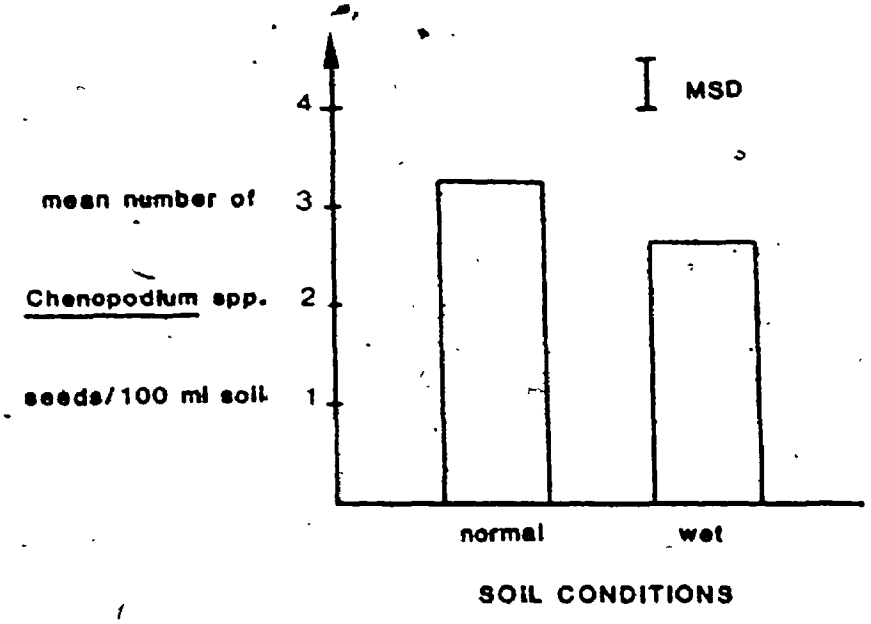
NS = non significant

Fig. 6). Sampling units that were collected from harvested areas with impeded drainage had greater numbers of seeds/100 ml soil. Consequently, these four sampling units were excluded from the subsequent analysis of variance.

There were no significant differences between samplers of different sizes in estimating the number of Chenopodium spp. seeds or the total number of seeds on a per volume basis (100 ml) (Fig. 7). However, the small sampler is recommended over the other sizes since samples of a smaller size are easier to collect and can be processed faster than larger ones. For the same total volume of soil sampled, the small sampler permitted a greater number of sampling units to be collected.

This result is in line with Kropáč's (1966) opinion that a large number of smaller sampling units is more advantageous than a few large ones. By subsampling an initial large sample, Rabotnov (1958) had already demonstrated that a small sample (1/10 of the original volume) could be used instead of the larger one for the estimations of the total number of seeds and the number of seeds of the most abundant species in the soil. Tulikov et al. (1981) found that smaller soil samples (100 g) overestimated significantly ($P \leq 0.01$) the total number of seeds in the soil. However, Forcella (1984) showed that the relationship between seed density and increasing size of sampling unit was poor, indicating that seed density was more or less constant.

Figure 6 The effects of the soil conditions on the estimation of the mean number of Chenopodium spp. seeds and the mean total number of seeds per 100 ml of soil. Results are given as transformed data ($\sqrt{x + 0.5}$). MSD refers to the minimum significant difference as calculated by the GT2-method (see Sokal and Rohlf (1981, p. 242-252) for the description of the method).


MSD
4
3
2
1
mean number of
Chenopodium spp.
seeds/100 ml soil
normal
wet
SOIL CONDITIONS

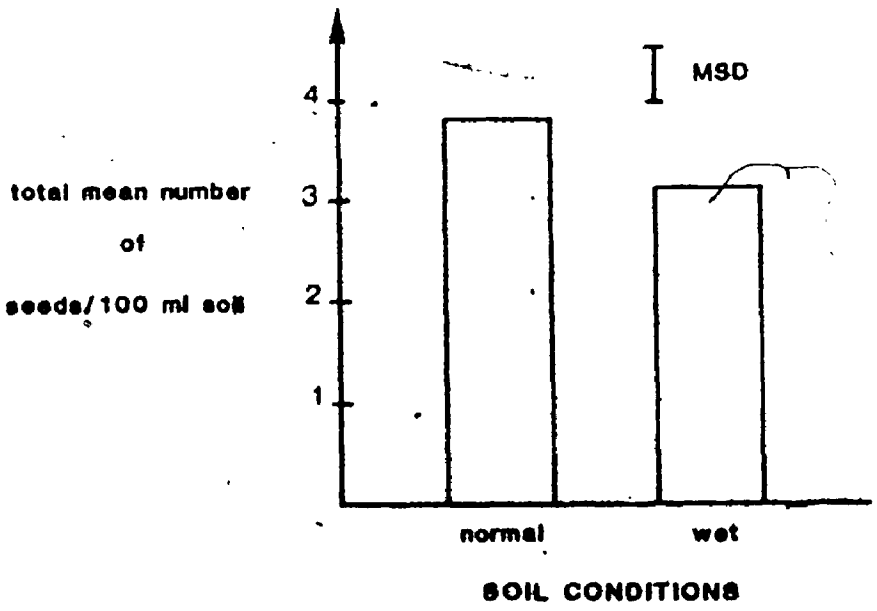
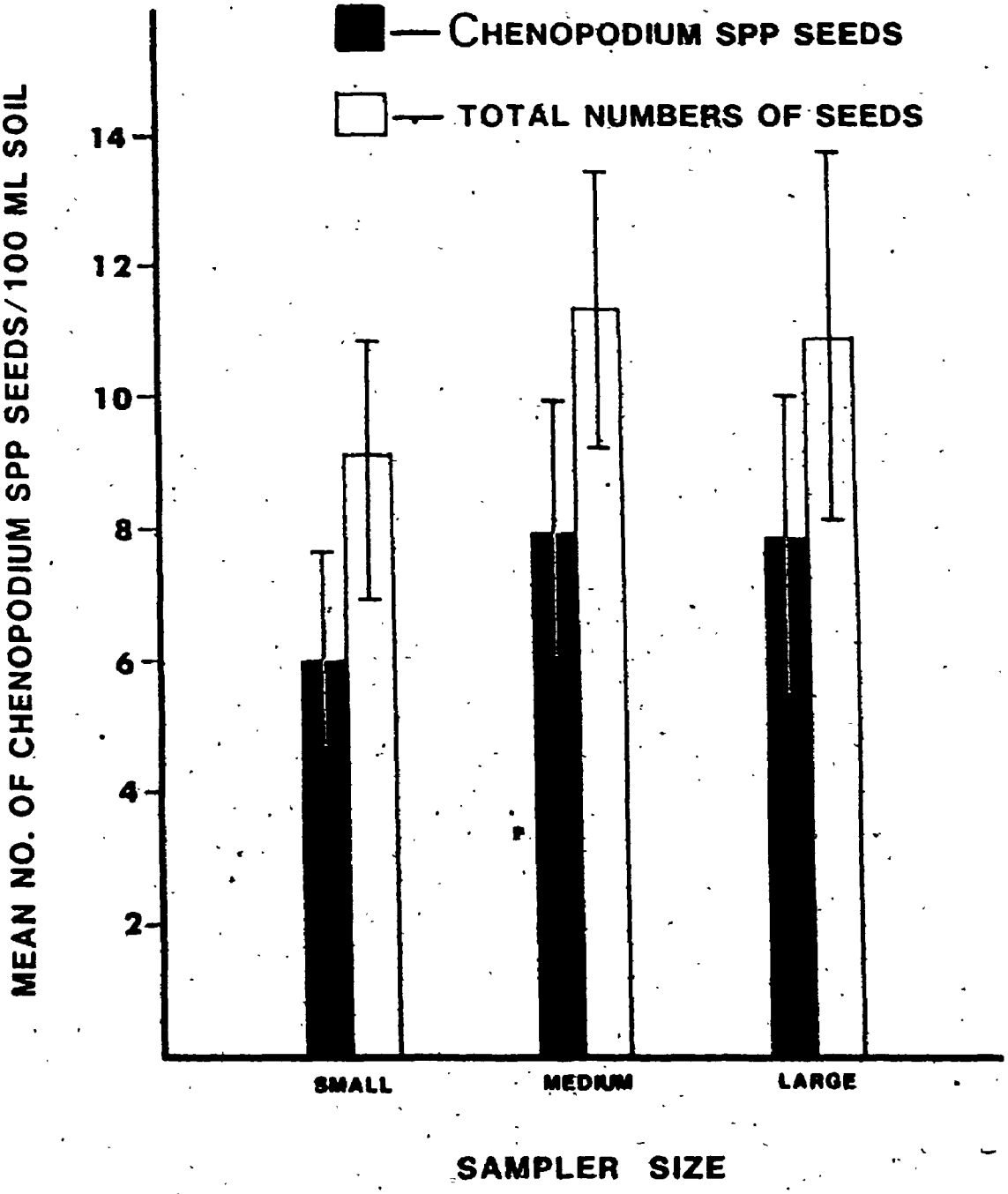

MSD
4
3
2
1
total mean number
of
seeds/100 ml soil
normal
wet
SOIL CONDITIONS

Figure 7 Comparison of different sizes of samplers in estimating $\bar{X}$ ± 95% CI of Chenopodium spp. seeds and the total number of seeds per 100 ml soil (small n = 58; medium n = 28; large n = 20). The small, medium and large sampler had diameters of 1.9 cm, 2.7 cm and 3.3 cm respectively. Results represent the retransformed data.


CHENOPODIUM SPP SEEDS
TOTAL NUMBERS OF SEEDS
MEAN NO. OF CHENOPODIUM SPP SEEDS/100 ML SOIL
14
12
10
8
6
4
2
SMALL
MEDIUM
LARGE
SAMPLER SIZE

2.6. Objective II

To determine the homogeneity of variance of the sampling units used to estimate the seed distribution in the soil over a small area (0.25 m^2).

2.6.1. Sampling Procedure

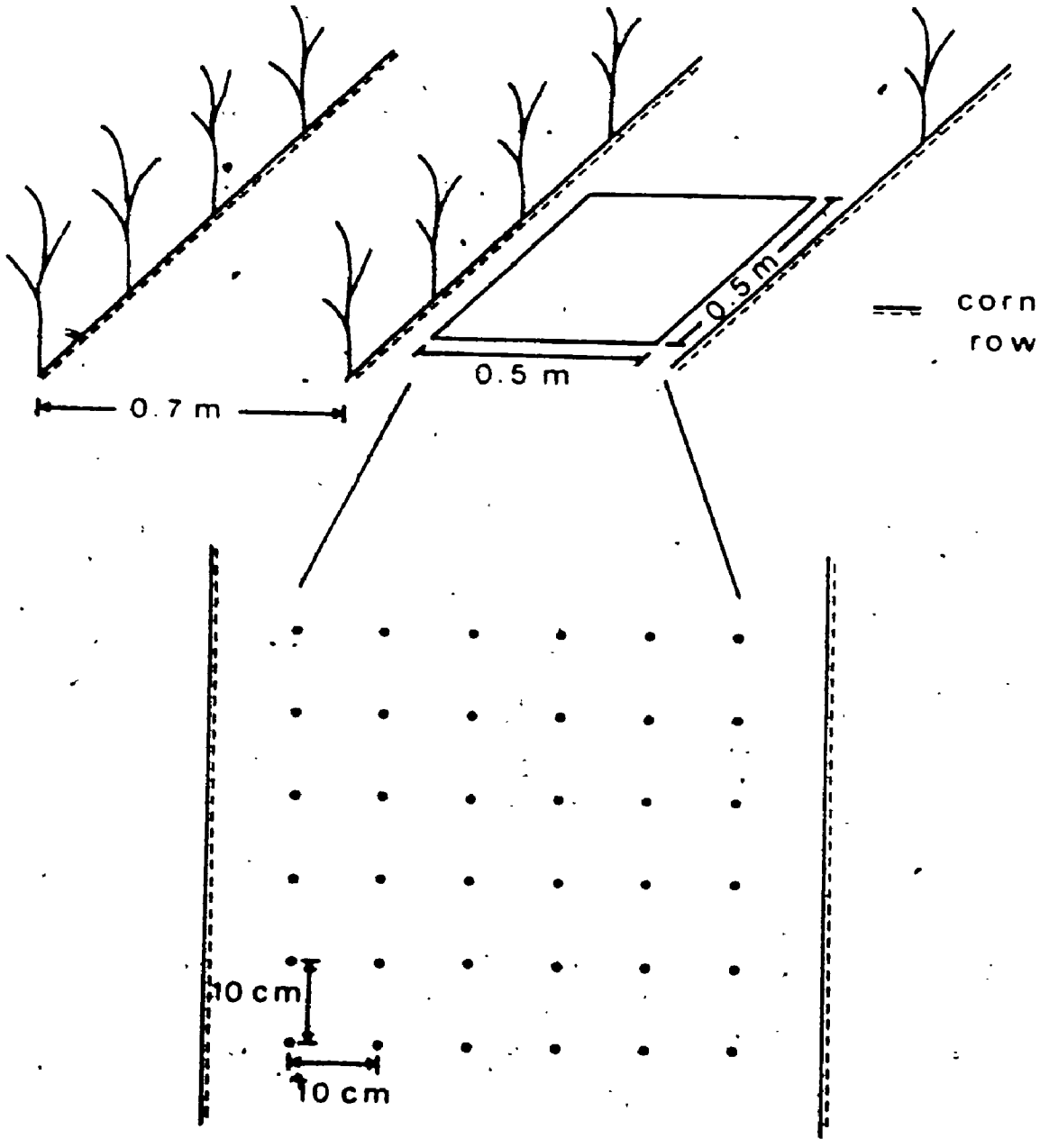
Four quadrats (50 cm x 50 cm) were located within the sampling site using random number co-ordinates (expressed as paces). All quadrats were sited between parallel corn rows. Thirty six soil cores were sampled at 10 cm intervals in each quadrat according to the arrangement in Figure 8.

Sampling was done on 21 October 1982 to a depth of 15 cm using a soil sampler of 1.9 cm diameter. The soil cores were removed carefully from the sampler and sealed individually in numbered plastic bags. They were stored immediately in a constant temperature room (6.3 ± 0.8°C) until the soil cores could be processed. Seeds were extracted from the soil cores by means of the procedure described in Section 2.5.3 and Appendix B.

2.6.2 Statistical Analysis

The program 'ONEWAY' (Nie et al., 1975) was used to carry out an analysis of variance and Scheffé's test was used to detect differences in the average number of Chenopodium spp. seeds and the total number of

Figure 8 Schematic representation of the sampling procedure over small areas (50 cm x 50 cm) in a corn field in Oxford County, Ontario.


0.7 m
0.5 m
0.5 m
corn row
10 cm
10 cm
corn row
soil- sample

seeds between the four quadrats. Since both variables were counts, the data was transformed by $(\sqrt{(X + 0.5)})$ and the subsequent analyses was done on the transformed data. Some sampling units were removed before the analysis since compacted soil or rocks prevented the auger from reaching the standard 15 cm sampling depth.

The seed distribution within each quadrat was further investigated. All calculations were done with the MINITAB computer language (Ryan et al., 1976). For those quadrats where there were missing sampling units, the number of seeds was interpolated for those missing sampling units using the method described by Snedecor and Cochran (1980, p. 276). The goodness of fit to a Poisson distribution for the number of Chenopodium spp. seeds in each quadrat was checked by means of a chi-square test. It was later used to test the homogeneity of row and column totals of both the total number of seeds and the number of seeds of Chenopodium spp. in each quadrat. A row total is formed by the summation of the members of a horizontal axis of the matrix outlined by the quadrat while a column total is formed by the summation of the members of a vertical axis of the matrix. The vertical axis of the matrix (i.e. column total) was designed to run parallel to the corn rows in the field.

2.6.3 Results

The analysis of variance demonstrated significant differences ($P \leq 0.05$) between quadrats for both the mean number of Chenopodium spp. seeds and the mean total number of seeds per sampling unit. The third quadrat was significantly different ($P \leq 0.05$) from quadrats 2 and 4 in

both cases (Table 6).

One way of examining the seed distribution in each quadrat is illustrated in Figure 9. The distributions of Chenopodium spp. seeds in quadrats 1 and 2 followed Poisson distributions while those for quadrats 3 and 4 did not (Table 7). If the single extremely high seed value due to seed shedding in quadrat 4 is removed from the data, then the goodness of fit to the Poisson distribution of the resulting seed distribution is accepted by the chi-square test (Table 8).

The hypothesis of homogeneity of row totals of quadrat 1 and 2 was accepted for both the total number of seeds and the number of Chenopodium spp. seeds but it was rejected for both attributes for quadrats 3 and 4 ($P \leq 0.05$) (Table 9). Similarly, the hypothesis of homogeneity of column totals of both the total number of seeds and the number of Chenopodium spp. seeds was rejected ($P \leq 0.05$) for all quadrats except the first one (Table 9).

2.6.4 Discussion

The third quadrat had significantly more seeds than the two other quadrats because some of its sampling units had very large numbers of seeds (Table 6). The occurrence of these large values indicated that seed shedding had occurred at the time of sampling, and this shedding resulted in strong clustering of seeds over very small areas (i.e. areas the size of the sampling units). The other quadrats which had lower mean numbers of seeds per sampling unit either had Poisson seed

Table 6. Comparison of the mean number of Chenopodium spp. seeds and the mean total number of seeds per sampling unit in different quadrats.

Quadrat No.	No. of sampling units(n)	Chenopodium spp. seeds/ sampling unit			Total number of seeds/ sampling unit		
		$\bar{X}$*	95% CI†		$\bar{X}$*	95% CI	
			Lower	Upper		Lower	Upper
1	33	4.16ab	3.44	4.94	5.53ab	4.71	6.41
2	36	3.81a	2.97	4.74	5.00a	4.00	6.09
3	35	6.39 b	4.68	8.35	7.83 b	5.92	9.99
4	35	2.90a	1.87	4.11	3.89a	2.67	5.32

* Means followed by the same letter are not different ($P \leq 0.05$) according to Scheffé's test. Results represent the retransformed data.

† CI = confidence interval.

Figure 9 Seed distribution for Chenopodium spp. and total seed number per sampling unit for four 50 cm x 50 cm quadrats (n = 36)

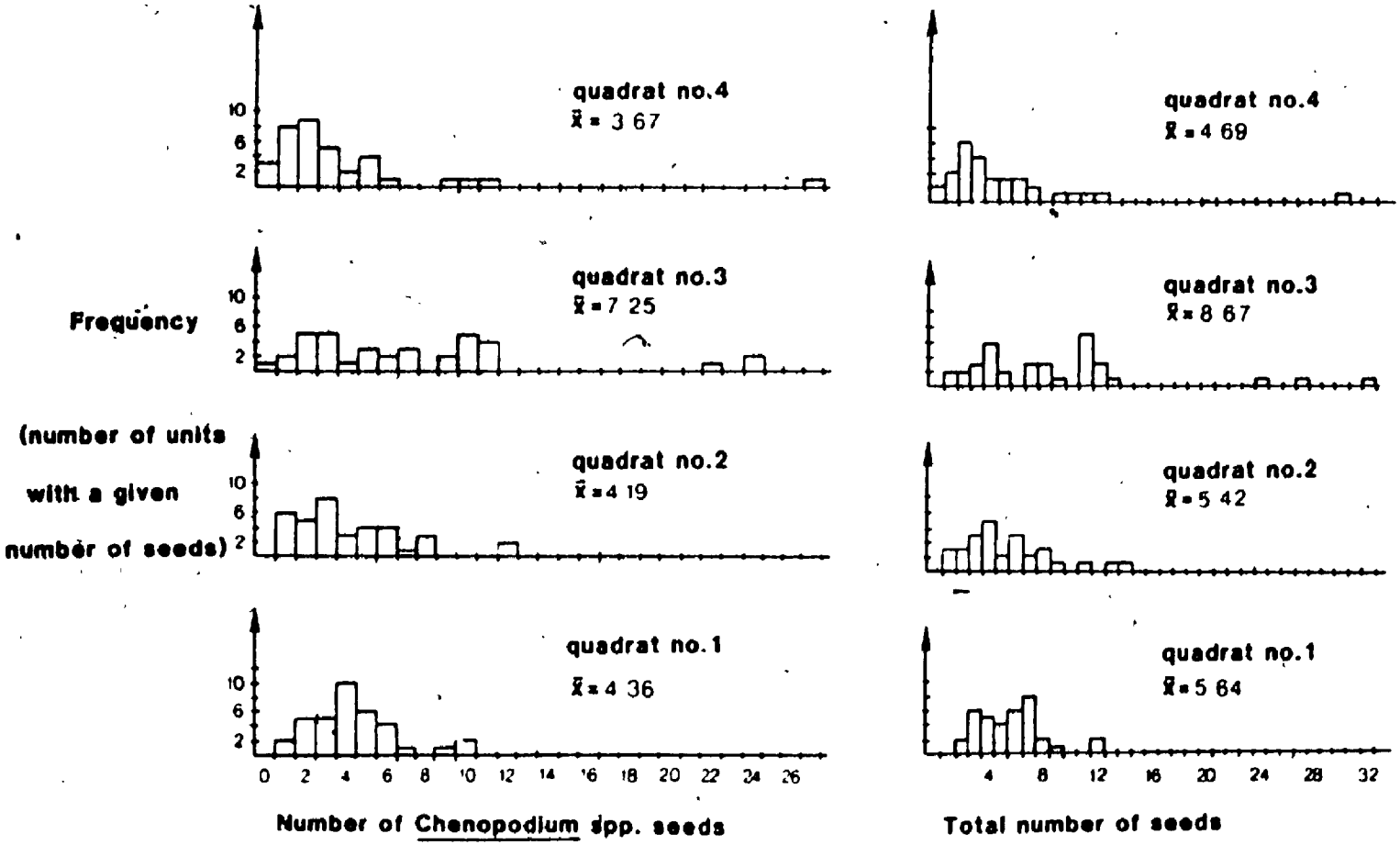

quadrat no.4
x̄ = 3 67
quadrat no.4
x̄ = 4 69
quadrat no.3
x̄ = 7 25
quadrat no.3
x̄ = 8 67
quadrat no.2
x̄ = 4 19
quadrat no.2
x̄ = 5 42
quadrat no.1
x̄ = 4 36
quadrat no.1
x̄ = 5 64
Frequency
(number of units with a given number of seeds)
10
6
2
0 2 4 6 8 10 12 14 16 18 20 22 24 26
4 8 12 16 20 24 28 32
Number of Chenopodium spp. seeds
Total number of seeds

Table 7 A summary of the chi-square test to determine the goodness of fit to the Poisson distribution of the number of Chenopodium spp. seeds/sampling unit for the four quadrats surveyed. Expected frequencies were pooled if they were less than one and the minimum expected frequency at each tail of the distribution was at least one.

Quadrat no. 1					Quadrat no. 2				
Number of Chenopodium spp. seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=4.36	χ^2 pooled	$\chi^2_{0.05,4}$	Number of Chenopodium spp. seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=4.19	χ^2 pooled	$\chi^2_{0.05,4}$
≤ 2	7	6.8364	2.081	9.488	≤ 2	11	7.5924	8.269	9.488
3	5	6.3540			3	8	6.6780		
4	10	6.9264			4	3	7.0020		
5	6	6.0408			5	4	5.8716		
6	4	4.3920			6-7	5	6.5628		
≥ 7	4	5.4576			≥ 8	5	2.286		

Quadrat no. 3					Quadrat no. 4				
Number of Chenopodium spp. seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=7.25	χ^2 pooled	$\chi^2_{0.05,4}$	Number of Chenopodium spp. seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=3.67	χ^2 pooled	$\chi^2_{0.05,4}$
≤ 3	13	2.5056	57.029	9.488	≤ 1	11	4.2948	16.505	9.488
4-5	4	7.2108			2	9	6.1848		
6	2	5.1552			3	5	7.5600		
7	3	5.3424			4	2	6.9300		
8-9	2	8.7372			5	4	5.0832		
≥10	12	7.0416			≥6	5	5.9436		

H_o: The sampling units of Chenopodium spp. seeds in the quadrat came from a population having a Poisson distribution.

H_a: The sampling units of Chenopodium spp. seeds in the quadrat did not come from a population having a Poisson distribution.

Table 8. A summary of the chi-square test to determine the goodness of fit to the Poisson distribution of the number of Chenopodium spp. seeds/sampling unit for quadrat no. 4. The single extremely high seed number was excluded from the test. Expected frequencies were pooled if they were less than one and the minimum expected frequency at each tail of the distribution was at least one.

Number of Chenopodium spp. seeds/sampling unit	Observed frequency	Expected frequency for $\bar{X} = 3.00$	χ^2 pooled	$\chi^2_{0.05,3}$
≤ 1	11	6.9720	6.453	7.815
2	9	7.8400		
3	5	7.8400		
4	2	5.8800		
≥ 5	8	6.4645		

H_o is accepted

H_o: The sampling units of Chenopodium spp. seeds in quadrat no. 4 came from a population having a Poisson distribution.

H_a: The sampling units of Chenopodium spp. seeds in quadrat no. 4 did not come from a population having a Poisson distribution.

Table 9 A summary of the chi-square test to determine the homogeneity of row (column) totals for Chenopodium spp. and total seed number for the four quadrats surveyed.

Quadrat number	Chenopodium spp. seeds				Total number of seeds			
	Row totals χ^2 cal		Column totals χ^2 cal		Row total χ^2 cal		Column totals χ^2 cal	
1	1.408	H_o accepted	3.930	H_o accepted	1.857	H_o accepted	5.345	H_o accepted
2	4.245	H_o accepted	21.252	H_o rejected at $P(X) \leq 0.001$	6.323	H_o accepted	20.600	H_o rejected at $P(X) \leq 0.001$
3	16.310	H_o rejected at $P(X) \leq 0.01$	56.724	H_o rejected at $P(X) \leq 0.001$	26.192	H_o rejected at $P(X) \leq 0.001$	59.308	H_o rejected at $P(X) \leq 0.001$
4	22.182	H_o rejected at $P(X) \leq 0.001$	42.364	H_o rejected at $P(X) \leq 0.001$	24.456	H_o rejected at $P(X) \leq 0.001$	4.822	Ho rejected at $P(X) \leq 0.001$

$\chi^2_{0.05,5} = 11.070$ $\chi^2_{0.01,5} = 15.086$

H_o: row (column) totals are homogeneous

H_a: row (column) totals are not homogeneous

distributions (Table 7) or had them after the removal of an unique sampling unit with a high seed number resulting from localized seed shedding (Table 8). This result follows the trend documented by Goyeau and Fablet (1982) whereby species with fewer seeds tend to have a Poisson distribution. Indeed, all count data for randomly distributed population of discrete units should have a Poisson distribution. It will be more pronounced for data with low values because with high values the normal and the Poisson distribution essentially merge (Goyeau and Fablet, 1982).

The heterogeneity of column totals occurred in all quadrats except the first (Table 9). Weeds that escaped the control measures were usually found in or near the corn rows. These plants tended to be tall and in October many had fallen between the rows and away from the corn. Since seed dispersal is usually near the parent plant, it seems probable that seed shedding was heavier in the middle position between the corn rows, as observed by the seed distribution in the quadrats (data not shown).

Because soil sampling was done in October when seed dispersal had already begun, strong clustering of seeds over small areas was evident. Such clustering may have altered the seed distributions such that they could not be described conclusively as having Poisson distributions or as being homogeneous over small areas.

2.7. Objective III

To determine the homogeneity of variance of the sampling units used to estimate seed distribution in the soil over a large area (1.35 ha).

2.7.1. Sampling Procedure

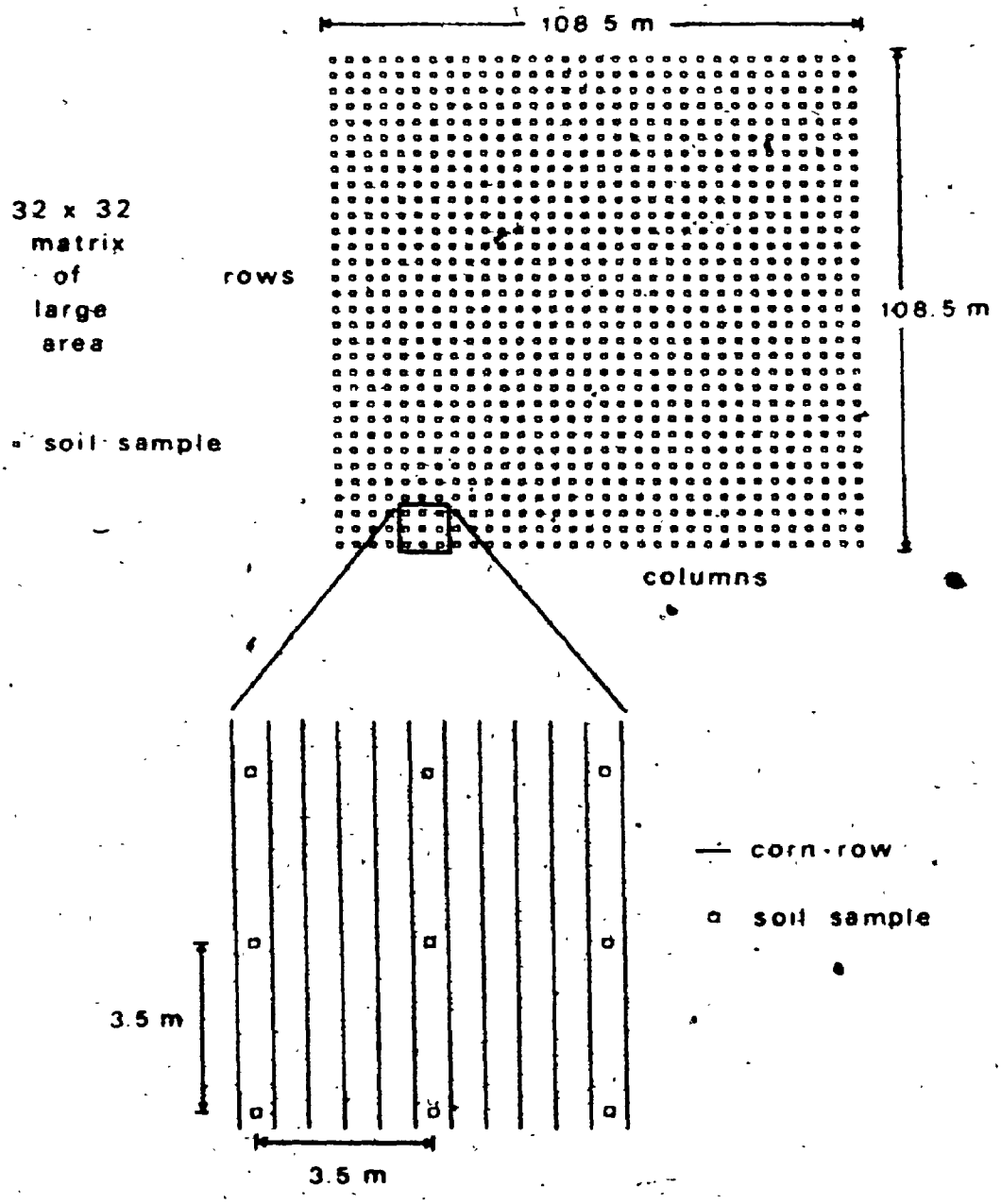
Soil cores of 1.9 cm diameter and 15 cm deep were taken systematically at 3.5 m (5 pace) intervals throughout the sampling site. This created a total of 1024 sampling units arranged in a 32 x 32 matrix (Fig. 10). Sampling was done from 5 August to 9 August 1982. Each soil core was numbered and placed in a plastic bag. The cores were stored on the date of collection in a constant temperature room (6.3 ± 0.8°C) until they could be processed. Seeds were extracted from the soil cores by means of the procedure described in Section 2.5.3 and Appendix B.

2.7.2 Statistical Analysis

An attempt was made to describe over a large area the distributions of Chenopodium spp. seeds and the total number of seeds in the soil. The goodness of fit to a Poisson distribution for both the Chenopodium spp. seeds and the total number of seeds was investigated by means of a chi-square test.

In a Poisson distribution the variance is equal to the mean so that their ratio is equal to one (Zar, 1974, p. 302). The variance: mean ratio can be considered as a measure of randomness (Kershaw, 1973) and a

Figure 10 Diagrammatic representation of the sampling procedure over the sampling site (108.5 m x 108.5 m) in a corn field in Oxford County, Ontario.


108 5 m
32 x 32
matrix
of
large
area
rows
108.5 m
soil sample
columns
corn row
soil sample
3.5 m
3.5 m

t-test can thus be used to test the population for departure from randomness.

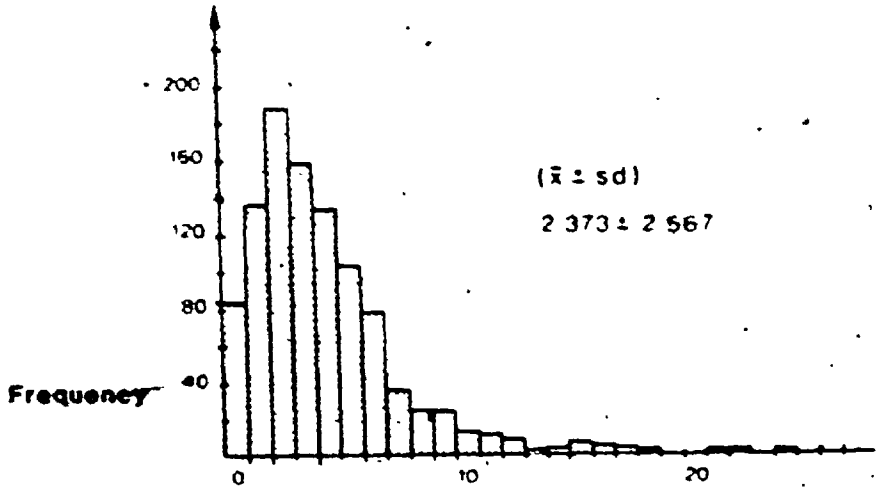
The homogeneity of row and column totals for both the total number of seeds and the number of Chenopodium spp. seeds in the matrix outlined by the sampling site was checked by means of the chi-square test. A row total of the matrix represents the summation of its horizontal members while a column total represents the summation of its vertically aligned members. With the latter, the vertical axis is parallel to the corn rows in the field. The MINITAB computer language (Ryan et al., 1976) was used for all computations of chi-square values.

2.7.) Results.

The distribution of the number of Chenopodium spp. seeds and the total number of seeds over the sampling site is illustrated in Figure 11. It indicated that a large number of sampling units had very few seeds per unit. However, the chi-square test showed that the populations of Chenopodium spp. seeds and total seeds within the sampling site did not exhibit Poisson distributions ($P \leq 0.001$) (Table 10). The variance: mean ratio test similarly showed a rejection of the goodness of fit to a Poisson distribution with $P \leq 0.001$ for both the total number of seeds and the number of Chenopodium spp. seeds (Table 11).

The row and column totals for total seed number and the column totals for Chenopodium spp. seeds were not homogeneous at $P \leq 0.001$ using the chi-square test (Table 12). The hypothesis of homogeneity of

Figure 11 Distribution of Chenopodium spp. seeds and total seeds per sampling unit for a 108.5 m x 108.5 m area (n = 1024).


200
150
120
80
40
Frequency
0
10
20
(x̄ ± sd)
2 373 ± 2 567

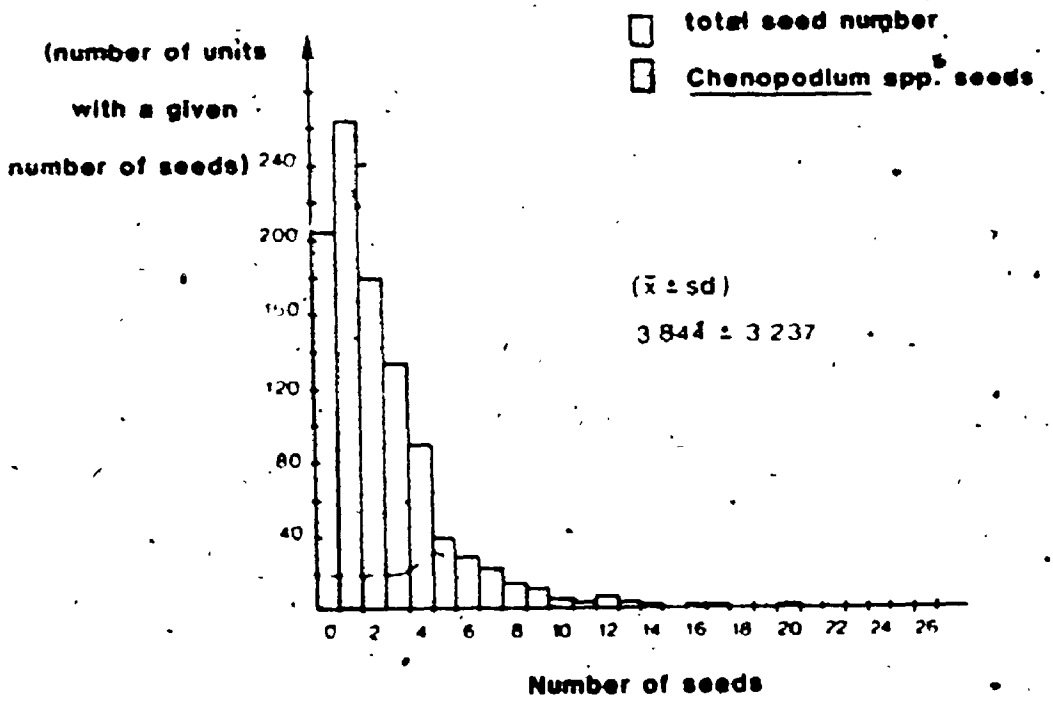

total seed number
Chenopodium spp. seeds
(number of units with a given number of seeds)
240
200
160
120
80
40
0 2 4 6 8 10 12 14 16 18 20 22 24 26
Number of seeds
(x̄ ± sd)
3 844 ± 3 237

Table 10. A summary of the chi-square test to determine the goodness of fit to the Poisson distribution of the number of Chenopodium spp. seeds and total seeds/sampling unit for the sampling site (108.5 m x 108.5 m). Expected frequencies were pooled if they were less than one and the minimum expected frequency at each tail of the distribution was at least one.

Number of Chenopodium spp. seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=2.373	χ^2 pooled	$\chi^2_{0.05,7}$	Total number of seeds/ sampling unit	Observed frequency	Expected frequency for $\bar{X}$=3.844	χ^2 pooled	$\chi^2_{0.05,10}$
0	215	95.44	943.23	14.07	0	84	21.91	1163.6	18.31
1	264	226.51			1	137	84.28		
2	181	268.70			2	188	162.00		
3	134	212.58			3	158	207.57		
4	90	126.05			4	133	199.48		
5	40	59.80			5	102	153.29		
6	29	23.65			6	78	98.20		
7	22	7.99			7	36	53.97		
8	14	2.36			8	25	25.91		
9	11 } 49	0.61	3.07		9	25	11.06		
≥10	24	0.10			10	13	4.30		
					11	12	1.54		
					12	9 } 45	0.51	2.15	
					≥13	27	0.10		

H_o is rejected at $P(X) \leq 0.001$

H_o: the sampling units of Chenopodium spp. seeds came from a population having a Poisson distribution

H_a: the sampling units of Chenopodium spp. seeds did not come from a population having a Poisson distribution.

H_o is rejected at $P(X) \leq 0.001$

H_o: the sampling units of the total number of seeds came from a population having a Poisson distribution.

H_a: the sampling units of the total number of seeds did not come from a population having a Poisson distribution.

Table 11 The variance: mean ratio test for seeds of Chenopodium spp. and total seeds for the sampling site.

Seed category	Expected $S^2/\bar{X}$	Observed $S^2/\bar{X}$	$t_{calculated}$	$t_{1000(1)0.001}$
Chenopodium spp.	1	2.78	40.25**	3.30
Total seed number	1	2.72	38.84**	3.30

** Differences between expected and observed ratios are significant at $P \leq 0.001$.

Table 12 A summary of the chi-square test to determine the homogeneity of row and column totals for numbers of Chenopodium spp. seeds and total seeds for the sampling site.

Seed category	Row total		Column totals	
	χ^2 calculated	Rejection level P(X)	χ^2 calculated	Rejection level P(X)
Chenopodium spp.	58.467	$0.01 \leq P(X) \leq 0.005$	868.87	$P(X) \leq 0.001$
Total seed number	68.237	$P(X) \leq 0.001$	709.49	$P(X) \leq 0.001$

$\chi^2_{0.05,31} = 44.985$ $\chi^2_{0.01,31} = 52.191$

H_o: row (column) totals are homogeneous

H_a: row (column) totals are not homogeneous

row totals of Chenopodium spp. seeds was rejected at $0.01 \leq P \leq 0.005$ but the calculated chi-square was close to the rejection level. This is best illustrated by Figure 12.

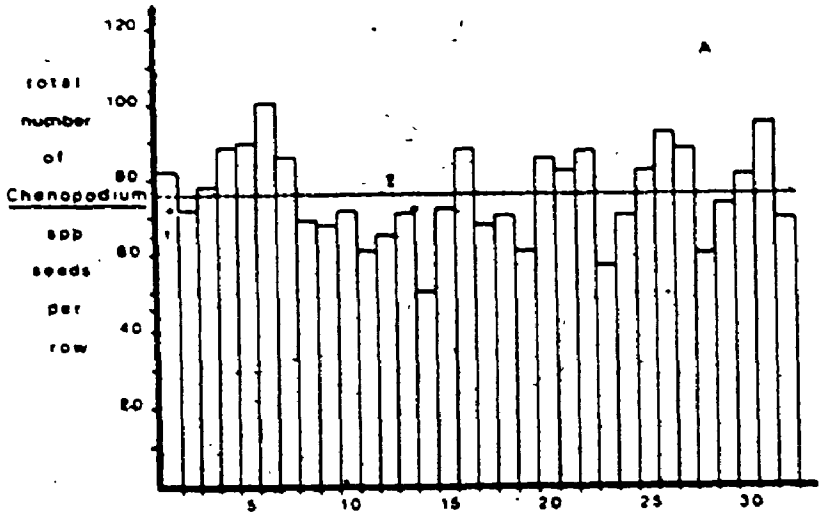
2.7.4 Discussion

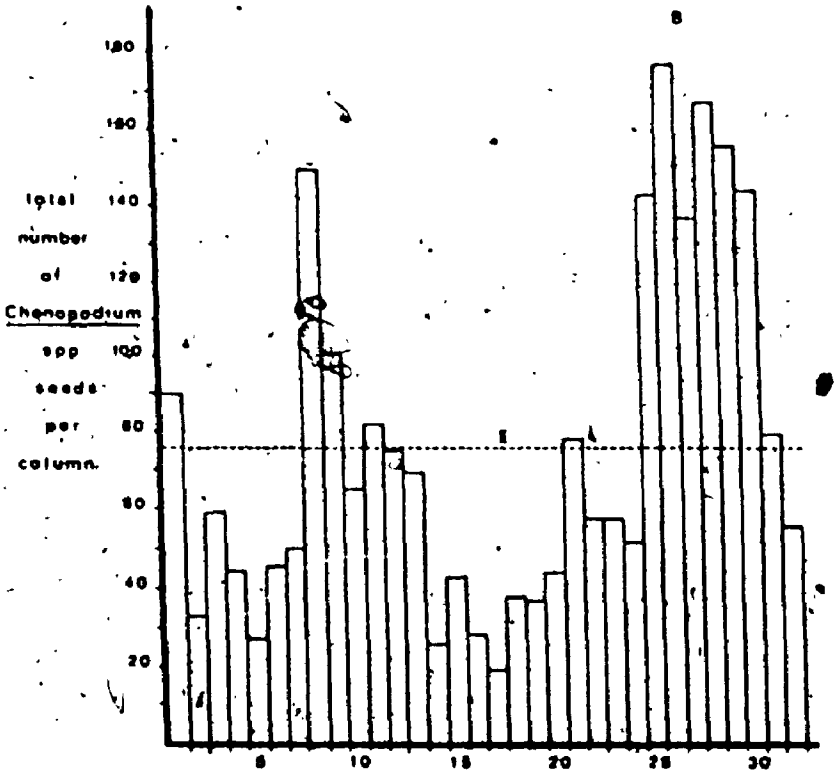
Both the chi-square test and the variance: mean ratio test were used to test the goodness of fit of the seed population of the sampling site to the Poisson distribution. The variance: mean ratio is a measure of randomness and as such this ratio can be used to further describe the distribution of the seed population.

A large number of sampling units had very low seed numbers per unit (Fig. 11), and one might expect that this would give a Poisson distribution. However, both the chi-square test and the variance: mean ratio test rejected the Poisson distribution as describing the distribution of either Chenopodium spp. seeds or the total number of seeds for the sampling site (Tables 10 and 11). Because the calculated variance: mean ratio is greater than one, the distribution is deduced as being clustered (Kershaw, 1973, p. 129).

Upon closer examination, the calculated chi-square values for row totals are much closer to the expected chi-square values ($\chi^2_{0.01,31} = 52.191$) than those calculated for column totals for both Chenopodium spp. seeds and the total number of seeds. This trend can be demonstrated by graphing the row and column totals for Chenopodium spp. seeds (Fig. 12). There is little variation between row totals and these,

Figure 12 Total number of Chenopodium spp. seeds/row and /column of the matrix outlined by the sampling site. a) Rows of matrix run perpendicular to corn rows in the sampling site; b) Columns of matrix run parallel to corn rows in the sampling site. The mean of the total number of Chenopodium spp. seeds per row or column ($\bar{X}$) is 75.9


A
total number of Chenopodium spp seeds per row
120
100
80
60
40
20
5
10
15
20
25
30
row number in matrix outlined by the sampling site


B
total number of Chenopodium spp seeds per column
160
140
120
100
80
60
40
20
5
10
15
20
25
30
column number in matrix outlined by the sampling site

oscillate closely about the mean (Fig. 12a). In contrast, there are large discrepancies between column totals (Fig. 12b). Since columns in the matrix correspond to corn rows in the field, the pattern is that of groups of corn rows with high numbers of Chenopodium spp. seeds and groups of corn rows with low seed numbers.

Heterogeneity in the seed bank between crop rows may be explained by noting that farm machinery moves along the same axis of the field each year. This pattern results in weed seed dispersal along crop rows rather than across them. Eventually, areas with consistently high weed populations or with poor weed control may develop large seed banks in the soil. Areas which either have good weed control or a microenvironment favouring germination or rapid decay of weed seeds may end up with relatively small seed banks. To my knowledge, such a pattern in the seed banks of row crops has not been documented in previous literature.

Standifer (1980) stated that repeated cultivations resulted in a 'more nearly normal' distribution of seeds in the soil. However, an indication of the scale at which results are observed should be stated. Indeed, after seed dispersal many seed populations in the soil may exhibit a strong clustered distribution. Cultivations may in this case lead to a 'more normal' seed distribution on a microscale (a few meters). However, on a macroscale (a large field), repeated cultivations tend to create a clustered distribution associated with row cropping, as was observed in this study.

This pattern within the sampling site should be kept in mind as it

will affect the efficiency of the sampling methods examined in subsequent sections of this thesis.

2.8 Objectives IV and V

To determine the minimum number of sampling units needed to provide an acceptable estimate of the mean density and the sampling variance of a population.

To determine which sampling method minimizes the sampling variance.

2.8.1. Sampling Procedure

Soil cores sampled systematically throughout the sampling site as described in the previous section were used as a framework for testing the last two objectives. This 32 x 32 matrix encompassing 1024 sampling units can be used as a seed bank population with known parameters, the assumption being that each sampling unit in the matrix are immediately adjacent to each other and form a contiguous population. The variable under investigation was seeds of Chenopodium spp. in the soil.

a) Determination of minimum number of sampling units

The minimum number of sampling units needed to estimate the true population mean (μ) was determined by visually comparing the sample size obtained by random sampling within the matrix and the corresponding Monte Carlo estimate of sampling variance. The sample size tested ranged from 2 to 512.

By definition, the sampling variance of the mean ($S^2_{\bar{x}}$) estimates, for all samples, the dispersion of the sample mean ($\bar{x}_i$) from the true population mean (μ) (Kenkel, 1981). The Monte Carlo technique consists of calculating a desired statistic for each random sample drawn from a population and thereby provides a sampling distribution of the statistic (Snedecor and Cochran, 1980). The variance of the sampling distribution is called the sampling variance (Stuart, 1976). The desired statistic in this case is the sample mean ($\bar{x}_i$) and the general formula to calculate the Monte Carlo estimate of the sampling variance of the mean is given below.

$$\text{M.C. } S^2_{\bar{x}} = \frac{\sum_{i=1}^{n} \left(\bar{x}_{i.} - \bar{x}_{..}\right)^2}{n}$$

WHERE

$$\bar{x}_{i.} = \frac{\sum_{j=1}^{m} x_{ij}}{m}$$

$$\bar{x}_{..} = \frac{\sum_{i=1}^{n} \bar{x}_{i.}}{n}$$

x_{ij} is the j^{th} sampling unit of the i^{th} sample

$i = 1,\ldots n$

$j = 1,\ldots m$

n is the total number of samples drawn from a population

m is the total number of sampling units in a sample

b) Comparison of sampling methods

The sampling methods which were selected for this study were random, systematic, stratified random and cluster sampling. The Monte

Carlo estimate of sampling variance (M.C. $S^2_{\bar{x}}$) was the statistic used to compare the efficiency of the different sampling methods in estimating the true population mean (μ). The formulas used to calculate the Monte Carlo estimate of sampling variance of the mean for the different sampling methods, are given in Appendix C. All are based on the general formula presented in Section 2.8.1a.

At all times, sampling with replacement was used whereby at any draw, every member of the population is given an equal chance of being drawn. Four hundred samples (n = 400) were drawn at random from the population for each sample size studied with each sampling method under investigation. The sample sizes investigated with each sampling method are listed in Appendix D along with their respective statistics.

FORTRAN computer programs used for sampling within the population (hereafter referred to as the matrix) were kindly written by Norm Kenkel, former graduate student of the Plant Sciences Department of the University of Western Ontario. These are detailed in Appendix C.

2.8.2 Statistical Analysis

The results of all sampling methods - random, systematic, stratified random and cluster - were graphed to illustrate the effect of sample size on the Monte Carlo estimate of sampling variance. With stratified random sampling, the effect of increased stratification on the Monte Carlo estimate of variance was investigated for fixed sample sizes. Similarly with cluster sampling, the effect of increasing the number of

sampled clusters on the Monte Carlo estimate of the sampling variance was studied when the sample size was kept constant. All feasible permutations of cluster and stratified random sampling within a 32 x 32 matrix were made and their results are reported in Tables IV and V of Appendix D. However, within the text, the graphical representation of the results of both the stratified random and cluster sampling methods will be restricted to 4 and 8 strata (or clusters) and to sample sizes of 64 and 128 units.

The relationships between sample size and both the Monte Carlo estimate of variance and the theoretical sampling variance were studied for random sampling. The original data exhibited a decay curve and the natural logarithm transformations (ln) of the values of both variables resulted in a linear relationship on which the simple regression program REGRESSION/OK (Orloci and Kenkel, 1985) was used. This transformation is justified since homoscedasticity is maintained when the residuals are plotted as a function of their corresponding independent variable (i.e. sample size) (Fig. II of Appendix E). The Student's t tests described in Zar (1974) were used to test the equality of regression coefficients (p. 228-229) and the equality of elevations (p. 229-231) for both regression lines.

Multiple pairwise comparisons of Monte Carlo estimates of sampling variance for different sampling methods were conducted using the F test. The explanation for the choice of multiple pairwise comparisons of sampling variances is given in Appendix F. The sampling methods were represented by selected examples of two sample sizes (64 and 128). The

results of these pairwise comparisons of Monte Carlo estimates of sampling variance are given in Tables VI to VIII of Appendix D.

2.3.3 Results

a) Determination of the minimum number of sampling units

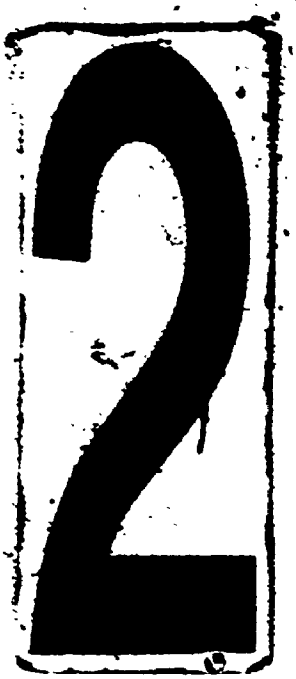
The seed bank of Chenopodium spp. seeds can most effectively be described by a sample size ranging between 60 and 100 sampling units (Fig. 13).

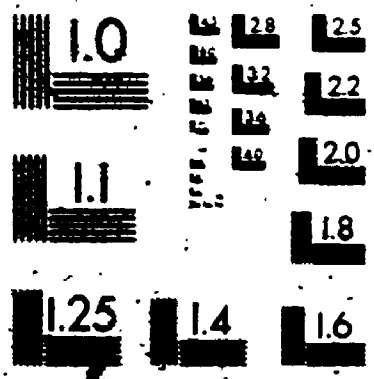
b) Comparison of sampling methods

Random sampling

With random sampling, as the total number of sampling units increases, the Monte Carlo estimate of the sampling variance decreases following an exponential decay curve (Fig. 13). By transforming the values of both the sample size and the sampling variance, the relationship between these two variables can be depicted as linear (Fig. 14). The criterion of least square deviations described the regression line for the population sampling variance as $\ln y = 2.216 - 1.114 \ln x$ and for the Monte Carlo estimate of sampling variance as $\ln y = 1.885 - 0.944 \ln x$ (Fig. 14 and Table 13).

In both cases, the analysis of variance for the linear regression rejected the null hypothesis $H_0: B = 0$ ($P \leq 0.001$) (Table 13). The Student's t test demonstrated that the regression coefficients and the





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Figure 13 The effects of different total numbers of sampling units on the population sampling variance and the Monte Carlo estimate of sampling variance. The random sampling method was used.

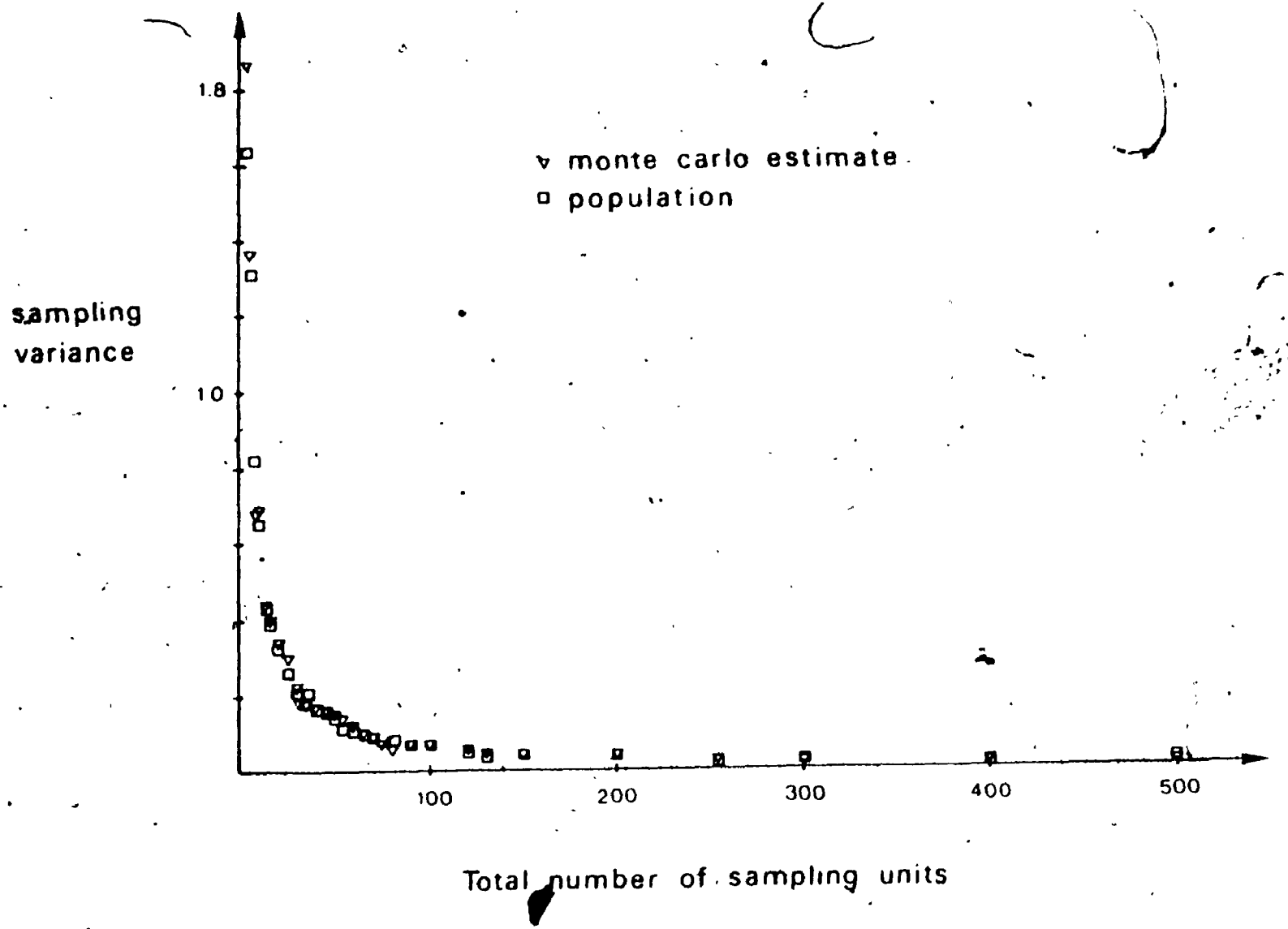

monte carlo estimate
population
sampling variance
1.8
1.0
100
200
300
400
500
Total number of sampling units

Figure 14 Linear regressions of a) the transformed Monte Carlo estimate of sampling variance (Ln) and b) the transformed population sampling variance (Ln) on the transformed sample size (Ln).

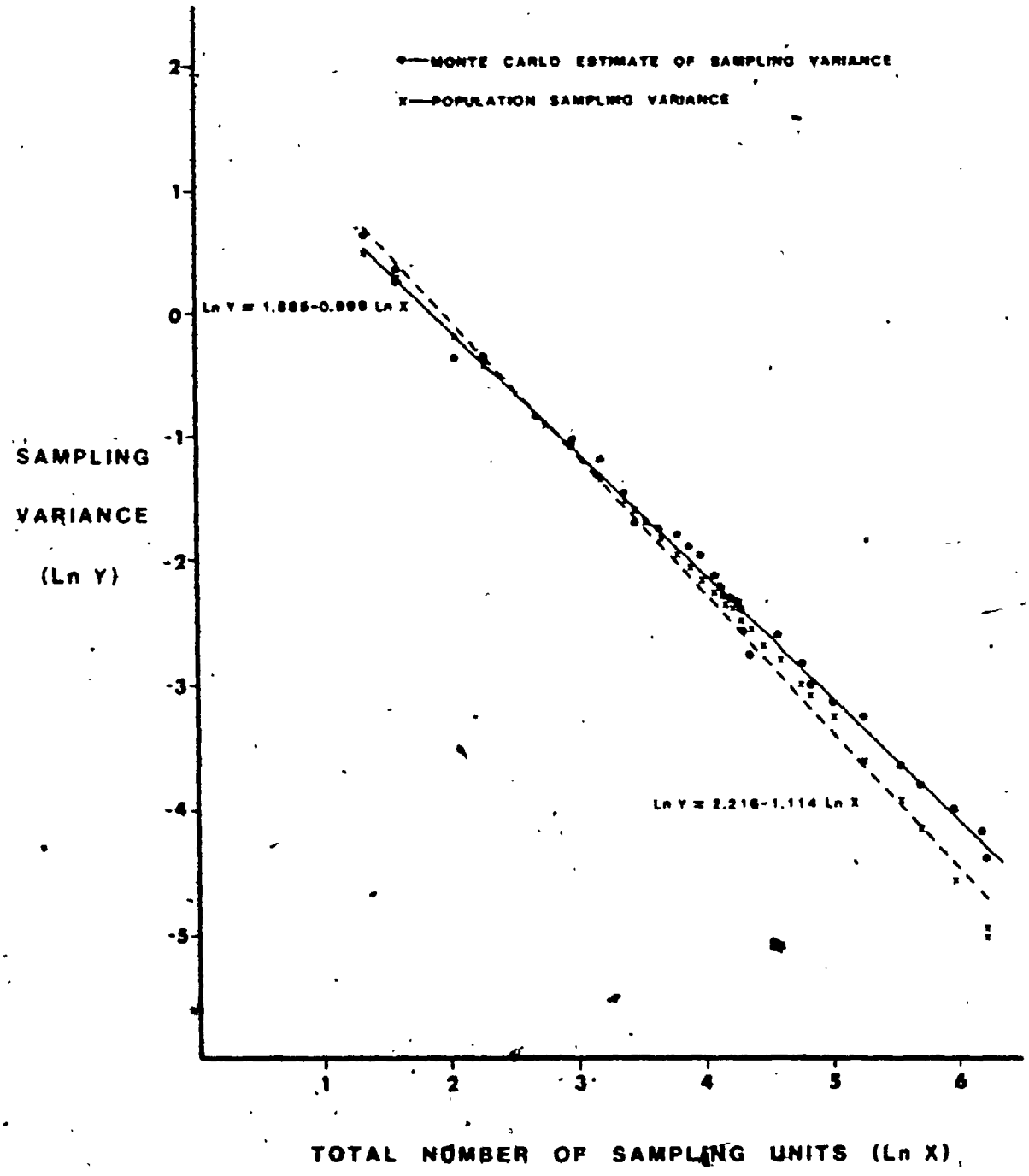

MONTE CARLO ESTIMATE OF SAMPLING VARIANCE
POPULATION SAMPLING VARIANCE
Ln V = 1.885-0.999 Ln X
Ln V = 2.216-1.114 Ln X
SAMPLING VARIANCE (Ln Y)
TOTAL NUMBER OF SAMPLING UNITS (Ln X)
2
1
0
-1
-2
-3
-4
-5
1
2
3
4
5
6

Table 13 Summary of analysis of variance for testing $H_o: \beta = 0$ for both the Monte Carlo estimate of sampling variance (Ln) and the population sampling variance (Ln) regression lines.

Source of variation	Monte Carlo estimate of sampling variance (Ln) regression line				Population sampling variance (Ln) regression line			
	SS	DF	MS	F	SS	DF	MS	F
Regression	49.02	1	49.02	4478.11***	60.87	1	60.87	4818.17***
Residual	0.37	30	0.01		0.38	30	0.01	
Total	49.35	31			61.25	31		
a	1.89				2.22			
b	1.00				-1.11			
r^2	0.99				0.99			

$F_{0.05(1)\,1,30} = 5.57$

*** significant at the 0.01 level

r^2 = coefficient of determination = SS_{res}/SS_{total}

H_o: the regression coefficient (b) comes from a population with a population regression coefficient of zero ($\beta = 0$)

H_a: the regression coefficient (b) does not come from a population with a population regression coefficient of zero ($\beta \neq 0$).

elevations (Tables IX and X of Appendix D respectively) of the regression line of population sampling variance and the regression line of the Monte Carlo estimate of sampling variance were not significantly different.

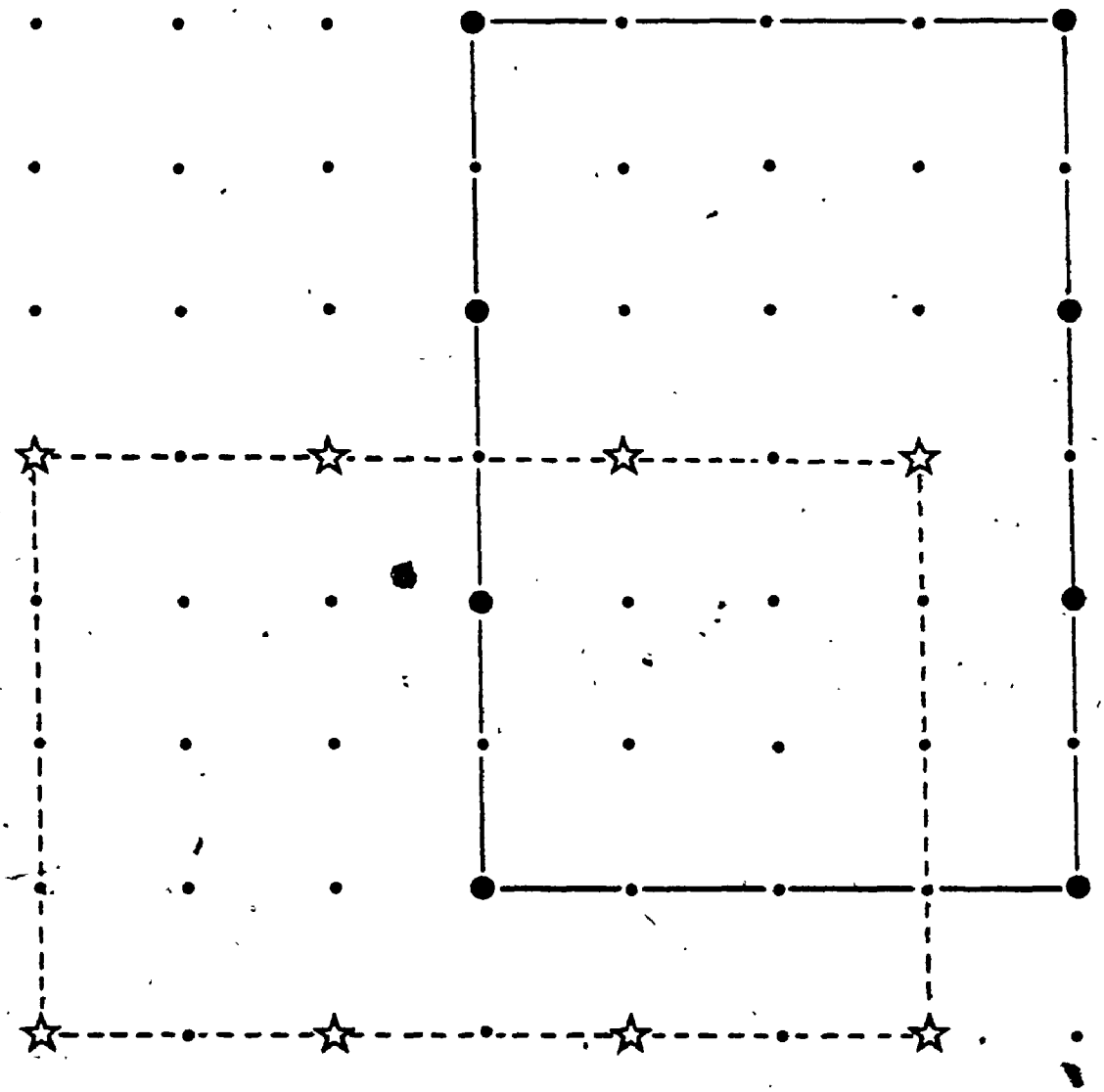
Systematic sampling:

When sampling a matrix systematically, every i^{th} row in the matrix and every j^{th} column is selected from a randomly chosen pivot unit (or starting unit) (Fig. 15). The j columns correspond to the corn rows in the field. The sampling interval can be identified by the i and j interval selected (i - j) and may vary depending on the choice of the investigator (e.g. Figure 15).

As the total number of sampling units increases, the Monte Carlo estimate of the sampling variance decreases (Fig. 16). For any sample size, the Monte Carlo estimate of sampling variance can fluctuate depending on the configuration of the sampling interval used. These fluctuations are less pronounced as the sample size increases (Fig. 16).

Similarly for any sample size, if the interval between the i units is large compared to the interval between the j units then the Monte Carlo estimate of the sampling variance is small and vice versa. When the interval between the i units is much smaller than that of the j units, the Monte Carlo estimate of sampling variance is greatly increased (Fig. 16).

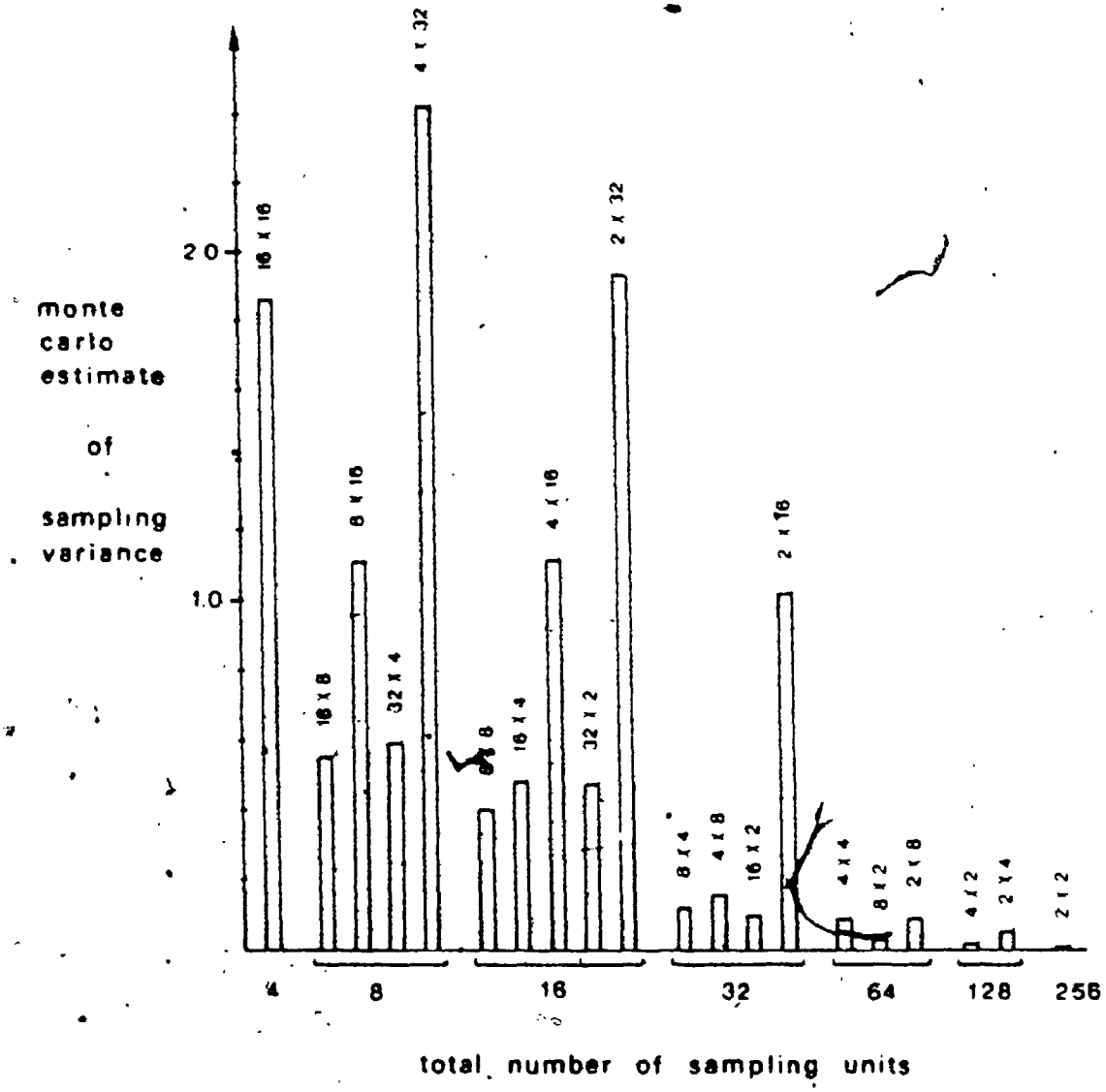
Figure 15 Diagrammatic representation of the systematic sampling method within the sampling site (or matrix). The first number of the sampling interval represents every i^{th} row selected in the matrix and the second number represents every j^{th} column selected in the matrix. The small dots indicate the possible sampling units in the matrix. The stars and the large dots represent the sampling units taken at 4-2 and 2-4 intervals respectively from a randomly chosen starting point.



4-2 sampling intervals

2-4 sampling intervals

Figure 16 The effect of increased sample size on the Monte Carlo estimate of sampling variance using the systematic sampling method. The numbers above each bar represent the sampling intervals. The first number represents the i^{th} row interval and the second number, the j^{th} column interval.


monte
carlo
estimate
of
sampling
variance
2.0
1.0
16 x 16
16 x 8
8 x 16
32 x 4
4 x 32
8
16 x 4
4 x 16
32 x 2
2 x 32
8 x 4
4 x 8
16 x 2
2 x 16
4 x 4
8 x 2
2 x 8
4 x 2
2 x 4
2 x 2
4
8
16
32
64
128
256
total number of sampling units

Stratified random sampling:

With stratified random sampling, three factors will influence the Monte Carlo estimate of sampling variance. These are a) the total number of sampling units, b) the number of strata into which the matrix is subdivided and c) the orientation of the strata.

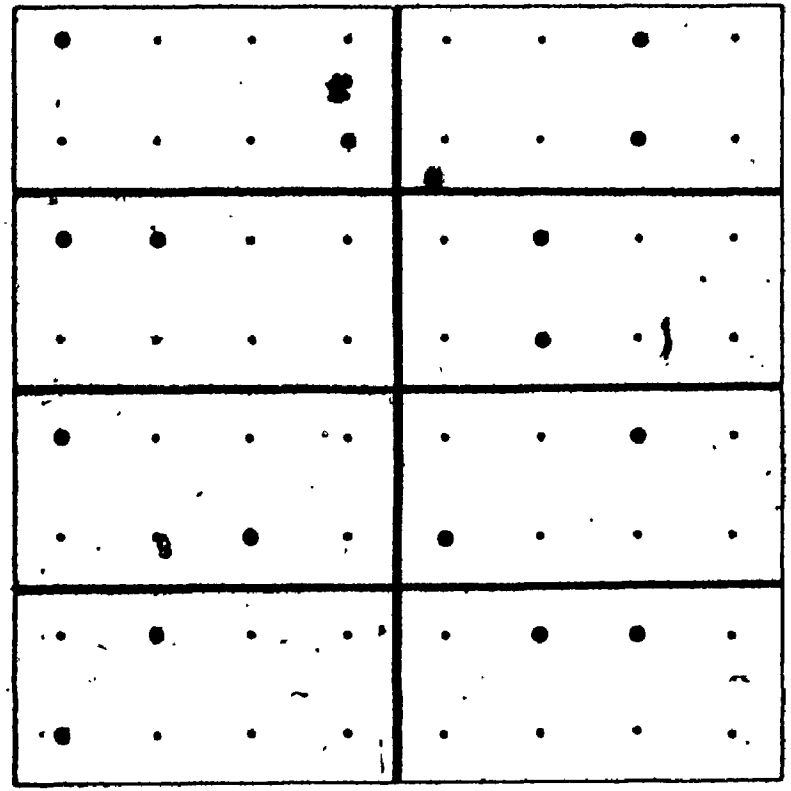
The orientation of the strata refers to the way the matrix is subdivided. Each stratum incorporates i number of successive rows and j number of successive columns of the matrix. Thus, any stratum identified by a large value for i and a small one for j is described as having a vertical orientation (Fig. 17b). Similarly a stratum identified by a small value for i and a large one for j is described as having a horizontal orientation within the matrix (Fig. 17a).

As the sample size increases, the Monte Carlo estimate of sampling variance decreases. This occurs regardless of the extent of stratification within the matrix (Fig. 18). The Monte Carlo estimates of sampling variance for a sample size of 64 were significantly different ($P \leq 0.003$) from those for a sample size of 128 (Fig. 19).

The orientation of the strata influences the Monte Carlo estimate of sampling variance. Subdivision of the matrix leading to vertically oriented strata results in smaller Monte Carlo estimates of sampling variance while the horizontally oriented strata have larger Monte Carlo estimates of sampling variance (Fig. 18). This trend attenuates as the sample size increases. The F test demonstrated for both sample sizes of 64 and 128 units significant differences ($P \leq 0.01$) between vertically

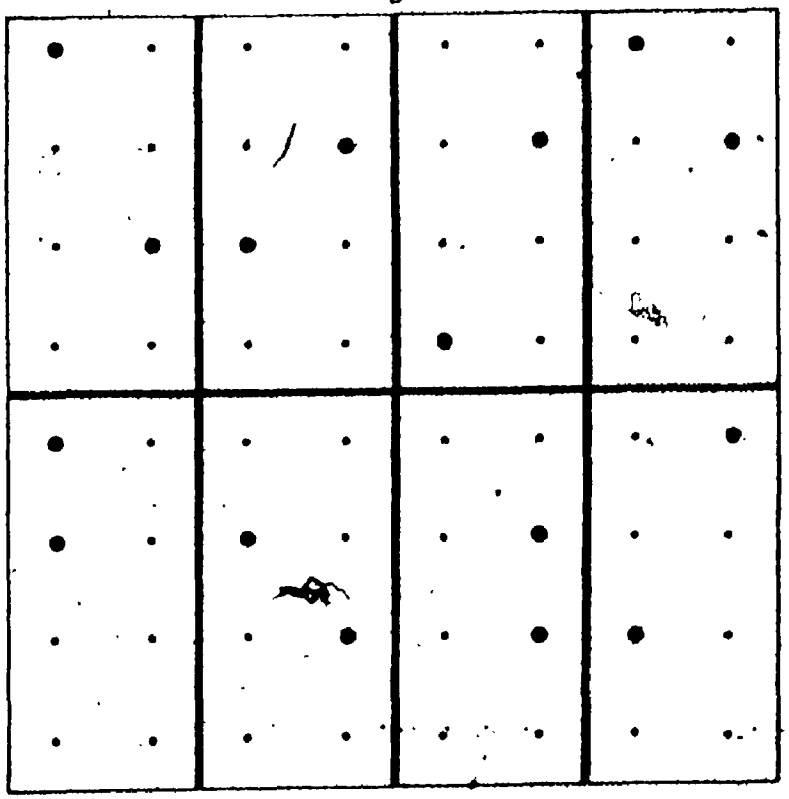
Figure 17 Diagrammatic representation of the stratified random sampling method within the sampling site or matrix. The orientation of the strata refers to the way the matrix is subdivided. The first number represents the number of i rows and the second one represents the number of j columns included in each stratum. The small dots indicate the possible sampling units in the matrix while the large dots represent the randomly chosen sampling units within each stratum.

A



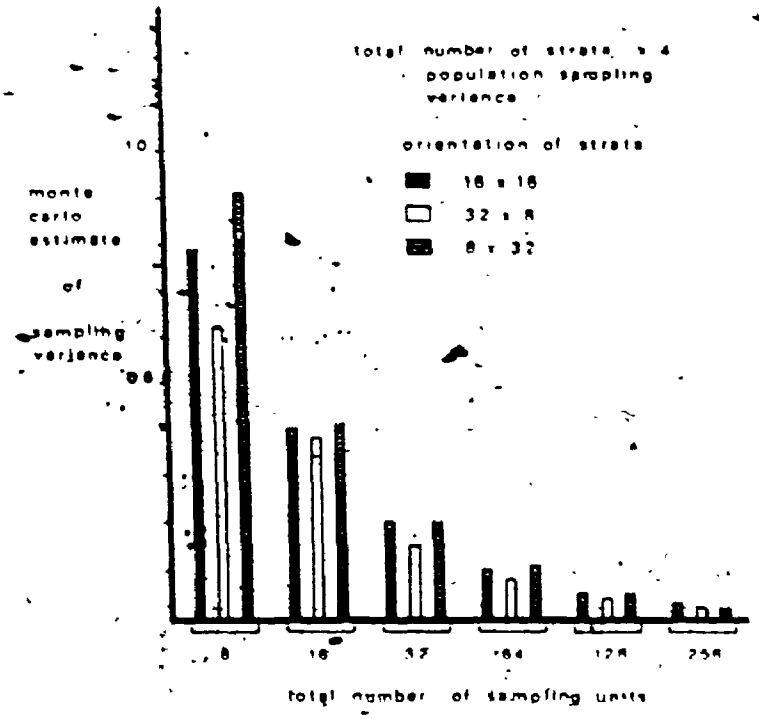
——..... orientation of strata : 2 x 4
number of strata : 8
number of sampling units/stratum : 2

B



——..... orientation of strata : 4 x 2
number of strata : 8
number of sampling units/stratum : 2

Figure 18 The effect of increased sample size on the Monte Carlo estimate of sampling variance for any given stratification using stratified random sampling. The first number of the orientation of the strata refers to the number of i rows and the second number refers to the number of j columns within any stratum.


total number of strata x 4
population sampling
variance
orientation of strata
16 x 16
32 x 8
8 x 32
monte
carlo
estimate
of
sampling
variance
1.0
0.8
8
16
32
64
128
256
total number of sampling units

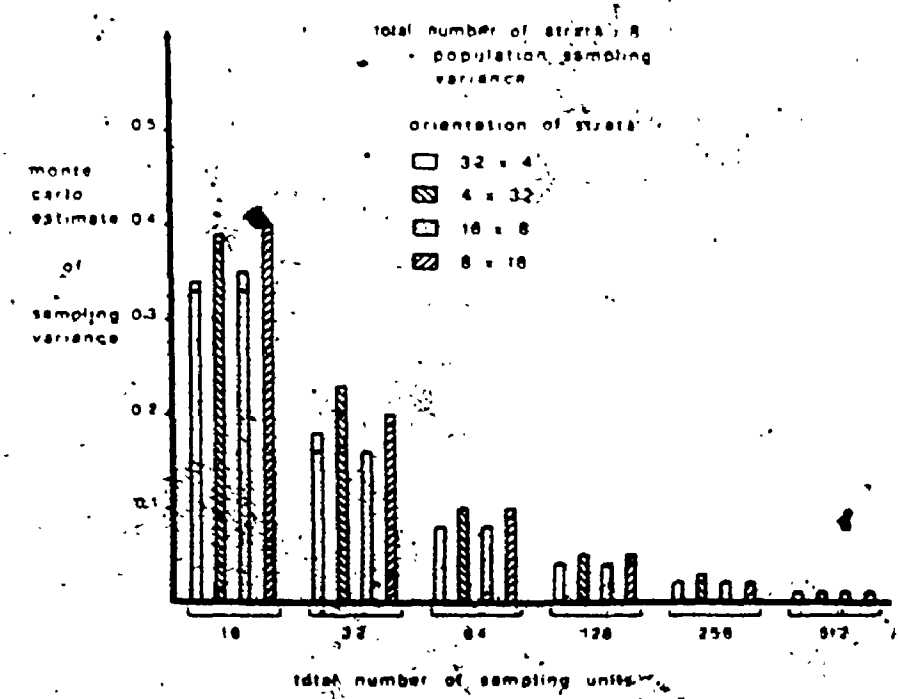
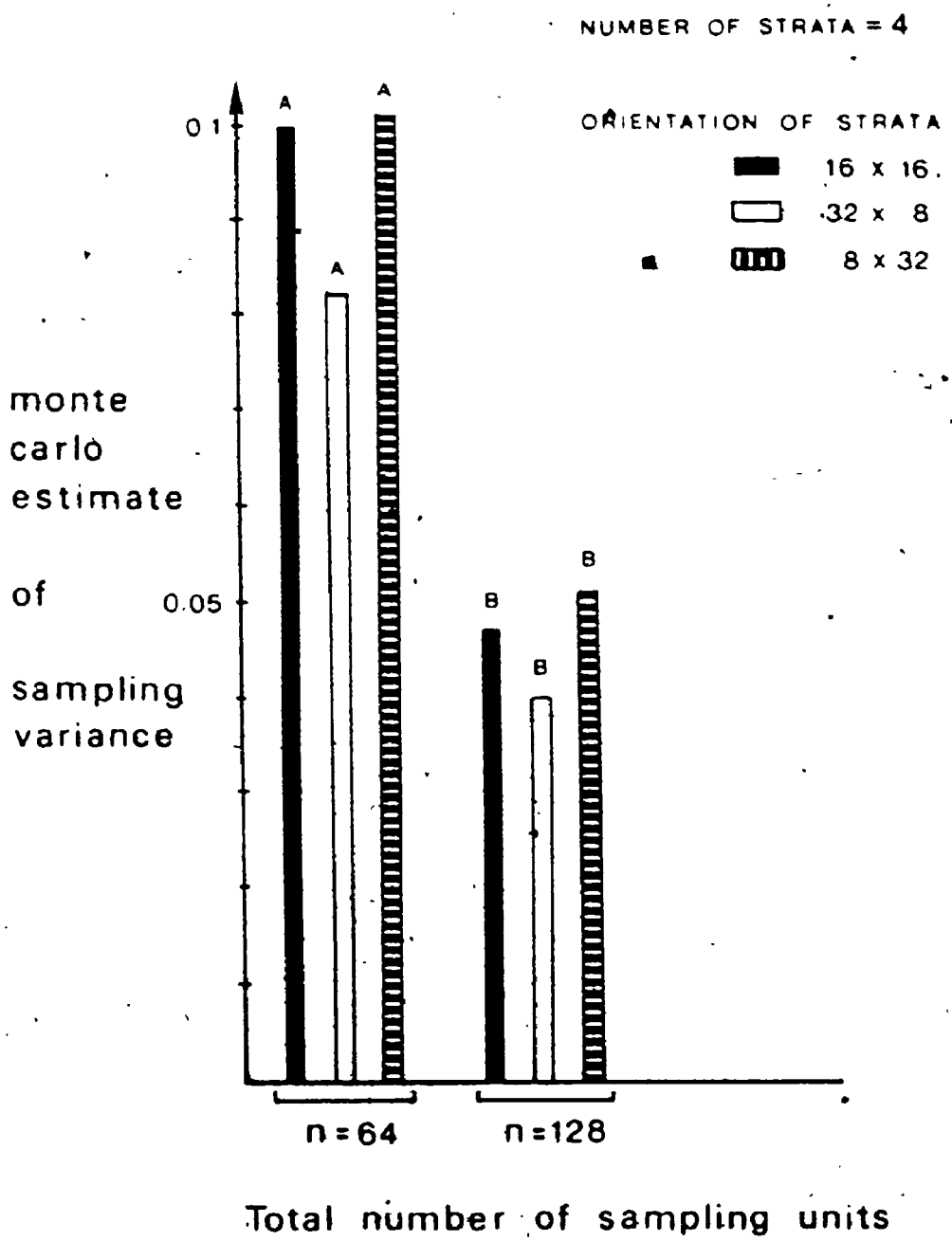

total number of strata x 8
population sampling
variance
orientation of strata
32 x 4
4 x 32
16 x 8
8 x 16
monte
carlo
estimate
of
sampling
variance
0.5
0.4
0.3
0.2
0.1
16
32
64
128
256
512
total number of sampling units

Figure 19 The effect of increased sample size on the Monte Carlo estimate of sampling variance for four strata using stratified random sampling. The first number of the orientation of the strata refers to the number of i rows and the second number refers to the number of j columns within any stratum. Means surmounted by different letters are significantly different at $P \leq 0.003$ by multiple pairwise F tests.


NUMBER OF STRATA = 4
ORIENTATION OF STRATA
16 x 16
32 x 8
8 x 32
0.1
0.05
A
A
A
B
B
B
monte carlo estimate of sampling variance
n=64
n=128
Total number of sampling units

oriented strata (16 x 2) and their horizontally oriented counterparts (2 x 16) (Fig. 20a).

Extensive stratification within the matrix does not lead to a decrease in the Monte Carlo estimate of sampling variance irrespective of the sample size used (Fig. 21).

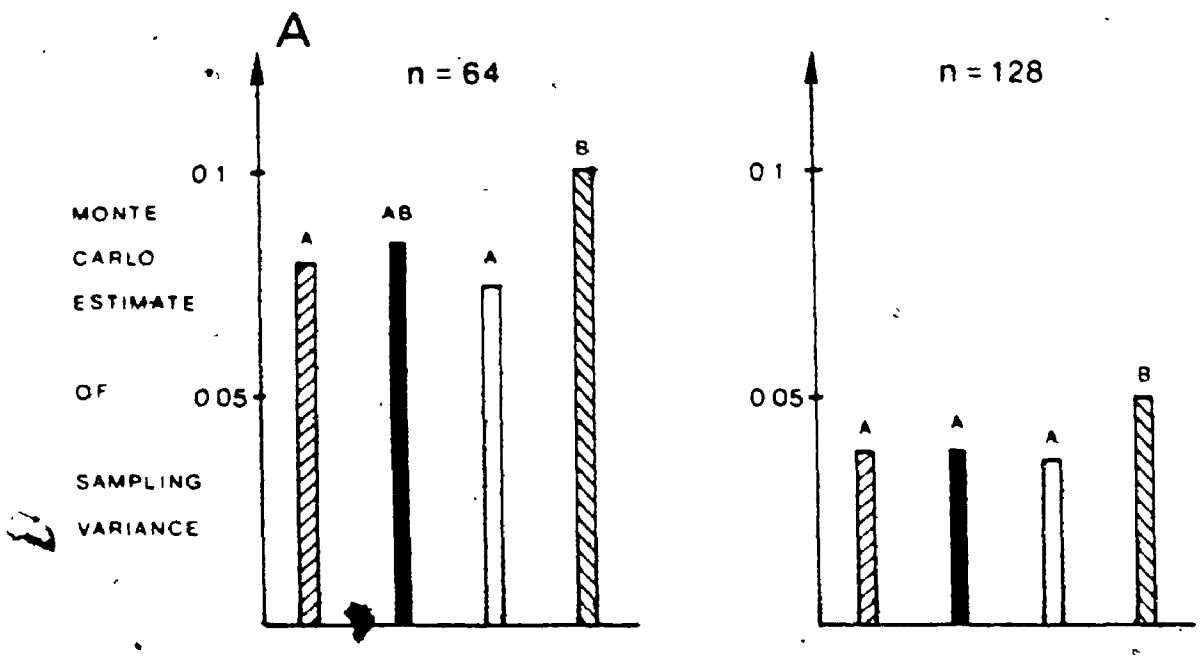
Cluster sampling:

As with stratified random sampling, three factors will influence the Monte Carlo estimate of sampling variance. These are a) the total number of sampling units, b) the total number of clusters sampled and c) the shape of the clusters.

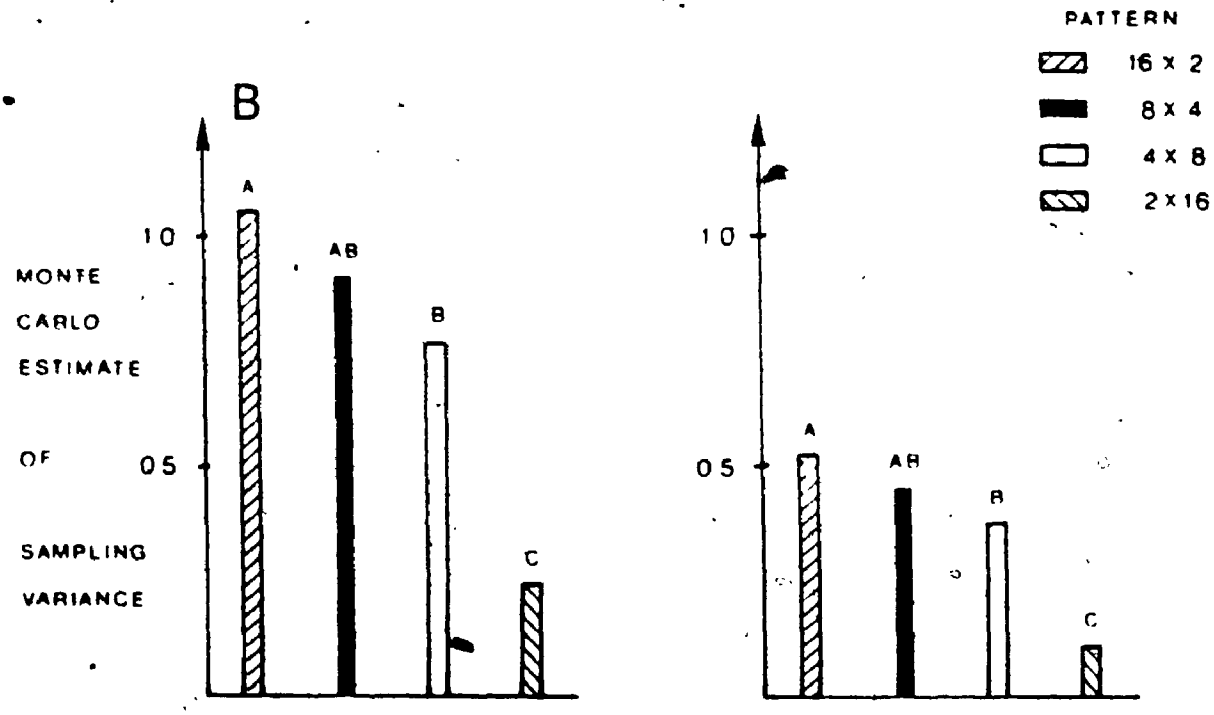
Cluster sampling involves the total enumeration of sampling units within each cluster. There are however, several cluster shapes which will result in the same number of sampling units per cluster. The shape of a cluster can be described by the number of i rows and the number of j columns it encompasses. A horizontally shaped cluster is one where the value of i is smaller than j (Fig. 22b) and a vertically shaped cluster is one where the value of i is larger than j (Fig. 22a).

The shape of the cluster has a strong influence on the Monte Carlo estimate of sampling variance. Sampling with horizontally shaped clusters (across corn rows) results in a decrease in the Monte Carlo estimate of the sampling variance (Fig. 23). The opposite occurs when vertically shaped clusters (along corn rows) are used (Fig. 23). This trend is consistent regardless of both the total number of sampling units and

Figure 20 Effects of different patterns of stratified random and cluster sampling on the Monte Carlo estimate of sampling variance for sample sizes of 64 and 128 units. a) Comparison of different orientations of strata; b) Comparison of different shapes of cluster. Means surmounted by different letters are significantly different at $P \leq 0.01$ by multiple pairwise F tests.

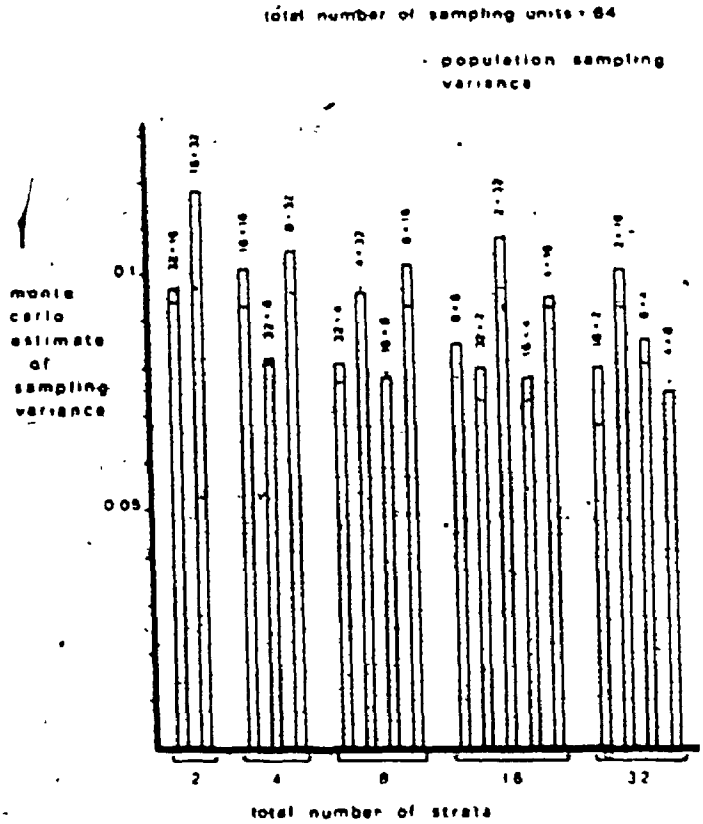


Stratified random sampling



Cluster sampling

Figure 21 The effect of increased stratification within the matrix on the Monte Carlo estimate of sampling variance for any constant sample size using the stratified random sampling method. The first number of the orientation of the strata refers to the number of i rows and the second number refers to the number of j columns within any stratum.


total number of sampling units = 64
- population sampling variance
monte carlo estimate of sampling variance
0.1
0.05
2
4
8
16
32
total number of strata

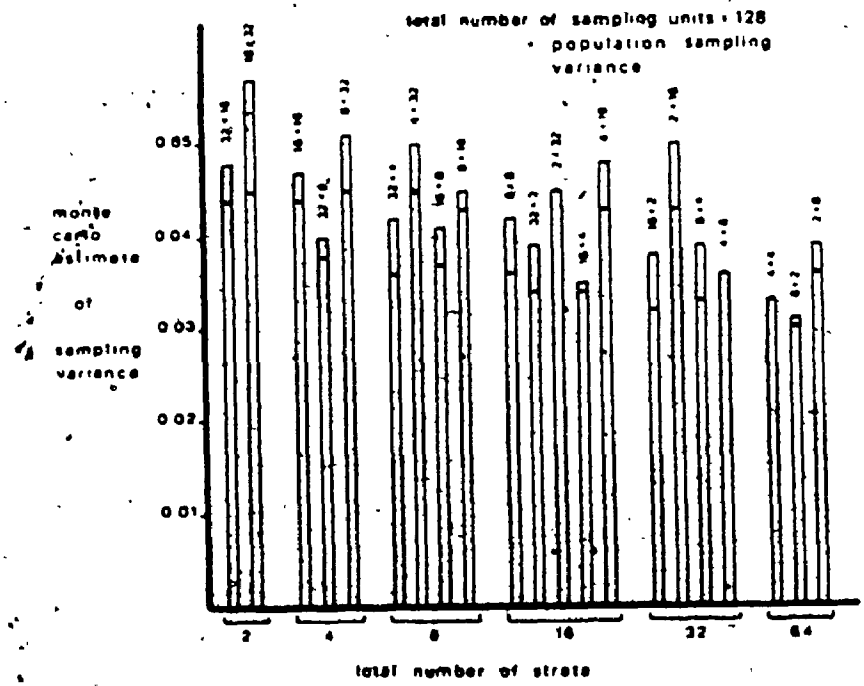
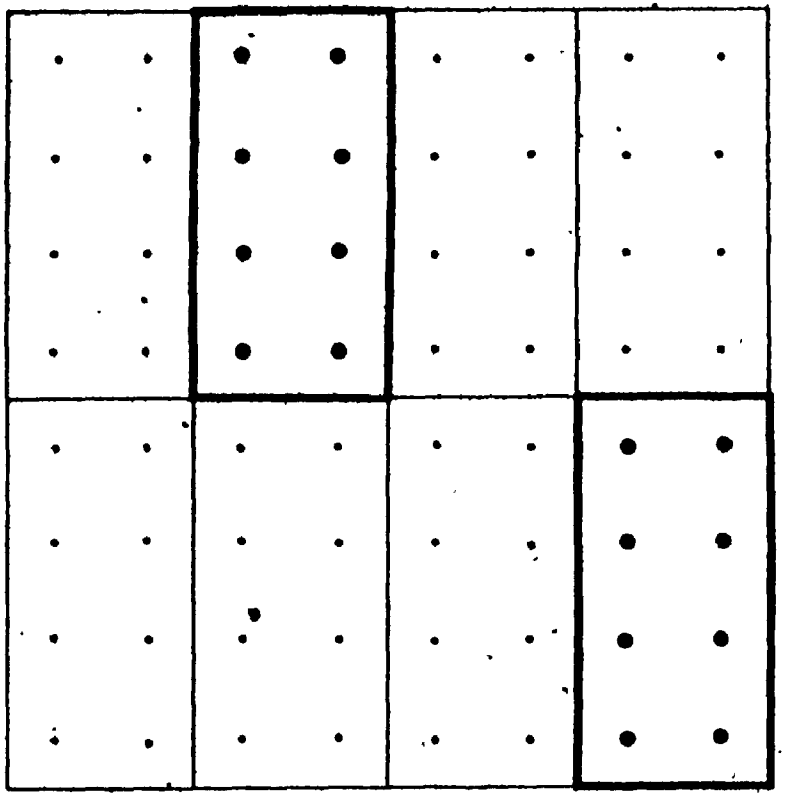

total number of sampling units = 128
- population sampling variance
monte carlo estimate of sampling variance
0.05
0.04
0.03
0.02
0.01
2
4
8
16
32
64
total number of strata

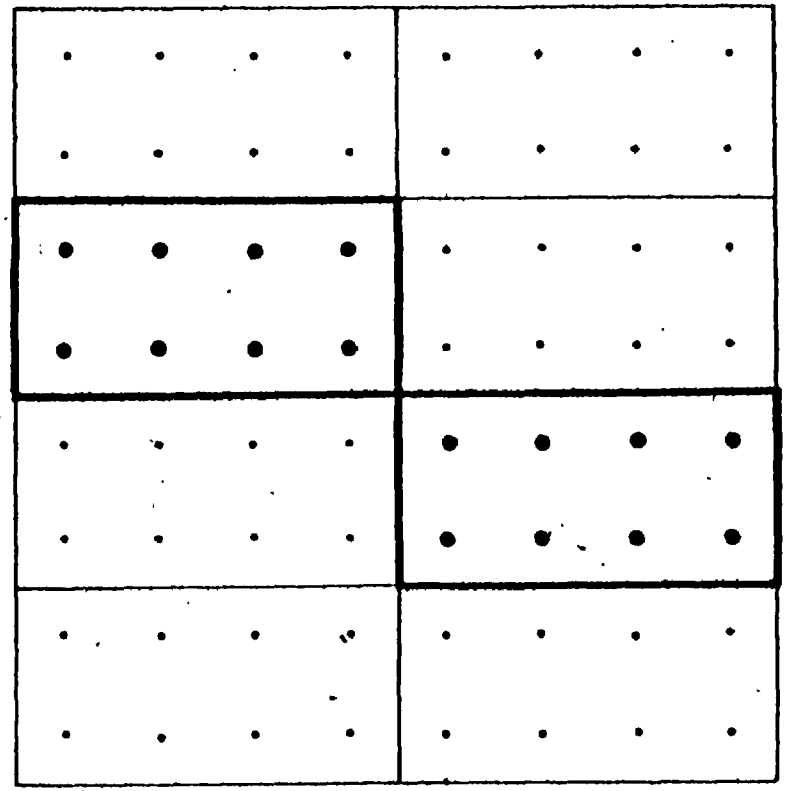
Figure 22 Diagrammatic representation of the cluster sampling method within the sampling site or matrix. The shape of a cluster is described by the number of i rows and the number of j columns it encompasses. The small dots indicate the possible sampling units in the matrix. The large dots represent the sampling units taken within each cluster.

A



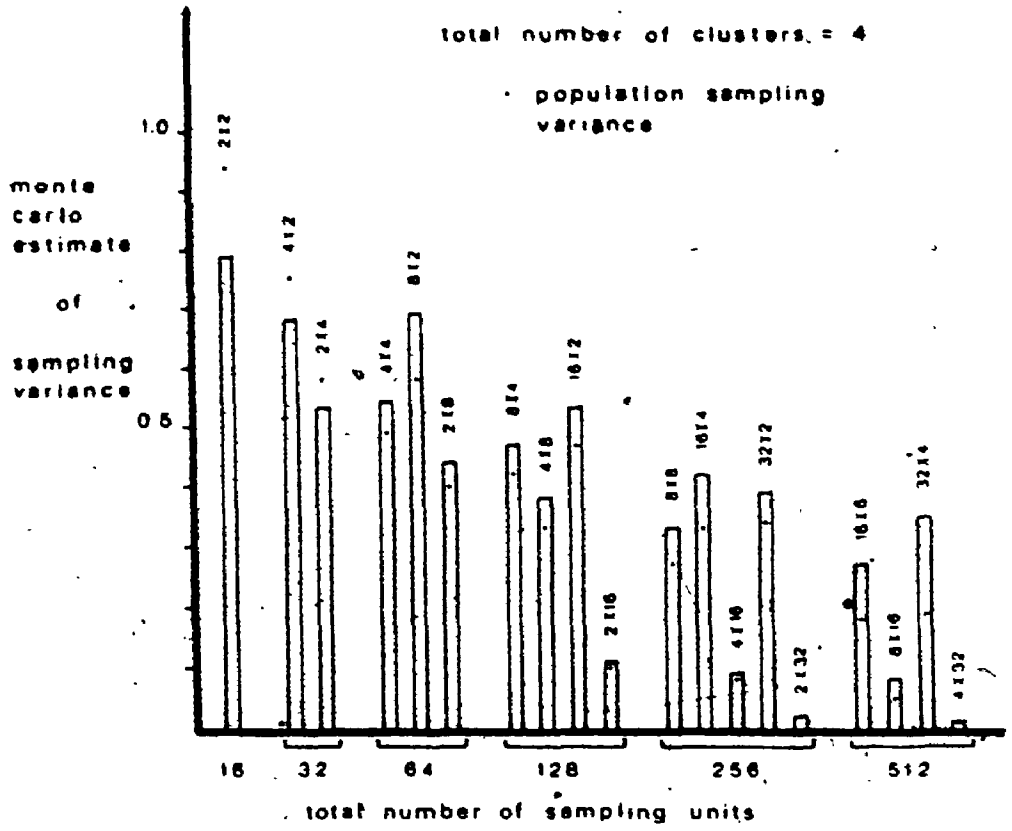
——....cluster layout = 4×2
number of clusters = 2
number of sampling units / cluster = 8

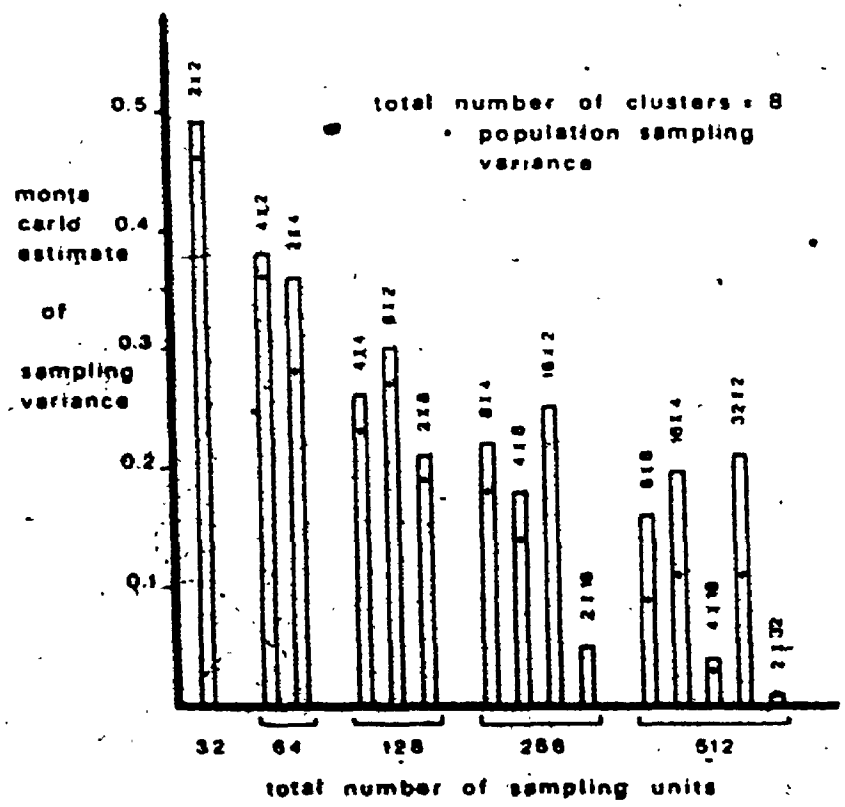
B



——....cluster layout = 2×4
number of clusters = 2
number of sampling units / cluster = 8

Figure 23 The effect of increased sample size on the Monte Carlo estimate of sampling variance for any given number of sampled clusters using the cluster sampling method. The numbers above each bar represents the cluster shape used for sampling. The first number refers to the number of i rows and the second one refers to the number of j columns in each cluster.


total number of clusters = 4
• population sampling variance
monte carlo estimate of sampling variance
1.0
0.5
2/2
4/2
2/4
4/4
8/2
2/8
8/4
4/8
16/2
2/16
8/8
16/4
4/16
32/2
2/32
16/8
8/16
32/4
4/32
16
32
64
128
256
512
total number of sampling units


total number of clusters = 8
• population sampling variance
monte carlo estimate of sampling variance
0.5
0.4
0.3
0.2
0.1
2/2
4/2
2/4
4/4
8/2
2/8
8/4
4/8
16/2
2/16
8/8
16/4
4/16
32/2
2/32
32
64
128
256
512
total number of sampling units

the number of clusters sampled (Fig. 23). For sample sizes of both 64 and 128 units, the differences between the vertically shaped cluster (16 x 2) and its horizontally shaped counterpart (2 x 16) were significant at $P \leq 0.01$ (Fig. 20).

As the total number of sampling units increases, the Monte Carlo estimate of sampling variance greatly varies regardless of the number of clusters sampled (Fig. 23). For any sample size, the Monte Carlo estimate of sampling variance decreases as the number of clusters increases (Fig. 24).

Comparison of sampling methods:

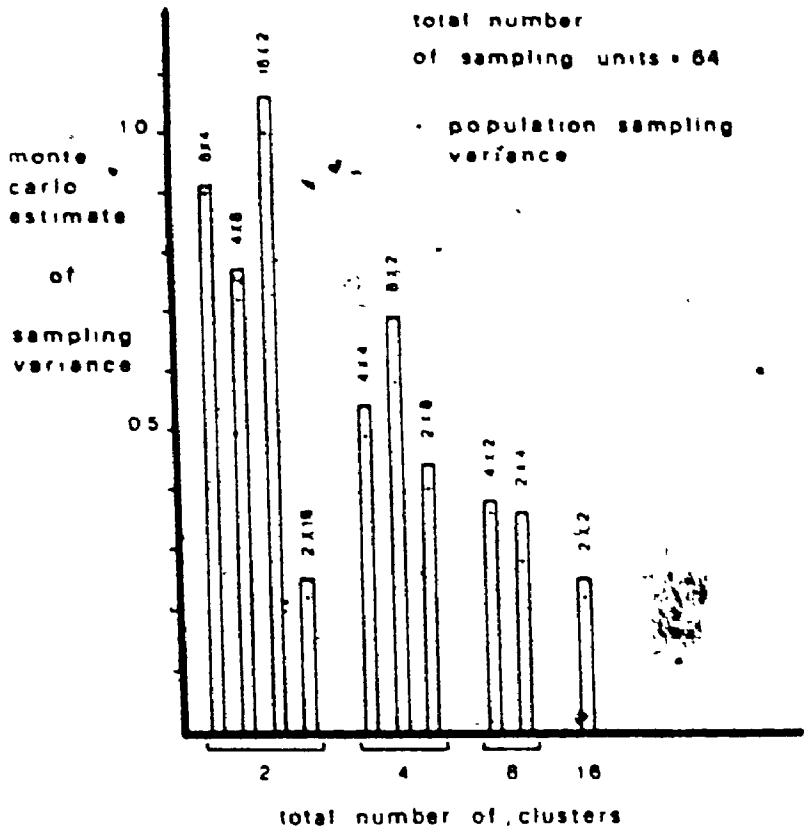
For a fixed sample size of 64 units, the different sampling methods were compared in their determinations of the Monte Carlo estimate of sampling variance. Results indicate that cluster sampling is significantly less precise ($P \leq 0.001$) from all other sampling methods (Fig. 25). Similarly, the sampling interval 8-2 used in systematic sampling gave a significantly more precise Monte Carlo estimate of sampling variance from all other sampling methods ($P \leq 0.001$) (Fig. 25).

2.8.4. Discussion

a) Determination of the minimum number of sampling units

If my results have general application, then the number of sampling units needed to describe the seed bank of an abundant species such as Chenopodium spp. should range between 60 and 100 sampling units. Below

Figure 24 The effect of increasing the number of clusters sampled on the Monte Carlo estimate of sampling variance for any given sample size using the cluster sampling method. The numbers above each bar represents the cluster shape. The first number refers to the number of i rows and the second one refers to the number of j columns in each cluster.


total number
of sampling units = 64
• population sampling
variance
monte
carlo
estimate
of
sampling
variance
1.0
0.5
8/4
4/8
16/2
2/16
4/4
8/2
2/8
4/2
2/4
2/2
2
4
8
16
total number of clusters

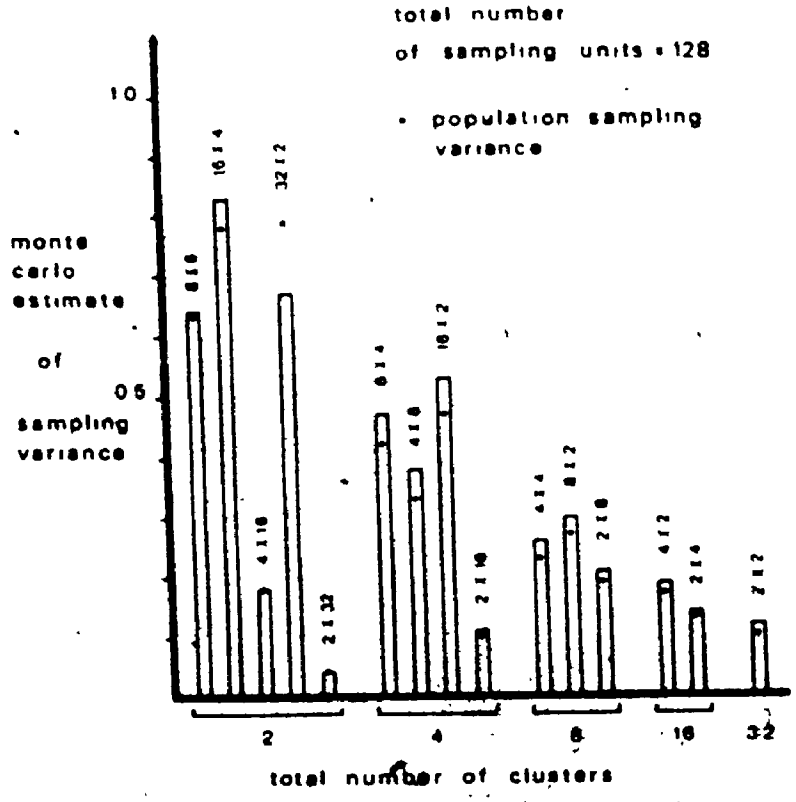
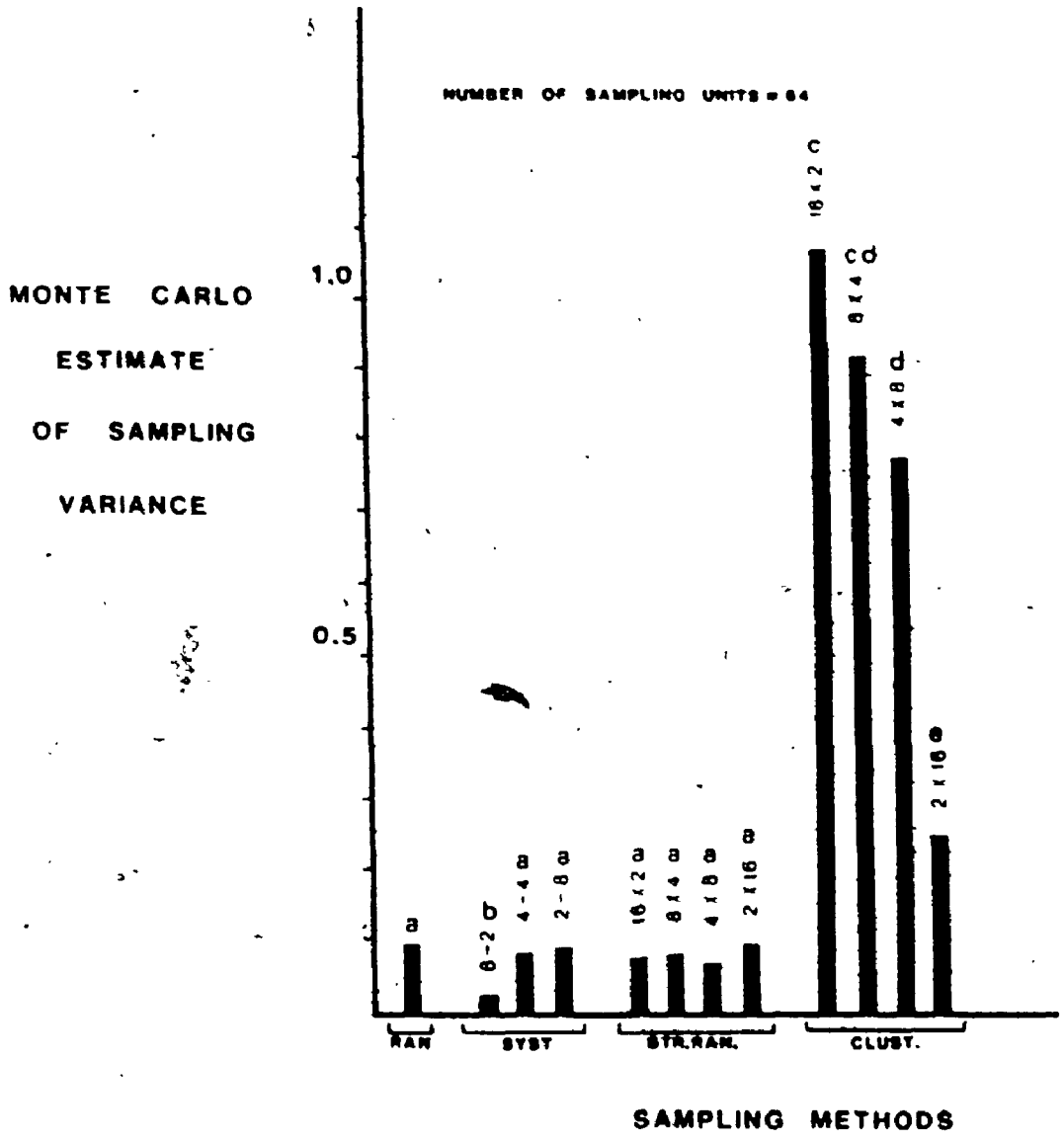

total number
of sampling units = 128
• population sampling
variance
monte
carlo
estimate
of
sampling
variance
1.0
0.5
8/8
16/4
32/2
4/16
2/32
8/4
4/8
16/2
2/16
4/4
8/2
2/8
4/2
2/4
2/2
2
4
8
16
32
total number of clusters

Figure 25 Comparison of the Monte Carlo estimate of sampling variance for different sampling methods of sample size of 64 units. Means surmounted by different letters are significantly different at $P \leq 0.001$ by multiple pairwise F tests. RAN. = random; SYST. = systematic; STR.RAN = stratified random; CLUST. = cluster.


NUMBER OF SAMPLING UNITS = 64
MONTE CARLO ESTIMATE OF SAMPLING VARIANCE
1.0
0.5
a
8-2 b
4-4 a
2-8 a
16 x 2 a
8 x 4 a
4 x 8 a
2 x 16 a
16 x 2 c
8 x 4 cd
4 x 8 d
2 x 16 e
RAN
SYST
STR.RAN.
CLUST.
SAMPLING METHODS

this range, the number of sampling units collected is too small so that the Monte Carlo estimate of the sampling variance is large as predicted by the population sampling variance (Fig. 14). Beyond 100 sampling units the decrease in the Monte Carlo estimate of sampling variance is too small to justify by the extra labour needed to collect and process these additional sampling units.

According to Forcella (1984), sample size of 800-1000 cm^2 is not only large enough to represent the species diversity of the seed bank of a pasture but also large enough to adequately estimate the densities of its species. My estimate of sample size (60-100 units) for Chenopodium spp. seeds represents a much smaller combined surface area of replicated soil samples (170-284 cm^2). This is not critical since both the presence of seeds of very common species and of seeds in general can be detected with individual samples of 1-4 cm^2 (Forcella, 1984) as used in this study.

My estimate of an optimal sample size approximate previous findings by Rabotnov (1958) and Goyeau and Fablet (1982). For the total seed number, the most abundant species and those species evenly distributed in the soil, Rabotnov (1958) concluded that no fewer than 100-200 sampling units should be collected regardless of their dimensions.

Goyeau and Fablet (1982) made two important observations:

1) If the seed distribution is expected to be aggregated, then the sample size should be greater than one hundred.

2) If the expected mean seed density per sampling unit (5 cm diameter, 30 cm deep) ranges between five and forty, then ranging a sample size of approximately 50 is needed to estimate the mean seed density with 20% precision ($\alpha = 0.01$).

The seed distribution of Chenopodium spp. for the area surveyed (i.e. the matrix) was shown to be clustered (Table 11, page 68) with a population mean for Chenopodium spp. seeds of 2.37 ± 2.568 ($\bar{X}$ ± SD) (Fig. 11, page 65). According to the findings of Goyeau and Fablet (1982), the number of Chenopodium spp. seeds would be described by a sample size of 50. My results indicate that a sample size ranging between 60 and 100 sampling units would be adequate to describe the seed bank of Chenopodium spp. in the soil only if its population is the same as the one described by the overlay of regularly spaced sampling units forming the matrix. It is, however, unjustified to assume that the seed distribution in the matrix emulates the field as a whole.

b) Comparison of sampling methods

The sampling methods were tested on a matrix created by sampling units taken systematically from a field. Thus the matrix might have been influenced by the method used to sample the field. It is possible that the sampling interval coincided with a regularly repeated pattern in the seed population of the field as a whole. Indeed this seemed to have occured. Since the matrix is assumed to represent a population of contiguous sampling units, the population of Chenopodium spp. seeds formed by the matrix showed, in this case, directionality (Fig. 12, page

71). This characteristic of the population formed by the matrix had an influence on the efficiency of the sampling methods tested.

Random sampling:

The Student's t tests indicated no significant differences between either the regression coefficients (slope) or the elevations of the regression lines of the population sampling variance and the Monte Carlo estimate of sampling variance (Tables IX and X of Appendix D). Since the two regression lines not only are parallel but also have the same elevations, we can then conclude that these two regression lines coincide (Fig. 14). The decrease of the Monte Carlo estimate of sampling variance with increasing sample size then follows the same pattern as the one for the population sampling variance. This give further evidence of the adequacy of the Monte Carlo technique in estimating a desired statistic.

Systematic sampling:

The population of Chenopodium spp. seeds identified by the matrix shows directionality, where groups of corn rows exhibit high seed numbers while others exhibit low ones (Fig. 12 and Table 12). Because of this pattern, the configuration of the sampling interval is important in determining the Monte Carlo estimate of sampling variance.

When the interval between i rows is less than that between j columns, the Monte Carlo estimate of sampling variance is large. This means that a large number of the sampling units are collected from only a few j columns (or corn rows). There is a greater chance that the

interval between j columns coincides with the periodic occurrence (or its multiple) of corn rows with high seed density (Fig. 15). The resulting sample will be badly biased (Greig-Smith, 1964; Elliott, 1977; Snedecor and Cochran, 1980).

On the other hand, when the interval between i rows is greater than that between j columns, the Monte Carlo estimate of sampling variance is small. This means that only a few sampling units are collected from a large number of j columns (or corn rows). The result is a better distribution of sampling units over the entire matrix or sampling site.

An equal sampling interval (where the interval between i rows equals that between j columns) may be preferable to an irregular sampling interval when the underlying distribution of the seed population in the soil is unknown.

Stratified random sampling:

The main advantage of stratified random sampling is that the population under investigation can be divided into subpopulations or strata which are more homogeneous than the entire population. The consequence is a substantial gain in precision in sampling (Snedecor and Cochran, 1980). This is demonstrated by a reduction in the variation of the estimate of the population parameters (Steel and Torrie, 1960).

Stratified random sampling also allows the use of relevant information about the population (Snedecor and Cochran, 1980). In this case, the aggregate seed distribution of Chenopodium spp. in the soil along

the corn rows makes stratification advantageous.

When the orientation of the strata coincides with the corn rows (i.e. the value of i is greater than that of j) (Fig. 17), the Monte Carlo estimate of sampling variance is small (Fig. 18). This means that each stratum covers only a few corn rows (j columns) over a long distance (many i rows). Thus stratification along corn rows will allow the variance within strata to be minimized while the variance between strata is maximized. The final result is a gain in sampling precision over simple random sampling (Fig. 25).

Alternatively, when the orientation of the strata is such that the value of i is less than that of j (Fig. 17), the Monte Carlo estimate of sampling variance is large (Fig. 18). Each stratum thus covers many corn rows (j columns) over very short distances (few i rows). This stratification across the corn rows will not minimize the variance within the strata since each stratum will extend over a wide range of seed density. This variation in the number of Chenopodium spp. seeds in the different corn rows has been illustrated in Figure 12, page 87.

The discrepancy between the Monte Carlo estimate of sampling variance of horizontally and vertically oriented strata decreases with increasing sample size (Fig. 18 and 19). Indeed, for any pre-determined number of strata, an increase in the total number of sampling units translates into an increase in the number of sampling units per stratum. This is beneficial, since the need for at least six sampling units per stratum in order to obtain a reliable estimate of variance for that

stratum has been pointed out by Sampford (1962).

Similarly for a given sample size, an increase in stratification within the matrix does not lead to a decrease in the Monte Carlo estimate of sampling variance (Fig. 21). As stratification increases, the number of sampling units per stratum decreases, rendering the estimate of variance for that stratum unreliable (Sampford, 1962).

Cluster sampling:

The aggregate seed distribution of Chenopodium spp. seeds in the soil has a strong influence on the precision of cluster sampling. With horizontally shaped clusters (where the i value is less than the j value), the Monte Carlo estimate of sampling variance is small (Fig. 20b, 23). These clusters cover many corn rows (j columns) over a short distance (few i rows). The result is a large within-cluster variance and a small between-cluster variance. This is consistent with the clustering principle (Stuart, 1976). By making the between-cluster variation as small as possible, the variation caused by the random selection of clusters is minimal (Sampford, 1962).

With vertically shaped clusters (where the i value is larger than the j value), the Monte Carlo estimate of sampling variance increases (Fig. 20b, 23). Each cluster covers only a few corn rows (j columns) - but over a long distance (many i rows). The comparable number of seeds of Chenopodium spp. sampled within each corn row may ensure that the sampling units within the cluster tend to be similar. This is contrary to the clustering principle where heterogeneous clusters are needed

(Stuart, 1976).

When the total number of sampling units selected is fixed, the Monte Carlo estimate of sampling variance decreases as the number of clusters increases (Fig. 24). These numerous small clusters result in better precision of estimates (Kenkel, 1981). The random selection of a large number of clusters may provide a better distribution of these clusters over the sampling site (Kenkel, 1981).

However, when the cluster size is fixed, the effect of an increase in the sample size on the precision of the estimate is dependent on the underlying distribution of the variable (Kenkel, 1981). The aggregate seed distribution of Chenopodium spp. seeds ensures that cluster shape has a strong influence on the precision of the estimate. This is evident by the lack of any discernable trend in the behavior of the Monte Carlo estimate of sampling variance with increasing sample size associated with fixed cluster size (Fig. 23).

Comparison of sampling methods:

The multiple pairwise comparisons of sampling methods indicated clearly that random, systematic and stratified random sampling methods were not significantly different from one another (Fig. 25). It was also demonstrated that an 8-2 sampling interval used for systematic sampling was significantly different ($P \leq 0.001$) from random sampling (and all other sampling methods) for the Monte Carlo estimate of sampling variance (Fig. 25). In the former case, the Monte Carlo estimate of sampling variance was lower since the population had a fairly consistent

trend for the measured variable (Sampford, 1962). However, the opposite can also occur if the sampling interval coincides with regularly repeated features. Regardless of this inconvenience, systematic sampling is often preferred over other methods since 1) it is easier to execute than a random sampling method (Sampford, 1962; Grieg-Smith, 1964), 2) the sampling units are more evenly distributed over the area (Elliott, 1977) and 3) a randomly sited systematic sample will give an unbiased estimate of the population mean (μ) (Sampford, 1962).

Systematic sampling may be quite satisfactory if the typification of an area (i.e. the description of distinguishable groups) is desired, provided that no sampling variance is required. An unbiased sampling variance cannot be estimated even with a randomly sited systematic sample (Sampford, 1962). If estimation of population parameters is the primary objective of the sampling procedure, then these estimates must be unbiased and the calculation of confidence limits about the estimates must be possible (Kenkel, 1981). Thus, the sample obtained from the selected sampling methods should maximize the precision of the statistic (that is, minimize the sampling variance of the statistic) (Kenkel, 1981). Such an objective can be achieved with random, stratified random and cluster sampling methods.

The Monte Carlo estimates of sampling variance for the cluster sampling method were significantly different ($P \leq 0.001$) from all other sampling methods tested (Fig. 25). This substantial loss of precision is often characteristic of cluster sampling (Stuart, 1976). The clustering principle demands that sampling units within each cluster vary as

much as possible while the variation between clusters is minimized (Stuart, 1976). However, for cluster sampling, all the units within a cluster are selected so that the sampling variance for an estimated parameter depends solely on the variation between clusters (Sampford, 1962). Simultaneously, the seed distribution in the soil over the area surveyed exhibited bands of high and low seed densities parallel to the corn rows (Fig. 12). Randomly located clusters within the surveyed area would reflect this pattern, accentuating the variation between clusters. This is in direct contradiction to the clustering principle. The only valid reason for using cluster sampling is that the sampling cost (i.e. the ease of obtaining the sampling units) compensates for the loss in precision of the estimates (Stuart, 1976).

Figure 25 indicates no significant difference between the Monte Carlo estimates of sampling variance of the random and stratified random sampling methods. The gain in precision from using stratified random sampling over random sampling depends on the variation between means of strata. As the latter increases, so does the gain in precision (Stuart, 1976). As long as the sampling fraction (sample size/population size) is negligible, there can be no loss in precision and a uniform sampling fraction in each stratum almost always increases the precision (i.e. reduces the sampling variance (Stuart, 1976). The gain in precision over random sampling will depend on making the strata in a heterogeneous population as homogeneous as possible (Snedecor and Cochran, 1980). This results in an increase in the variation between means of strata.

In this instance the stratified random sampling method did not give

any gain in precision over the random sampling method. The advantage of stratified random sampling is in the use of physical characters of a field such as drainage gradients, fertility levels, location of weed infestations of orientation of crop rows in delimiting the strata. Such characters may prove useful in explaining the seed distribution in the soil.

2.9. Summary

In order to determine the sampling procedure that should be used in the study of seed bank, five objectives were defined and the results of these tests are summarized below.

Objective I:

To determine the most appropriate diameter of sampler to estimate the density of seeds in the soil.

There were no significant differences between the three sizes of soil sampler (1.9 cm, 2.7 cm and 3.3 cm in diameter) in the estimation of the number of seeds of Chenopodium spp. and the total number of seeds per 100 ml of soil. The smaller sampler is recommended since samples of smaller size are easier to collect and can be to processed faster than larger ones.

Objective II:

To determine the homogeneity of variance of the sampling units used to estimate the seed distribution in the soil over a small area (0.25 m^2).

At the time of sampling (late October), some seed shedding had already occurred and clustering of seeds of Chenopodium spp. was evident on the soil surface. Because of this seed shedding, the seed distribution of Chenopodium spp. over small areas (50 cm X 50 cm) could not be conclusively described as homogenous or as showing a Poisson distribution. Half of the quadrats sampled had a Poisson distribution while the others did not.

Objective III:

To determine the homogeneity of variance of the sampling units used to estimate the seed distribution in the soil over a large area (1.35 ha).

Over the large area tested (1.35 ha) the distribution of seeds of Chenopodium spp. and that of the total number of seeds did not follow a Poisson distribution. Instead, they exhibited clustering on a macro-scale. This cluster distribution was associated with areas of large numbers of Chenopodium spp. seeds among corn rows.

Objective IV.

To determine the minimum number of sampling units needed to provided an acceptable estimate of the mean density and the sampling variance of a population.

For the population studied, the minimum number of sampling units needed to describe the seed bank of Chenopodium spp. ranged between 60 and 100 sampling units.

Objective V:

To determine which sampling method minimizes the sampling variance.

With random sampling, as the sample size increased the Monte Carlo estimate of sampling variance decreased. With systematic sampling, the configuration of the sampling interval greatly influenced the Monte Carlo estimate of sampling variance since the underlying distribution of the Chenopodium spp. seeds in the field exhibited a clustered pattern.

Extensive stratification did not lead to a reduction in the Monte Carlo estimate of sampling variance when stratified random sampling was used. Since the seed distribution of Chenopodium spp. was clustered, the orientation of the strata may have influenced the Monte Carlo estimate of sampling variance although these differences tended to decrease with increasing sample size. Strata oriented along the same axis as the corn rows resulted in smaller Monte Carlo estimates of sampling variance than their counterparts.

The underlying distribution of Chenopodium spp. seeds in the soil had a strong influence on the precision of cluster sampling. Increasing both the total number of sampling units and the number of clusters and using clusters which included as many as corn rows as possible, decreased the Monte Carlo estimate of sampling variance.

When comparisons were made of all four sampling methods, both cluster and systematic sampling were strongly influenced by the underlying aggregate seed distribution of Chenopodium spp. seeds. Cluster sampling

resulted in a loss of precision of the estimates and systematic sampling could not give an unbiased estimate of sampling variance. There were no significant difference between random and stratified random sampling in their determination of the Monte Carlo estimate of sampling variance. Based on my results, one of these sampling methods (random or stratified random) could be used to study the seed banks of weeds in the soil. In situations such as mine, stratified random sampling is more advantageous since the stratification makes use of known physical, biological or environmental characters of the area.

CHAPTER 3

ESTIMATION OF THE SEED BANK OF *Chenopodium* spp. IN CULTIVATED FIELDS

3.1 Influence of crop husbandry on the sizes of the seed banks of weeds

The seed bank of weeds in the soil is a reflection of the cropping history of the land as well as an indication of the effectiveness of the weed control measures used in the past (Roberts, 1966, 1981). A seed bank under cropping conditions is described often as the number of viable seeds in the top 15 to 20 cm of soil. Various components of crop husbandry such as manuring, crop rotation, fallowing, cultivation and herbicides have an effect on the size of the seed population of weeds in arable soils.

Manuring:

Neither the continuous use of farmyard manure (Roberts, 1962; Roberts and Stokes, 1965; Allott, 1970; Roberts and Feast, 1973a) nor of inorganic fertilizers (Roberts, 1972) had any effect on the numbers of viable weed seeds as long as good weed control was maintained. However, Allott (1970) mentioned that raspberry plots which had received a mulch of farmyard manure had slightly more viable weed seeds in the soil than plots which had not received a mulch cover.

Crop rotation:

Dvořák and Krejčíř (1974) reported that in a crop rotation, the

preceding crop does not appear to influence the size of the seed bank of weed species while Dotzenko et al. (1969) observed the contrary situation. However, in later studies, Dvořák and Krejčíř (1980a,b) found that smaller seed populations of weeds in the soil were present in rotations having a high proportion of broad-leaved crops than in a cereal (wheat) monoculture. In Morocco, a crop rotation of three years of rice and three years of dryland crops had the lowest number of Echinochloa crusgalli (L.) Beauv. seeds in the soil of all crop rotations used for rice fields (Bouhache et al., 1973). Any depletion of the soil seed reserves occurred only when the weed control methods were successful. Weed control is usually difficult to maintain under crop rotation (Roberts and Stokes, 1965). Where a vegetable rotation is introduced, the species composition of the seed population in the soil may be altered (Roberts and Stokes, 1965) to include a greater proportion of weed species associated with vegetable cropping and intensive cultivation (Roberts, 1962; Roberts and Stokes 1965).

Fallowing:

A third component of crop husbandry which can influence the size of a seed population of weeds in arable soils is fallowing. Its effectiveness in reducing the seed bank of a weed population is governed by a series of factors and their interactions. These are the frequency and thoroughness of cultivation, the timing of cultivation with regard to seedling emergence, the environmental conditions such as temperature and rainfall and the kinds of weeds present in the population (Brenchley and Warington, 1933, 1936, 1945). However, the differences in seed dormancy of the different weeds (Brenchley and Warington, 193[illegible]) and in their

response to cultivation will result in various degrees of reduction in their seed populations in the soil (Brenchley and Warington, 1933, 1945). Archibold and Hume (1983) also indicated that dispersal of weed seeds onto fallow land is an important factor in maintaining the seed bank, as well as influencing subsequent weed populations in cultivated land in Saskatchewan.

Cultivation:

Cultivation is another component of crop husbandry which can greatly influence the size of a seed bank. In several experiments the rate of decrease in the number of viable seeds in the soil increased as the number of cultivations per year increased (Roberts, 1966; Roberts and Dawkins, 1967; Roberts, 1970 Roberts and Feast, 1973a; Cook, 1980). In the absence of seed production, the weed seed population in the soil declined more rapidly with cultivation than without cultivation (Roberts, 1966; Roberts and Dawkins, 1967; Roberts, 1970; Roberts and Feast, 1973a; Froud-Williams et al., 1983; Warnes and Andersen, 1984). Where cultivation is intensified, there is a general tendency for weed species associated with intensive cropping (e.g. vegetable production) to increase in relative importance (Roberts, 1962; Roberts and Stokes, 1965).

Variations in the effect of different deep ploughing treatments on seed banks of weeds have been small (Roberts, 1963c; Roberts and Stokes, 1965) and not statistically different (Roberts, 1963a,c). Indeed, differences between cultivation treatments appeared as differences in the distribution of seeds in different layers of soil rather than in the

total number of seeds present throughout the working depth (Roberts, 1963c; Roberts and Stokes, 1965).

Herbicides:

The last component which can influence the size of a seed bank is the use of herbicides. Their use is dictated by the crops sown and the rotation used. If adequate weed control is obtained with herbicide application and seed production of weeds is prevented, then the seed population in the soil can be reduced by 90% within four years for continuous corn with minimum tillage (Schweizer and Zimdahl, 1984a). However, if herbicide application is discontinued, the seed bank of weeds will increase (Schweizer and Zimdahl, 1984a).

Better weed control was obtained when intensive use of herbicides rather than moderate use was incorporated into a crop rotation (Schweizer and Zimdahl, 1984b). The rate of decline in seed numbers is determined by the annual percentage of germination and by the longevity of the weed seeds in the soil (Chancellor, 1979). When intensive management systems involving fertilizers and herbicides are used, then seed banks of weeds can be reduced by 38% on average (Zawislak, 1980). However, if environmental conditions delay herbicide application or tillage, then the number of weed seeds in the soil can be expected to increase (Schweizer and Zimdahl, 1984b).

Long-term herbicide application to the same crop has been reported to alter the species composition of the seed bank (Roberts, 1970; Hurle, 1974; Roberts, 1981). However, after several years of various

herbicide application, various authors have reported a change in the number of seeds for individual species but no alteration to the species composition of the seed bank (Dvořák and Krejčíř, 1980b; Chancellor, 1979; Roberts and Neilson, 1982).

3.2 Objectives of the study

The main objective of this study was to compare the seed banks of Chenopodium album in cultivated fields with different cropping histories. Since the extraction method did not permit the identification of the seeds to the species level, they were grouped as Chenopodium spp. However, surveys of growing plants in the area revealed that Chenopodium album was the only common species of Chenopodium in that community and it was very abundant.

The second objective was to determine the proportional contribution of black and brown seeds of Chenopodium spp. to the seed bank and describe their physical state.

The third objective was to examine the effect of the sampling procedure on the estimate of the size of the seed bank of Chenopodium spp.

3.3 Description of sampling site

Fields with different cropping histories were sampled on Tucsok's farm to estimate the seed bank of Chenopodium spp. The location of this farm is described in Section 2.4. The layout of the seven fields or

areas sampled on the farm is schematically represented in figure 4 on page 36. The soil differed slightly from field to field but was fairly uniform within each field. Table 14 gives a brief description of the soils encountered on Tucsok's farm. Most fields were well drained except for one low area (6) which had a muck soil.

This farm had a fifteen year history (1961-1976) of corn monoculture with yearly applications of atrazine (Tucsok, personal communication). In the last few years of this period, lamb's-quarters had become increasingly difficult to control. Application rates of atrazine had increased above the recommended rate without any success in controling this weed. It became evident that the population of lamb's-quarters on Tucsok's farm was triazine-resistant. As a result farm management practices were drastically altered. An intensive crop rotation program with little or no herbicide application was initiated in 1979 to reduce the cost of production, to control this lamb's-quarters' infestation more efficiently and to improve the soil texture. Table 14 gives a summary of the crops grown in each field (or area) over the last four years.

3.4 Sampling procedures

The seed bank was sampled on 1-15 July 1982. Soil cores (1.9cm in diameter and 15cm deep) were sampled and stored in numbered plastic bags in a constant temperature room (6.3 ± 0.8°C). The extraction of seeds from the soil followed the procedure described in Section 2.5.3 and Appendix B. Once dried, all Chenopodium spp. seeds were separated from the debris by hand under a dissecting microscope (6.4x). Recognizable

Table 14. Crop rotations on the surveyed fields on Tucsok's farm, Oxford County, Ontario, in 1979-1982.

Field No.	Surveyed area (ha)	Soil series	Crops in the rotation			
			1979	1980	1981	1982
1	17.6	Perth	Corn	Barley	Peas[1]	Soybeans[2]
2	0.5	Perth	Corn	Barley	Peas	Wheat
7	11.7	Perth & Grombie	Corn	Peas	Wheat	Corn
8	22.0	Crombie & Embro	Corn	Corn	Barley	Peas[1]
5	4.1	Perth	Corn	Corn	Soybeans	Corn[3]
6	4.1	Muck	Corn	Corn	Soybeans	Corn
3	0.1	Perth	--[4]	--	Fallow	Fallow
4	0.1	Perth	--	--	Fallow	Fallow

[1] Winter wheat was planted in the fall and ploughed under as green manure in the spring.
[2] Metolachlor was applied in the spring at 2.6 Kg ai/ha to control weeds.
[3] Manure was applied in the previous fall.
[4] -- = unknown crop history

Chenopodium spp. seeds were separated into either black or brown seeds. Those seeds that were included in the black category had a true ebony black color. Brown seeds exhibited a continuum of color ranging from light red to dark brown. My brown seed category did not exactly correspond to the one described by Williams (1963) and Williams and Harper (1965) since my brown seeds were of the same size range as the black ones.

Seeds were also classified as whole, damaged or underdeveloped and formed the seed population in the soil. Similar criteria as those described by Fleischman (1951) were used to describe the physical state of the seeds. Seeds were recognized as whole if they were plump and whole with no sign of damage to the testa. These whole seeds were considered viable and represented the seed bank. When cracks, indentations or perforations to the testa were visible, the seeds was considered as damaged. Underdeveloped seeds were defined as those seeds with a wrinkled or collapsed testa around the coiled embryo but with no visible signs of damage to the testa. The category of underdeveloped black seeds most probably represented an empty or malformed black seed rather than an immature seed as it was the case with brown seeds. Even though underdeveloped seeds may have contained some viable seeds, they most probably did not contribute to any extent to the seed bank of lamb's-quarters. Both damaged seeds and underdeveloped seeds were not part of the seed bank but they contributed to the seed population of lamb's-quarters in the soil. The number of seeds in the different Chenopodium spp. seed categories was determined for every soil sample. The different seed categories used in this study are listed in Table 15.

Table 15. List of the Chenopodium spp. seed categories † enumerated in every soil sample

Total number of seeds/m^2
Number of black seeds/m^2
Number of brown seeds/m^2
Number of whole seeds/m^2
Number of damaged seeds/m^2
Number of underdeveloped seeds/m^2
Number of whole black seeds/m^2
Number of whole brown seeds/m^2
Number of damaged black seeds/m^2
Number of damaged brown seeds/m^2
Number of underdeveloped black seeds/m^2
Number of underdeveloped brown seeds/m^2

† Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

All fields were measured by careful pacing of their perimeters. Certain areas in some fields were not included in the survey since they either had been planted with a different border crop, had been placed under cultivation after recent lumbering operation or were contaminated with subsoil from a recently excavated drain. Figures III to IV of Appendix E give a detailed map of every field (or area) surveyed on Tucsock's farm. Each field was subdivided into 40.3m x 40.3m (50 paces x 50 paces) sampling areas.

Sampling was done following a stratified cluster design where 25 soil cores were taken systematically 8.06m apart (10 paces) within each randomly chosen sampling area (from now on, refered to as a cluster). Fields were divided into strata to permit a relatively uniform positioning of the clusters to be surveyed. Clustering allowed for easier relocation of the sampling points within each field in subsequent sampling. Since a maximum of 800 soil cores could be processed, a total of 32 clusters were sampled for all fields, indicating an overall sampling intensity (f) of 0.087, where f is defined as:

$f = n/N$ where n = total number of clusters to be sampled for all fields

N = total possible number of clusters for all fields

This sampling intensity was maintained for all field surveyed and is summarized in Table 16. In this table, strata, each consisting of approximately 30 clusters, are mentioned. It was decided arbritarily that three randomly chosen clusters would be sampled per stratum. Areas

Table 16. Allocation of actual number of clusters surveyed per field on Tucsok's farm in 1982.

Field No.	Surveyed area (ha)	Total # clusters (0.16 ha)	possible # clusters to be surveyed*	actual # clusters surveyed	Size of stratum (total # clusters)
1	17.56	108	9.39	9	36
2	0.49	3	0.26	1	--†
7	11.71	72	6.26	6	31
8	21.95	135	11.74	12	33 - 34
5	4.06	25	2.17	2	--†
6	4.06	25	2.17	2	--†
All fields		368		32	

* All fields were sampled at equivalent sampling intensity (F = 0.087) as related to their size

† Calculations not applicable

from each field were grouped in approximately equal sized strata. If there were fewer than 30 possible clusters in a field, it was considered as a single stratum. However, if there were fewer than ten possible clusters in a field, at least one cluster was randomly chosen for sampling. Figures III to V of Appendix E give the exact location of every cluster surveyed in each field.

A small section on Tucsok's farm was rented as a testing site to a chemical company. Within this section, two small fields (3 and 4), 34.7m x 33.1m (43 paces x 41 paces) and 9.7m x 59.7m (12 paces x 75 paces) respectively, had not been cultivated for two consecutive years (1981 and 1982). In both years high density populations of Chenopodium album were found growing on both fallow fields. Within each of these fields, soil cores were taken systematically 7.3m apart (9 paces) for a total of 25 soil cores in field 3 and 16 cores in field 4.

3.5 Statistical analysis

The original data had an underlying distribution which was not normal. Consequently, those variables whose underlying distribution could be normalized by the transformation ($\sqrt{x + 0.5}$) were transformed and analysed. Such variables were the total number of seeds/m^2, the number of black seeds/m^2, the number of brown seeds/m^2, the number of whole seeds/m^2, the number of damaged seeds/m^2, the number of underdeveloped seeds/m^2 and the number of whole black seeds/m^2. All analyses were done on the transformed data but the results are reported in a retransformed format. The SAS program "GLM" (general linear models) for unbalanced

designs (Anonymous, 1982) was used to perform the analysis of variance for each variable associated with the different cultivated fields surveyed by stratified cluster sampling. The model used for the analysis of variance was a three factor hierarchical mixed model with unequal cell frequencies. Field and stratum were considered fixed factors while cluster was declared a random factor. Strata were nested within fields and clusters were nested within both fields and strata. The expected values of the mean squares for the model are given in Table 17.

The residuals of each transformed variable were plotted as a function of their corresponding independent variable (i.e. field or clusters within field) in order to check the homoscedasticity of the transformed data. The comparisons of the means of the measured variables from the different fields were made using Scheffé's multiple contrasts test. The GLM program was used also to perform an analysis of variance for each of the variables on the fallow fields surveyed by systematic sampling (Anonymous, 1982).

The square root transformation did not improve the normality of the underlying distribution of the data for the number of whole brown seeds/m^2. Similarly the arcsine transformation was inefficient in normalizing the underlying distribution of the any of variables which were expressed as ratios of the seeds in the soil. Consequently these ratio variables and the number of whole brown seeds/m^2 were ranked using the RANK procedure of the SAS program. This procedure ranks together all of the observations of each variable from the smallest value with the rank of one to the largest value. Tied observations were given averaged ranks. An

Table 17. The expected values of the mean squares for a three-factor hierarchical model with the form $X_{i(j)k} = \mu_{...} + \alpha_i + \beta_{j(i)} + \gamma_{k(ij)} + \varepsilon_{i(j)k}$ and with unequal cell frequencies. Factors α_i and $\beta_{j(i)}$ are fixed and factor $\gamma_{k(ij)}$ is random. *

Source of variation	dF	Expected values of mean squares
Field α_i	p-1	$a\sigma_\varepsilon^2 + b\sigma_\gamma^2 + c\sigma_\alpha^2$
Stratum within field $\beta_{j(i)}$	$\sum_{i=1}^{p}(q-1)$	$a\sigma_\varepsilon^2 + b\sigma_\gamma^2 + d\sigma_\beta^2$
Cluster within stratum and field $\gamma_{k(ij)}$	$\sum_{i=1}^{p}\sum_{j=1}^{q}(r-1)$	$a\sigma_\varepsilon^2 + b\sigma_\gamma^2$
Error $\varepsilon_{i(j)k}$	$\sum_{i=1}^{p}\sum_{j=1}^{q}\sum_{k=1}^{r}(n-1)$	$a\sigma_\varepsilon^2$

* α_i = main factor 'field' with i = 1...p
$\beta_{j(i)}$ = stratum with j = 1....q nested under field
$\gamma_{k(ij)}$ = cluster with k = 1...r nested under field and stratum
a, b, c, d are constants

analysis of variance using the GLM program for unbalanced designs and Scheffe's multiple contrasts test were performed on the ranked data (Anonymous, 1982). The results are reported on the original data. The validity of this technique has been discussed by Conover and Iman (1981).

3.6 Results and discussion

a) Mean number of Chenopodium spp. seeds/m^2

A summary of the analyses of variance on the mean numbers in the different categories of Chenopodium spp. seeds/m^2 in the different cultivated fields surveyed by stratified cluster sampling is given in Table I of Appendix G. For all variables examined, there was a significant contribution to the variance component by fields at various probability levels depending on the variable examined (Table I of Appendix G). However, there was no evidence of significant variance differences among strata within fields. No gain in precision for the measured variables was obtained by stratification since it did not allow the variance among strata to be maximized. The only benefit that stratification provided to the sampling procedure was to permit a more efficient use of the physical resources at the time of sampling by reducing the time and labour associated in collecting the soil cores. Since the criteria for locating the strata in the field were determined arbitrarily, they were not associated with any known physical character of the field.

There were highly significant variance differences among clusters within field and stratum ($P \leq 0.0001$) for all variables except the number of whole brown seeds (Table I of Appendix G). In this latter case, the added variance component for cluster within field and stratum was significant at $P \leq 0.05$ (Table I of Appendix G).

The homoscedasticity of the transformed variables was checked by plotting the residuals of each variable as a function of its corresponding field or cluster within field. The plots of the residuals are given in Figures VI to XIV of Appendix E. Variables such as the total number of Chenopodium spp. seeds/m^2 and the number of black seeds/m^2 showed the greatest homoscedasticity in all fields (Fig. VIa and IXa of Appendix E) and in clusters within each field (Fig. VIb, VII, VIII and Fig. IXb, X, XI of Appendix E). All other variables exhibited a greater spread of the residuals in all fields and in clusters within each field. This heteroscedasticitic pattern is demonstrated by the total number of brown Chenopodium spp. seeds/m^2 (Fig. XII to XIV of Appendix E.). The greatest spread of the residuals for all variables was observed for field 5 (Fig. VIa and IXa of Appendix E). This field had received an application of manure the previous fall. Many intact weed seeds including lamb's-quarters are found in manure (Dore and Raymond, 1942) and its distribution in field 5 most probably contributed to creating areas of high seed density of lamb's-quarters in the soil. Other possible means of creating high density seed populations are a) locally dense weed populations, b) crop harvesting methods which amass plant debris in rows or piles and c) uneven application of herbicides.

For all categories of Chenopodium spp. seeds examined, field 5 had significantly higher numbers of seeds at $P \leq 0.05$ than field 6 (Fig. 26a, 27a, 29a, 30a, 31a, 32a and 33a and Table II of Appendix G) except for the mean number of brown seeds/m^2 where significant differences between the means were not detected by Scheffé's multiple contrasts test (Fig. 28a and Table II of Appendix G). Fields 5 and 6 had similar crop rotations and they differed by the addition of manure the previous fall in field 5 (Table 14). This may have contributed to the high number of Chenopodium spp. seeds/m^2 found in field 5. Lewandowska and Skapski (1979) also observed that seed banks of dominant species were highest immediately after the application of manure and decreased with time. Field 5 had also significantly higher numbers of whole Chenopodium spp. seeds/m^2 and whole brown seeds/m^2 than all other fields ($P \leq 0.05$) (Fig. 29a and 33a). Greater number of intact (whole) Chenopodium spp. seeds to the seed bank may have contributed by the addition of manure.

Lower numbers of seeds/m^2 for all seed categories were found in field 6 but these quantities were not significantly different from those of fields 1, 7 and 8 (Fig. 26a to 33a). Field 6 was also the only field with muck soil. Lewandowska and Skapski (1979) reported that muck soils of Poland had the greatest number of weed seeds/m^2 but individual species such as Chenopodium album did not necessarily follow this tendency.

Fields 1 and 8 had comparable numbers of seeds/m^2 for all seed categories studied (Table II of Appendix G). Field 7 had consistently lower numbers of seeds/m^2 though not significantly fewer than fields 1 and 8 (Fig. 26a to 33a). These low numbers might have been a

Figure 26 Mean total number of Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in graph A surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test. Means in graph B not surmounted by any letter are not significantly different from any other mean by Scheffé's multiple contrasts test.

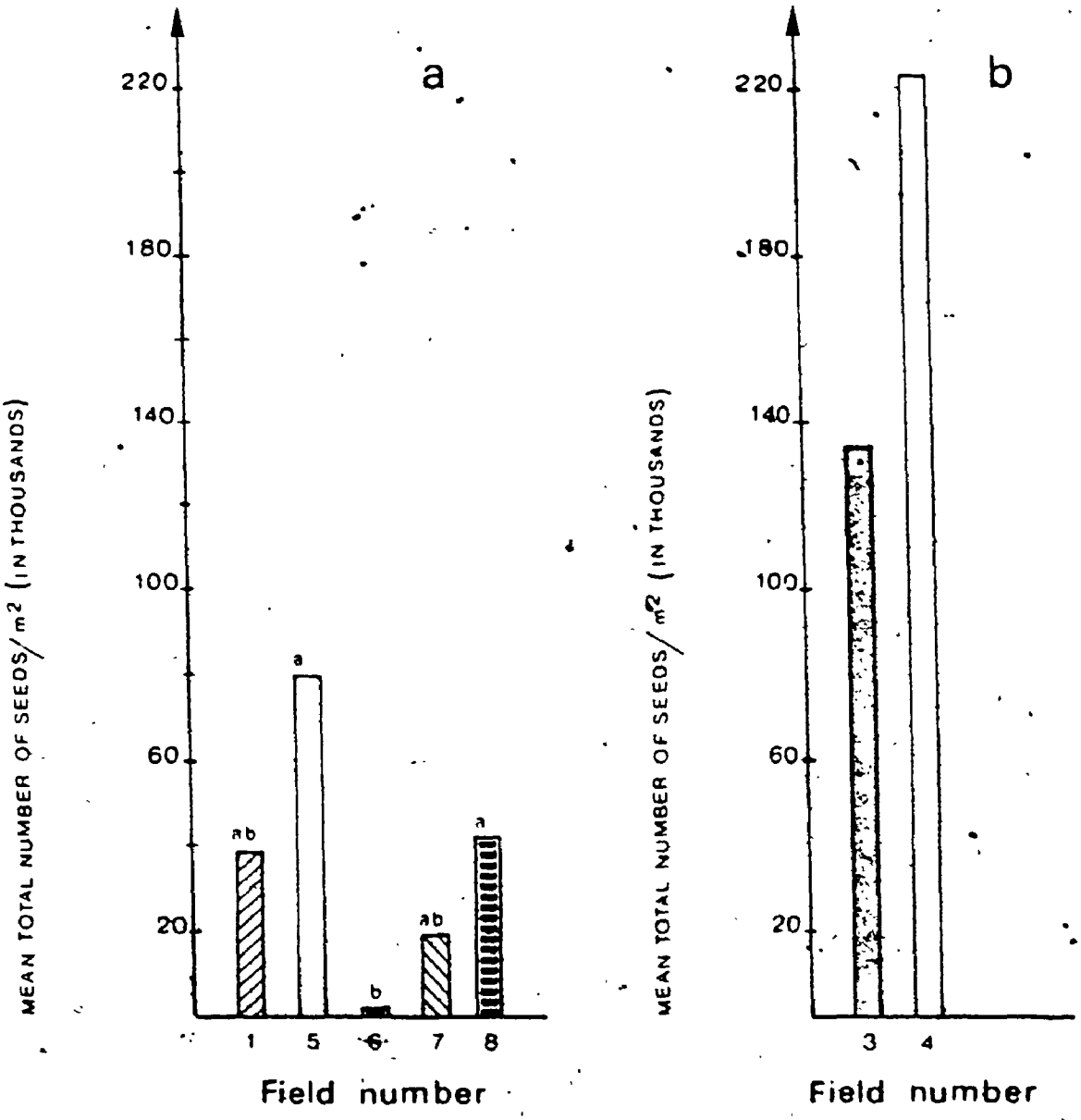

a
b
220
180
140
100
60
20
MEAN TOTAL NUMBER OF SEEDS/m² (IN THOUSANDS)
ab
a
b
ab
a
1
5
6
7
8
3
4
Field number
Field number

Figure 27 Mean number of black Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in each graph surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test.

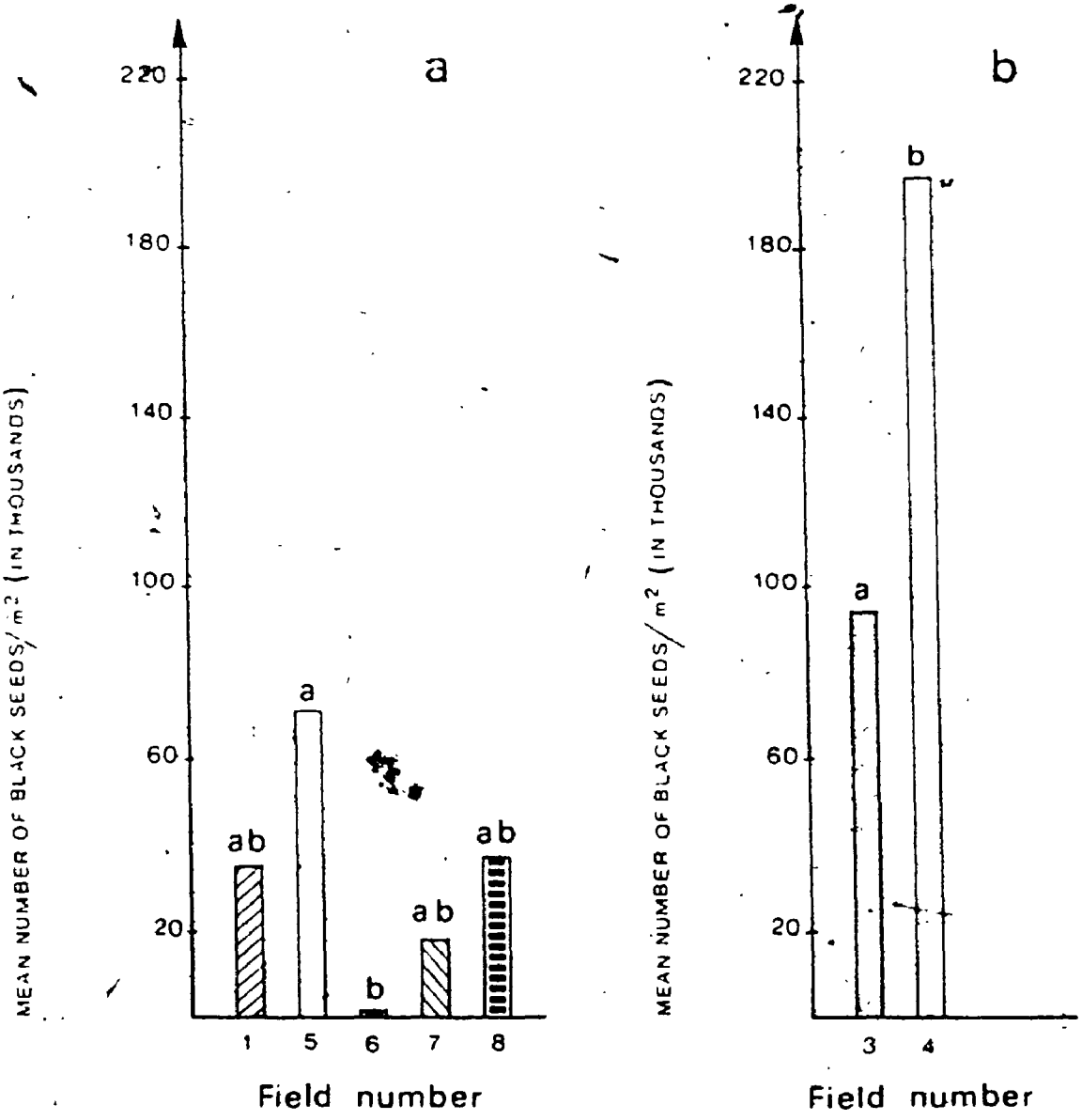

a
b
220
180
140
100
60
20
MEAN NUMBER OF BLACK SEEDS/m² (IN THOUSANDS)
ab
a
b
ab
ab
1
5
6
7
8
3
4
Field number
Field number

Figure 28 Mean number of brown Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in each graph not surmounted by any letter are not significantly different from any other mean by Scheffé's multiple contrasts test.

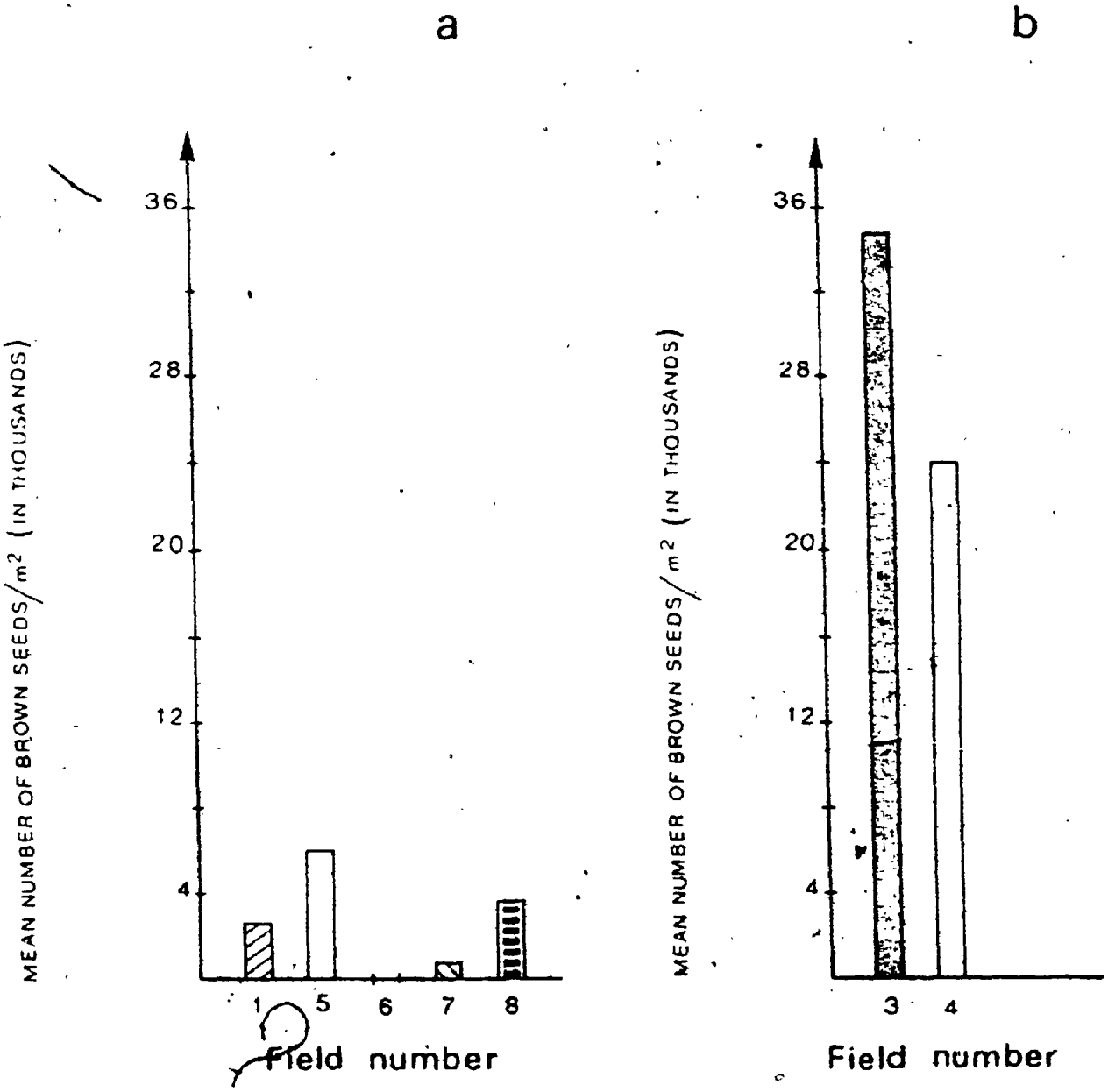

a
b
MEAN NUMBER OF BROWN SEEDS/m² (IN THOUSANDS)
36
28
20
12
4
1
5
6
7
8
Field number
3
4

Figure 29 Mean number of whole Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in graph A surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test. Means in graph B not surmounted by any letter are not significantly different from any other mean by Scheffé's multiple contrasts test.

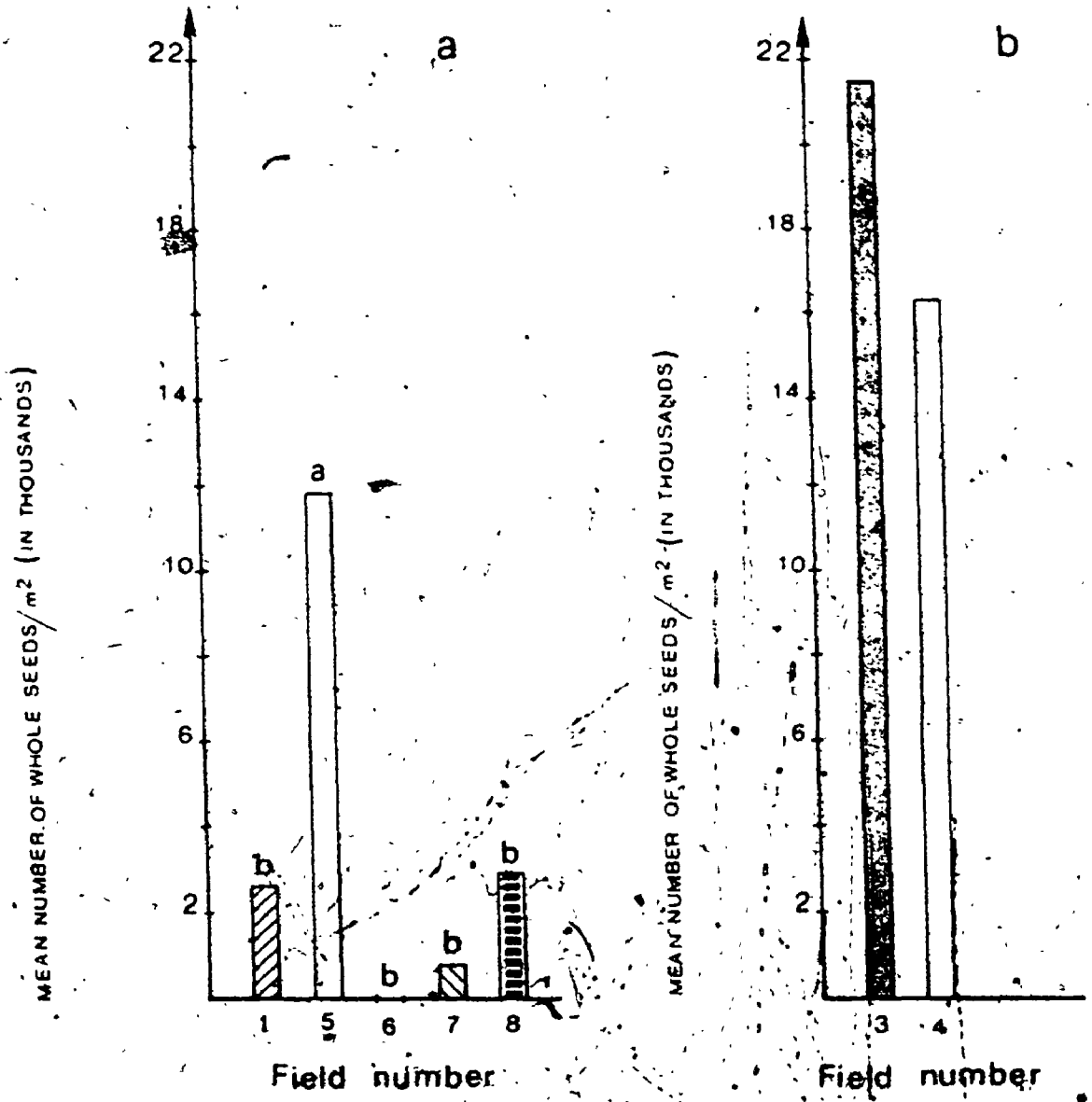
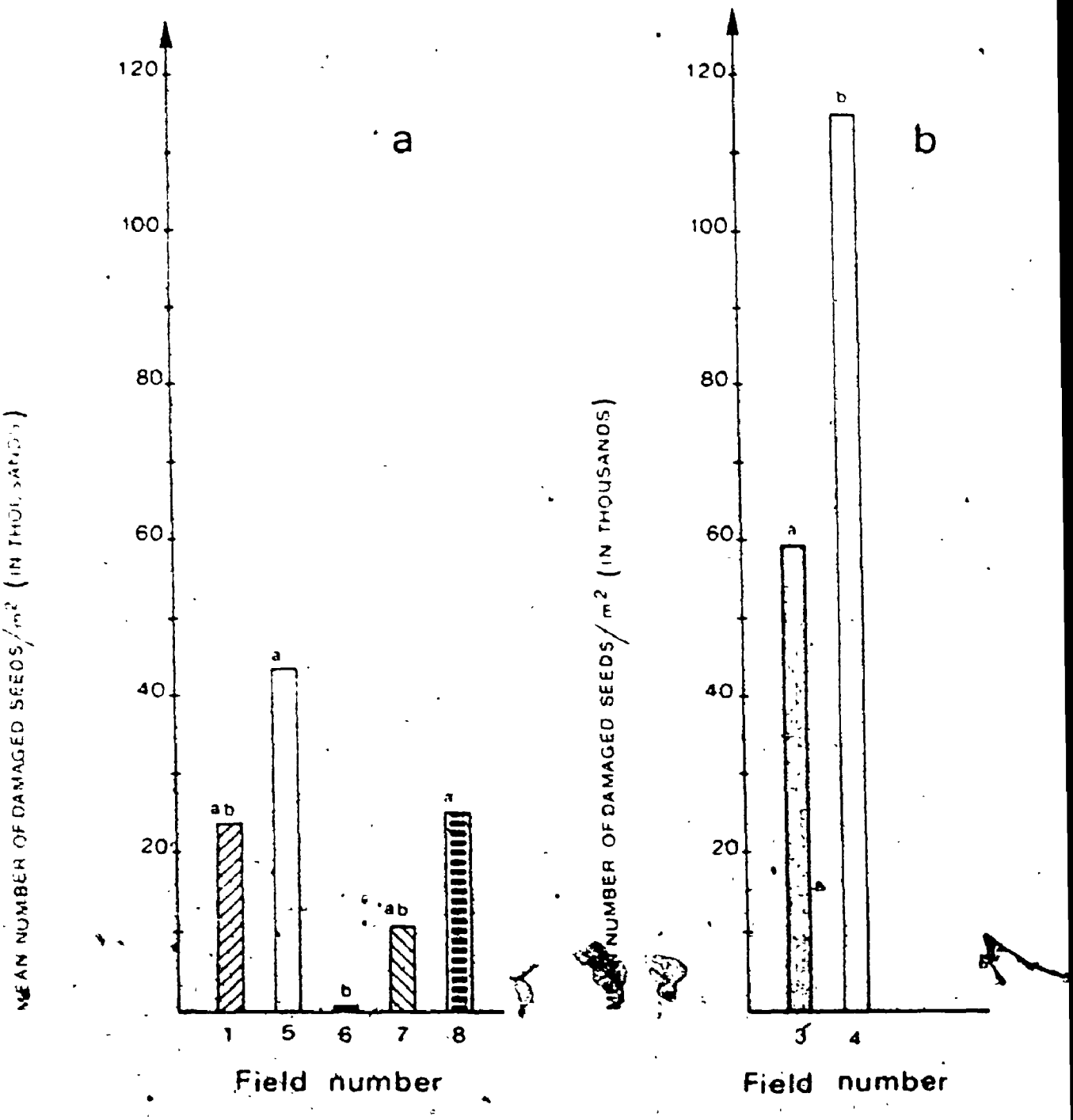

a
b
22
18
14
10
6
2
MEAN NUMBER OF WHOLE SEEDS/m² (IN THOUSANDS)
a
b
b
b
b
1
5
6
7
8
3
4
Field number
Field number

Figure 30 Mean number of damaged Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in each graph surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test.


a
b
120
100
80
60
40
20
ab
a
b
ab
a
a
1
5
6
7
8
3
4
Field number
Field number

gure 31 Mean number of underdeveloped Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in graph A surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test. Means in graph B not surmounted by any letter are not significantly different from any other mean by Scheffé's multiple contrasts test.

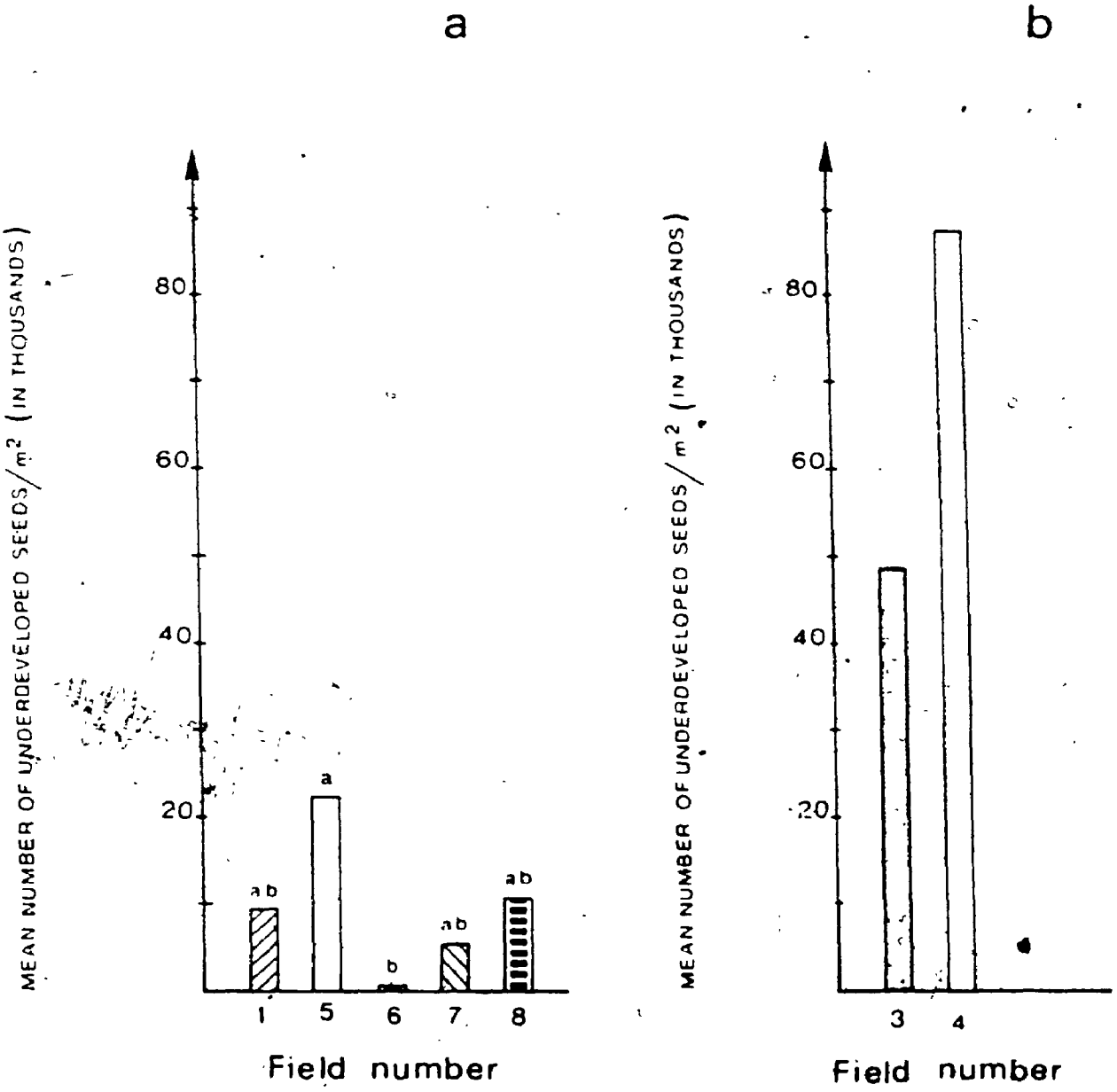

a
b
MEAN NUMBER OF UNDERDEVELOPED SEEDS/m² (IN THOUSANDS)
80
60
40
20
a b
a
b
a b
a b
1
5
6
7
8
Field number
3
4
Field number

Figure 32 Mean number of whole black Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in graph A surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test. Means in graph B not surmounted by any letter are not significantly different from any other mean by Scheffé's multiple contrasts test.

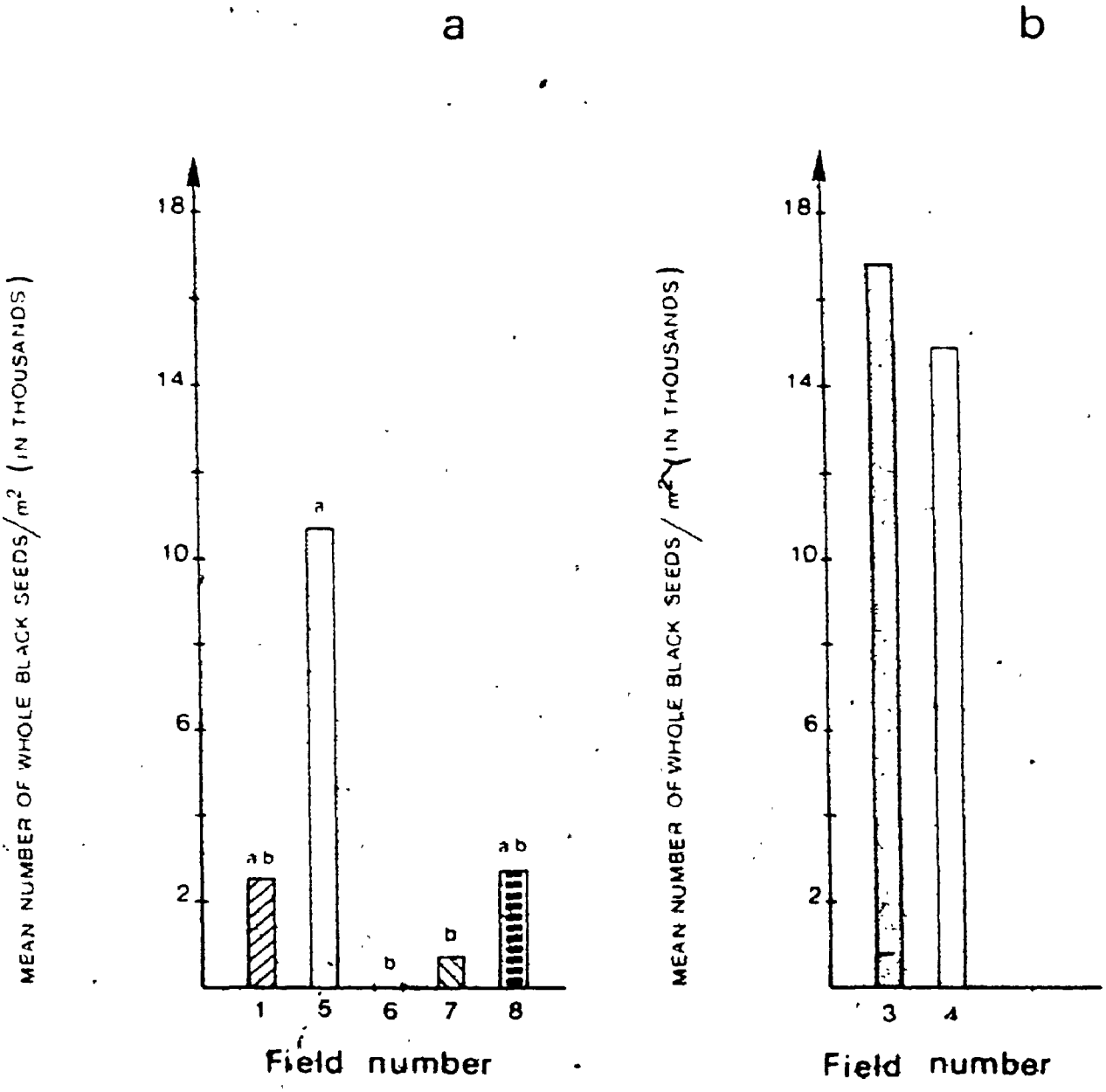
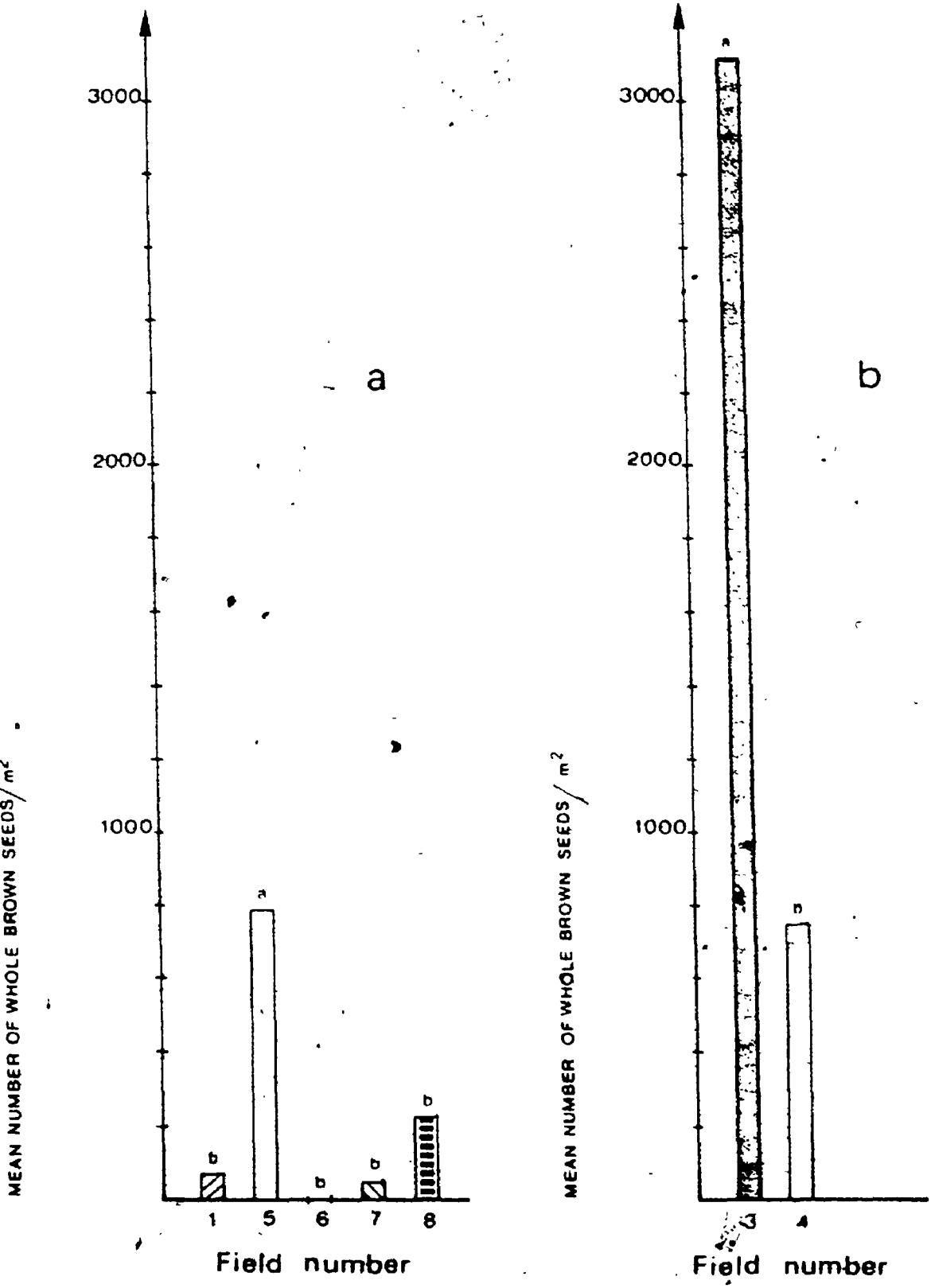

a
b
MEAN NUMBER OF WHOLE BLACK SEEDS/m² (IN THOUSANDS)
18
14
10
6
2
a b
a
b
b
a b
1
5
6
7
8
Field number
MEAN NUMBER OF WHOLE BLACK SEEDS/m² (IN THOUSANDS)
18
14
10
6
2
3
4
Field number

Figure 33 Mean number of whole brown Chenopodium spp. seeds/m^2 in a) different cultivated fields and in b) two fallow fields on Tucsok's farm, Oxford County, Ontario, in July 1982 (see Table 14 for description). Means in each graph surmounted by different letters are significantly different at $P \leq 0.05$ by Scheffé's multiple contrasts test.


3000
2000
1000
a
b
MEAN NUMBER OF WHOLE BROWN SEEDS / m²
1
5
6
7
8
3
4
Field number
Field number

characteristic of the seed bank of field 7 since no differences in soil type, crop rotation or weed control measures used could explain this slight difference. Dvořák and Krejčíř (1980a) have suggested that a smaller total bank of weed seeds could be expected in fields where there was less than 60% cereals in the rotation and where succeeding crops had widely differing growth characteristics and widely differing crop husbandry practices associated with them. The crop sequence is thought to be an important factor in influencing the size of the seed bank the following year (Dotzenko et al., 1969; Paatela and Ervio, 1971, cited in Dvořák and Krejčíř, 1980b). However, no trend attributable to crop sequence was observed in this study. Dvořák and Krejčíř (1980b) observed that the seed bank of Chenopodium album did not change substantially over the years and its proportional representation in the total seed bank remained unchanged regardless of the crop rotation.

There were no significant differences between the numbers of seeds/m^2 in fields 3 and 4 for the categories of brown seeds, whole seeds, underdeveloped seeds, whole black seeds and total number of seeds (Fig. 26b, 28b, 29b, 31b and 32b and Tables III and IV of Appendix G). There were significant differences at $P \leq 0.05$ between the number of seeds/m^2 in field 3 and the number in field 4 for the categories black seeds, damaged seeds and whole brown seeds (Fig. 27b, 30b and 33b). These differences are the consequence of seed dispersal close to the parent plant and a patchy distribution of seeds of lamb's-quarters in the soil. Those two adjacent small fields (3 and 4) are part of an area which had a similar management history. The lack of any weed control measures in field 3 and 4 allowed lamb's-quarters plants to reach maturity and shed

their seeds unhindered. This allowed the seed bank of lamb's-quarters in those two fields to become very large as can be observed when these two fields are compared with the other fields surveyed (Fig. 26 to 33).

b) Proportion of Chenopodium spp. seeds in different categories in the soil

The contributions of the different categories of Chenopodium spp. seeds to the seed population were approximately constant from field to field (Table 18). Black seeds contributed between 74.0% to 93.5% (Table 18) to the seed population of lamb's-quarters with an average contribution for all fields of 88.1%. A large percentage of these black seeds were damaged (overall mean percentage of 58.6 ± 4.5) and this may reflect the brittleness of the testa or its slow rate of decay in the soil once germination has occurred (Dvořák and Krejčíř, 1980c). Fields in this study had on average 55.8% (± 5.8) damaged seeds in the seed population of lamb's-quarters. Dvořák and Krejčíř (1980c) reported similar percentages of 'decomposed seeds' of lamb's-quarters in their cultivated fields (48.6% to 76.4% with an average of 62.6%).

Brown seeds contributed on average 11.9% (± 6.4) to the seed population of lamb's-quarters but most of the seeds within this category were underdevelopped (overall mean percentage of 62.5 ± 17.5) (Table 18). Lamb's-quarters is a species with an indeterminate flowering habit (Bassett and Crompton, 1978) so that when the plant population is destroyed in the fall by the harvesting and ploughing operations, seeds incorporated into the seed bank may be at various stages of development. Whole

Table 18. A summary of the mean percentages of different Chenopodium spp. seed categories in different fields in Tucsok's farm, Oxford County, Ontario, in July 1982

Seed category†	Mean percentage‡ Field number 1	3	4	5	6	7	8	All fields
Percent of total number of seeds								
Total number of black seeds	90.5	74.0	87.5	89.8	93.5	92.9	88.5	88.1
Total number of brown seeds	9.5	26.0	12.5	10.2	6.5	7.1	11.5	11.9
Total number of whole seeds	10.5	16.0	8.5	15.4	0.0	7.6	10.8	9.8
Total number of damaged seeds	63.6	48.7	50.7	55.4	51.2	60.0	60.8	55.8
Total number of underdeveloped seeds	25.9	35.3	40.8	29.2	48.8	32.4	28.4	34.4
Percent of total number of black seeds								
Number of whole black seeds	11.8	18.1	9.1	15.9	0.0	8.6	11.5	10.7
Number of damaged black seeds	64.6	57.8	53.2	57.9	53.0	60.4	63.3	58.6
Number of underdeveloped black seeds	23.5	24.1	37.7	26.2	47.0	31.0	25.2	30.7
Percent of total number of brown seeds								
Number of whole brown seeds	1.4	13.0	5.6	9.0	0.0	1.4	4.8	5.0
Number of damaged brown seeds	46.7	20.7	33.3	37.7	0.0	47.6	41.6	32.5
Number of underdeveloped brown seeds	51.9	66.4	61.1	53.3	100.0	51.0	53.7	62.5
Percent of total number of whole seeds								
Number of whole black seeds	98.5	76.9	92.3	91.3	.§	98.0	95.8	92.1
Number of whole brown seeds	1.5	23.1	7.7	8.7	..§	2.0	4.2	7.9
Percent of total number of damaged seeds								
Number of damaged black seeds	92.5	87.5	92.1	93.7	100.0	94.4	92.0	93.2
Number of damaged brown seeds	7.5	12.5	7.9	6.3	0.0	5.6	8.0	6.8
Percent of total number of underdeveloped seeds								
Number of underdeveloped black seeds	82.9	56.1	81.5	81.7	86.3	88.0	78.0	79.2
Number of underdeveloped brown seeds	17.1	43.9	18.5	18.3	13.7	12.0	22.0	20.8

† Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed around the embryo but with no visible damage to the testa

‡ Field 1 = mean of 224 soil samples
Field 3 = mean of 25 soil samples
Field 4 = mean of 16 soil samples
Fields 5 and 6 = mean of 49 soil samples
Field 7 = mean of 150 soil samples
Field 8 = mean of 299 soil samples

§ There were no whole seeds in any of the soil samples

seeds constituted on average 9.8% (± 5.4) of the seed bank of lamb's-quarters and of these 92.1% (± 8.0) on average were black and 7.9% (± 8.0) on average were brown (Table 18). These findings are in agreement with those of Dvořák and Krejčíř (1980c). They reported 11.65% to 20.12% 'healthy' seeds of Chenopodium album with different crop rotations.

It is interesting to note that the contribution of whole brown seeds to the seed bank was similar (0.0 to 8.7% excluding field 3) (Table 18) to the documented contribution of brown seeds to the total seed production of lamb's-quarters. Indeed, Williams and Harper (1965) reported that plants of Chenopodium album in the United Kingdom, produced between 0.2% and 5.0% brown seeds and that this proportion of brown seeds was fairly constant and was observed in every plant. Although my definition of 'brown seeds' differed slightly from that of Williams and Harper (1965) (see page 130), a comparison of our results suggests that we were both counting the same type of lamb's-quarters' seeds.

The analyses of variance of the ratios of the different seed categories in the cultivated fields is summarized in Table V of Appendix G.

Scheffé's multiple contrasts tests for the proportions of the different seed categories in the cultivated fields are reported in Tables 19 to 21. For the seed population of lamb's-quarters, significant differences ($P \leq 0.05$) between fields were apparent for the whole seed category but no significant differences for the damaged and underdeveloped seed categories were observed between fields (Table 19). Indeed

Table 19. A summary of the mean ratios of different Chenopodium spp. seed categories to the total number of seeds in different cultivated fields in Tucsok's farm, Oxford County, Ontario, in July 1982 †.

Field number	Seed category ‡ (ratio to total number of seeds)				
	black seeds	brown seeds	whole seeds	damaged seeds	underdeveloped seeds
1	0.91ab §	0.10ab	0.11a	0.64	0.26
5	0.90ab	0.10ab	0.15b	0.55	0.29
6	0.94ab	0.07ab	0.00c	0.51	0.49
7	0.93b	0.07a	0.08ac	0.60	0.32
8	0.86a	0.12b	0.11a	0.61	0.28

† The analysis of variance and Scheffé's multiple contrasts test were done on the ranked values of the variables. The results are given as the original values.
Field 1 = mean of 224 soil samples
Fields 5 and 6 = mean of 49 soil samples
Field 7 = mean of 150 soil samples
Field 8 = mean of 229 soil samples

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

§ Ratios in the same column followed by different letters are significantly different at 0.05 level using Scheffé's multiple contrasts test.

there were no significant differences for ratios of damaged or underdeveloped seeds within either the total number of black or brown seed categories (Table 20). No significant differences were observed either for the ratios of black or brown seeds to the total number of damaged or underdeveloped seeds (Table 21). Neither the crop rotation nor the soil type had any influence on the proportions of damaged and underdeveloped seeds in the seed population of lamb's-quarters. This could indicate that the rate of decay of either category of Chenopodium spp. seeds in the soil is constant.

Field 7 had a significantly greater ($P \leq 0.05$) proportion of black seeds and a significantly lower ($P \leq 0.05$) proportion of brown seeds in its seed population than field 8 (Table 19). However, these differences could not be attributed to the management practices used in these two fields but rather could arisen either from sampling or from inherent differences between the seed populations of fields 7 and 8.

Whole black seeds constituted between 91 and 99% of the seed bank of lamb's-quarters (Table 21). Factors affecting the size of the seed bank of lamb's-quarters will also affect the proportion of whole black seeds in similar manner. Field 5 had a significantly greater ($P \leq 0.05$) proportion of whole seeds to the total number of seeds (Table 19) and to the total number of black seeds (Table 20) than any other field. The application of manure to field 5 in the fall may have influenced the number of whole seeds in the soil the following year by the addition of intact Chenopodium spp. seeds to the soil. Crop sequence in the rotation had no influence on the numbers of whole Chenopodium spp. seeds in

Table 20. A summary of the mean ratios of different Chenopodium spp. seed categories to the total number of black and brown seeds in different cultivated fields in Tucsok's farm, Oxford County, Ontario, in July 1982 †.

Field number	Seed category ‡ (Ratio to total number of black seeds) whole seeds	damaged seeds	underdeveloped seeds	(Ratio to total number of brown seeds) whole seeds	damaged seeds	underdeveloped seeds
1	0.12b §	0.65	0.24	0.01a	0.47	0.52
5	0.16c	0.58	0.26	0.09b	0.38	0.53
6	0.00a	0.53	0.47	0.00ab	0.00	1.00
7	0.09ab	0.60	0.31	0.01a	0.48	0.51
8	0.12b	0.63	0.25	0.05a	0.42	0.54

† The analysis of variance and Scheffé's multiple contrasts test were done on the ranked values of the variables. The results are given as the original values.
Field 1 = mean of 224 soil samples
Fields 5 and 6 = mean of 49 soil samples
Field 7 = mean of 150 soil samples
Field 8 = mean of 229 soil samples

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

§ Ratios in the same column followed by different letters are significantly different at 0.05 level using Scheffé's multiple contrasts test.

Table 21. A summary of the mean ratios of different Chenopodium spp. seed categories to the total number of whole, damaged and underdeveloped seeds in different cultivated fields in Tucsok's farm, Oxford County, Ontario, in July 1982 †.

Field number	Seed category ‡ (Ratio to total number of whole seeds)		(Ratio to total number of damaged seeds)		(Ratio to total number of underdeveloped seeds)	
	black seeds	brown seeds	black seeds	brown seeds	black seeds	brown seeds
1	0.99a §	0.02a	0.93	0.08	0.83	0.17
5	0.91b	0.09b	0.94	0.06	0.82	0.18
6	— ¶	—	1.00	0.00	0.86	0.14
7	0.98a	0.02a	0.94	0.06	0.88	0.12
8	0.96ab	0.04ab	0.92	0.08	0.78	0.22

† The analysis of variance and Scheffé's multiple contrasts test were done on the ranked values of the variables. The results are given as the original values.
Field 1 = mean of 224 soil samples
Fields 5 and 6 = mean of 49 soil samples
Field 7 = mean of 150 soil samples
Field 8 = mean of 229 soil samples

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

§ Ratios in the same column followed by different letters are significantly different at 0.05 level using Scheffé's multiple contrasts test.

¶ There were no whole seeds present.

its seed population (Table 19) and on the proportions of black or brown whole seeds to its seed bank (Table 21).

No whole seeds (either black or brown) were found in field 6 and therefore, it was significantly different ($P < 0.05$) from all other fields except field 7 (Table 19). The seed population of lamb's-quarters in field 8 was composed exclusively of damaged and underdeveloped seeds (Tables 18 and 19). The explanation for such an occurrence is not clear since muck soils are known to contain large numbers of weed seeds (Lewandowska and Skapski, 1979). However, Dvorak and Krejcir (1980c) pointed out that crop rotations in which fewer cereal crops were included had lower proportions of 'healthy seeds' of all species and of 'healthy seeds' of lamb's-quarters. They explained this phenomenon as caused by higher microbial activity in the soil as a result of a higher frequency of broadleaved crops in the rotation. Field 6 had the highest frequency of broadleaved crops of all the fields surveyed, as well as the lowest proportion of whole seeds. Greater microbial activity would result in not only a lower proportion of whole seeds but also a greater proportion of damaged seeds (Dvorak and Krejcir, 1980c). However, this latter result was not evident in field 6 (Tables 18 and 19).

The analyses of variance for the two fallow fields indicated that there were significant differences between fields for the ratios of certain seed categories at probability levels ranging from $P < 0.05$ to $P < 0.001$ (Table 22). Indeed, there were significant differences ($P < 0.01$) between fields 3 and 4 for the ratios of black seeds, brown seeds and whole seeds to the seed population of lamb's-quarters in the soil while

Table 22. A summary of analyses of variance on the ratios of different Chenopodium spp. seed categories in two fallow fields (fields 3 and 4) on Tucsok's farm, Oxford County, Ontario, in July 1982†

Seed category ‡	Source of variation: Field	
	MS	F value
Ratio to total number of seeds		
Total number of black seeds	1356	12.08 **
Total number of brown seeds	1356	12.08 **
Total number of whole seeds	1109	9.35 **
Total number of damaged seeds	119	0.82 NS
Total number of underdeveloped seeds	160	1.12 NS
Ratio to total number of black seeds		
Number of whole black seeds	849	6.80 *
Number of damaged black seeds	181	1.27 NS
Number of underdeveloped black seeds	1640	15.61 ***
Ratio to total number of brown seeds		
Number of whole brown seeds	581	5.90 *
Number of damaged brown seeds	431	4.02 NS
Number of underdeveloped brown seeds	98	0.83 NS
Ratio to total number of whole seeds		
Number of whole black seeds	563	5.68 *
Number of whole brown seeds	563	5.68 *
Ratio to total number of damaged seeds		
Number of damaged black seeds	185	1.33 NS
Number of damaged brown seeds	185	1.33 NS
Ratio to total number of underdeveloped seeds		
Number of underdeveloped black seeds	1297	11.46 **
Number of underdeveloped brown seeds	1297	11.46 **

† The analysis of variance was done on the ranked values of the dependent variable. The degrees of freedom were distributed as follows: model = 1, field = 1, error = 59.
NS = non significant
* = significant at the 0.05 level
** = significant at the 0.01 level
*** = significant at the 0.001 level

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed around the embryo but with no visible damage to the testa

No such significant differences were observed for the ratios of damaged or underdeveloped seeds to the seed population. There were also significant differences ($P < 0.05$) between the two fallow fields for the ratios of whole black seeds and whole brown seeds to the seed-bank of lamb's-quarters (Table 22).

These differences between the seed banks of fields 3 and 4 were not associated with any management practices but rather were due to the distribution of the plant populations in those areas and to seed shedding by adult plants of lamb's-quarters. No patterns in the seed distribution in the soil were detected within either fields and the contribution of different seed categories of lamb's-quarters to the seed population is consistent with proportions found in other fields on Tucsok's farm (Table 18).

CHAPTER 4

GENERAL DISCUSSION

The optimal sampling procedure is defined by [illegible] components which allow an unbiased estimate of a population to be calculated while the sampling variance and the sampling effort are both minimized. These components were defined in this study as the dimension of the sampling unit, the sample size and the sampling method. The distribution of the underlying seed population in the soil may have a strong influence on the efficiency of the sampling method.

a) The dimension of the sampling unit

The sampling unit can be defined by weight (Dospekhov and Chekryzhov, 1972; Tulikov et al., 1981) or volume (Rabotnov, 1958; Numata et al., 1964a; Hayashi and Numata, 1971; Goyeau and Fablet, 1982; Forcella, 1984). Volume is often the easiest way to define a sampling unit since the sampling tool (auger) can be made to collect the desired volume. The volume of soil collected is not necessarily precise since compaction occur regardless of the dimension of the sampling tool (Böhm, 1979). Soil augers should not be used in heavy clay soil (Kropač, 1966).

The shape of the sampling unit and the depth to which taken, will depend on the purpose of the investigation. These factors were not examined in this study except for the diameter of the sampling unit. A sampler, circular in shape, was chosen and the sampling depth was 15 cm

so that soil from a sampling unit represented the ploughed layer of the field. It is acknowledged that some plough layers are deeper, but 15 cm encompassed the great part of the layer in this study.

Three sizes of sampler (1.9 cm, 2.7 cm and 3.3. cm in diameter), collecting 43 ml, 86 ml and 128 ml respectively, were compared for their efficiency in sampling for buried seeds. On a per volume basis (100 ml), there were no significant differences between samplers in estimating either the number of Chenopodium spp. seeds or the total number of seeds in the soil. Similarly, Forcella (1984) did not find any relationship between seed density and increasing soil surface of individual samples. Ultimately, the total soil volume sampled is the limiting factor in seed bank studies because of the time and labour needed to extract weed seeds from the soil regardless of the technique used. Thus, for a given soil volume sampled, the smaller auger permitted a greater number of sampling units to be collected. This larger sample size allows for an acceptable estimate of the mean (Kershaw, 1973) and a smaller sampling error (Elliott, 1977). This confirms the consensus among previous investigators that a large number of small sampling units is preferable in seed bank studies (Rabotnov, 1958; Roberts, 1958; Kropac, 1966; Roberts, 1970; Dospekhov and Chekryzhov, 1972).

b) The sample size

In most studies, the sampling cost, the available resources and the sampling tool available have influenced the choice of the sample size. However, many investigators have collected too few sampling units to

make reliable estimations of the total number of seeds in the seed bank (Whipple, 1978). My results indicated that the sample size needed to describe the seed bank of an abundant weed species such as Chenopodium spp. should range between 60 and 100 sampling units for a similar type of seed distribution in the soil. Below this minimum, the sampling variance increases rapidly and beyond 100 units, the gain in precision does not justify the extra labour needed to collect and process these additional units.

These results tend to confirm previous findings by Rabotnov (1958) and Goyeau and Fablet (1982). Rabotnov (1958) concluded that no fewer than 100-200 sampling units should be collected. This large sample size is desirable either when the total seed bank or the seed bank of the most abundant species is to be described or when the seed distribution is expected to be aggregated. Goyeau and Fablet (1982) suggested a sample size of 50 when the expected seed density per sampling unit (19.6 cm^2) ranges between five and forty. Indeed, some studies indicated that the sample size needed is dependent on the expected seed density and not on the size of the surveyed area (Goyeau and Fablet, 1982; Forcella, 1984; Pratt et al., 1984). Ideally the sampling units should be processed and recorded individually to permit the estimation of the sampling variance.

c) The distribution of Chenopodium spp. seeds in the soil

The problem of describing the seed distribution in the soil both horizontally and vertically, is often associated with its inherent

heterogeneity. Several authors have studied the seed distribution in the soil profile (vertical) in relation to cultural practices (Rabotnov, 1958; Roberts, 1963a,c; Roberts and Stokes, 1965; Kropáč, 1966; Dvořák and Krejčíř, 1980c; Froud-Williams et al., 1983). This study investigated specifically the spatial seed distribution (horizontal) of lamb's-quarters in the soil.

Seeds often are shed close to the parent plant so that the seed population in the soil can be expected to exhibit an aggregated distribution rather than a random normal one (Major and Pyott, 1966). Goyeau and Fablet (1982) found that seeds of the most abundant species often have a normal distribution while seeds of the less abundant ones usually had a Poisson or aggregated distribution on a microscale (an area of a few square meters). My description of the seed distribution of lamb's-quarters on a microscale (using quadrats) was inconclusive since some areas had a Poisson distribution while others had a strongly aggregated distribution. Seed dispersal had begun several weeks prior to sampling and clumps of fresh seeds were visible on the soil surface. The occurrence of these fresh seeds in some quadrats resulted in aggregated seed distribution for those quadrats.

On a macroscale (a large corn field), the total seed bank and the seed bank of lamb's-quarters did not have a Poisson distribution but rather exhibited a clustered distribution. Indeed, a pattern of groups of corn rows with high seed numbers and groups of corn rows with low seed numbers could be detected within the sampling site. In a field where cultivated row crops have been grown for several years, the pattern of

dispersal of weed seeds by farm machinery would be along crop rows rather than across them. Eventually, areas which consistently had higher weed populations may have developed large seed banks in the soil, whereas areas which either had good weed control or a microenvironment favouring germination or rapid seed decay may have developed relatively small seed banks. The spatial distribution of the seed bank of the Chenopodium species in a row crop has not been described previously in the literature.

d) The sampling methods

Systematic sampling was used to form the matrix on which the different sampling methods under investigation, were superimposed. The original sampling method may have influenced the nature of the matrix. Indeed, the sampling interval seemed to coincide with a regularly repeated pattern across corn rows in the seed population of the field. Thus, the matrix is assumed to represent adjacent sampling units forming a continuous population of Chenopodium spp. seeds. The main feature of this seed bank was its directionality. This pattern within the matrix should be remembered since it will affect the efficiency of the sampling methods as measured by the Monte Carlo estimate of sampling variance.

With random sampling, as the sample size increased the Monte Carlo estimate of sampling variance decreased. With systematic sampling, the configuration of the sampling interval greatly influenced the Monte Carlo estimate of sampling variance. If the interval coincided with the regular repeated pattern of seed density in the sampling site, the Monte

Carlo estimate of sampling variance was large and the estimate of the population could be biased (Greig-Smith, 1964; Elliott, 1977; Snedecor and Cochran, 1980).

When stratified random sampling was used, excessive stratification did not lead to a reduction in the Monte Carlo estimate of sampling variance. Because of the underlying clustered distribution of lamb's-quarters, the orientation of the strata within the sampling site may have influenced the Monte Carlo estimate of sampling variance. These differences decreases with increasing sample size. Strata oriented along the same axis as the corn rows had smaller Monte Carlo estimates of sampling variance than their counterparts. Stratification along corn rows allowed the variance within strata to be minimized and the variance between strata to be maximized. The result was a gain in precision over simple random sampling (Sampford, 1962; Snedecor and Cochran, 1980). However, this gain in precision is dependent on the strata in a heterogeneous population being as homogeneous as possible (Snedecor and Cochran, 1980).

When random sampling and stratified random sampling were compared for a given sample size of 64 units, no significant differences between the two sampling methods were observed even though the Monte Carlo estimate of sampling variance for stratified random sampling was slightly lower than that for simple random sampling. The main advantages of stratified random sampling are that the sampling units within each stratum are more evenly distributed throughout the sampling site (Yates, 1960; Elliott, 1977) and arbitrary factors useful in describing the

sampling site (e.g. crop rows, drainage patterns, fertility gradients) can be associated with stratification (Stuart, 1976). This allows further relevent information to be used to describe the population (Snedecor and Cochran, 1980). In this case, orientation of the strata along the axis of the corn rows proved to be advantageous.

The aggregated distribution of Chenopodium spp. seeds in the soil had a strong influence on the precision of cluster sampling. Rectangular-shaped clusters oriented across the corn rows had smaller Monte Carlo estimates of sampling variance than their counterparts. In the former, clusters covered as many corn rows as possible, resulting in a large within-cluster variance and a small between-cluster variance. This result is consistent with the clustering principle (Stuart, 1976). Increasing either the sample size or the number of clusters decreased the Monte Carlo estimate of sampling variance.

For a given sample size (n = 64), the Monte Carlo estimate of sampling variance for the cluster sampling was significantly larger ($P \leq 0.001$) than all other sampling methods tested. This substantial loss of precision is often characteristic of cluster sampling (Stuart, 1976), since the aggregated seed distribution of lamb's-quarters ensures that the sampling units within a cluster tend to be similar. Indeed, the main advantage of cluster sampling is the economical use of available resources since clusters are more easily identified and located within a population (Sampford, 1962). The sampling cost compensate for the loss in precision (Stuart, 1976). However, this is also achieved at the expense of greater complexity in the selection process and in the analysis

of the results (Stuart, 1976).

a) The seed bank of Chenopodium spp. in cultivated fields

In order to test the validity and the feasibility of the sampling procedure described above, seed banks of lamb's-quarters in cultivated fields were sampled using a stratified cluster sampling method. The small soil auger was used and a minimum sample size of 50 units was maintained in all the cultivated fields surveyed. Sampling units were allocated proportionally according to the size of the field so that sampling intensity was the same. It should be remembered that this study was carried out at the same time as the data for testing the sampling methods were being collected. Consequently one error in the sampling procedure was identified later. The stratification was made across the crop rows and as a result no gain in precision resulting from stratification was observed. The analysis of variance indicated that fields and clusters within field and stratum contributed significantly to the variance component of the linear model of stratified cluster sampling.

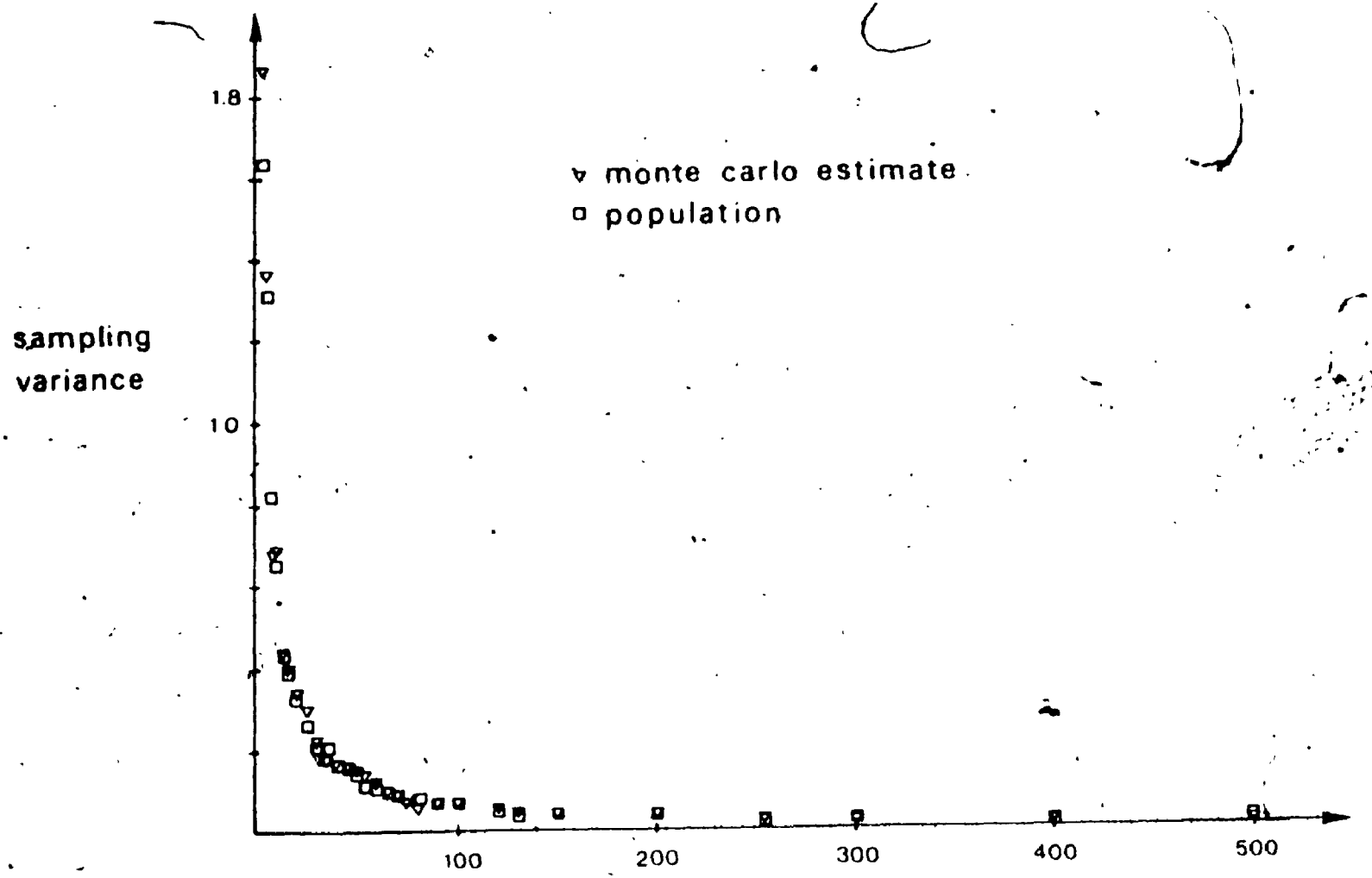
The mean numbers of whole Chenopodium spp. seeds/m^2 (0-15 cm layer) were 0, 802, 2621, 2912 and 11829 for fields 6, 7, 1, 8 and 5 respectively. These values are similar to the ones given in previous studies. Lewandowska and Skapski (1979) reported for Chenopodium album a range of 40 to 6640, 80 to 11800 and 120 to 8200 seeds/m^2 (0-20 cm layer) for cultivated podzolic, brown and muck soils respectively. Similarly, Dvořák and Krejčíř (1980c) reported average densities of Chenopodium album ranging between 4224 and 6143 seeds/m^2 (0-30 cm layer) in plots under

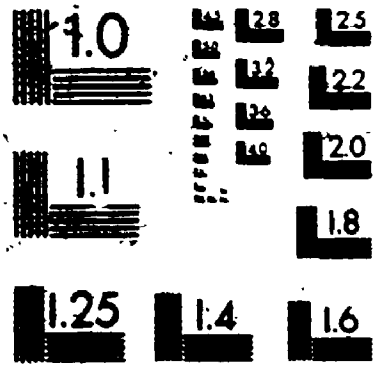
different crop rotations.

The application of manure was the most noticeable factor influencing the number of Chenopodium spp. seeds in the soil. Field 5 which had received an application of manure in the fall had a significantly ($P \leq 0.05$) higher number of whole Chenopodium spp. seeds/m^2 than any other field. This addition of manure may have contributed to a greater number of intact (whole) lamb's-quarters seeds in the soil since they are often found in large numbers in manure (Dore and Raymond, 1942).

The muck soil had no whole seeds (black or brown) and the seed population of lamb's-quarters was composed exclusively of damaged and underdeveloped seeds. Thus in that field, there were no seed bank of lamb's-quarters. No explanation for this result could be found since muck soils are known to have large numbers of weed seeds in them (Lewandowska and Skapski, 1979).

Neither crop sequence nor crop rotation had any influence on the size of the seed bank of lamb's-quarters in fields 1, 3 and 5. This is contrary to findings by Dotzenko et al. (1969); Pastela and Irvine (1971) and Dvořák and Krejčíř (1980a). However, Dvořák and Krejčíř (1980b) observed that the seed bank of Chenopodium album did not change substantially over the years and its proportional representation in the total seed bank remained unchanged regardless of the crop rotation. When seed shedding of lamb's-quarters was allowed to occur without interference in a fallow field, its seed bank became very large as compared to seed banks in the other cultivated fields.


monte carlo estimate
population
sampling variance
1.8
1.0
100
200
300
400
500
Total number of sampling units



The contribution of the different categories of Chenopodium spp. seeds to the seed population is approximately constant from field to field. The seed population of lamb's-quarters was comprised on average of 10% whole seeds, 56% damaged seeds and 34% underdeveloped seeds. Dvořák and Krejčíř (1980c) reported similar percentages of healthy and damaged seeds of lamb's-quarters in cultivated fields. Fields had on average 88% black seeds, 59% of which were damaged. This may reflect the brittleness of the testa and the slow rate of decay of the seeds in the soil (Dvořák and Krejčíř, 1980c).

Brown seeds contributed 12% on average to the seed population with most of them (63%) being underdeveloped. Lamb's-quarters with its indeterminate flowering habit has seeds at various stages of development when the plant populations are destroyed in the fall by harvesting and ploughing operations. Many underdeveloped seeds are incorporated into the seed bank. It is interesting to note that the contributions of whole brown seeds to the seed bank exhibited a similar range to the contribution of brown seeds to total seed production of lamb's-quarters as documented by Williams and Harper (1965). The proportions of damaged seeds and underdeveloped seeds in the seed population of lamb's-quarters were not significantly different among fields. This may indicate that the rate of decay of damaged seeds and underdeveloped seeds in the soil is constant regardless of the crop rotation or the soil type.

6) The implications of quantifying the seed banks of weed populations in arable soils

In the past, studies relating to seed banks of arable soils have concentrated on describing the contribution of different weedy species to the seed population. The influence of different types of cultivation and crop rotations on the size and the species composition of seed banks have been investigated thoroughly (Roberts, 1962; Roberts and Stokes, 1965; Roberts and Dawkins, 1967; Roberts and Feast, 1973a). At one time, it was thought that the knowledge of the species composition of a seed bank in a site could be used to predict the size and composition of its weed population. This idea was soon dropped since there was no correlation between the seed bank and the plant population of a site. Thus, seed banks cannot be used to predict the presence or the size of weed infestations.

However, the size of a seed bank could become a factor used to measure and compare the efficiency of weed control by various regimes of herbicide application. Seed banks are important elements in the life history of annual weeds. The effect of herbicide application on the population dynamics of annual weeds can be measured by the survival of the seedlings, their fecondity and the incorporation of their seeds into the soil. Modelling can then be used to predict the size of the weed population after several years of continuous herbicide use. The efficiency and the relative cost of various regimes of herbicide application can also be compared. McMahon and Mortimer (1980) successfully modelled the population dynamics of an important perennial weed (Agropyron repens (L.) Beauv.) under different chemical weed control regimes. A similar approach is also feasible for annual weeds. Modelling of the population dynamics of wild oats (Avena fatua L.) (Mortimer et al., 1978) to

simulate the consequences of various control measures has also been attempted.

To improve the reliability of these models, the estimate of the size of seed bank should be unbiased and precise. Thus, the choice of reliable sampling procedures as forwarded in this study become all the more important.

APPENDIX A

SUMMARIES OF SELECTED SEED BANK STUDIES

APPENDIX A

TABLE 1. Summary of selected seed bank studies in arable land and pastures.

Crop	Country	References
Vegetables	England	Roberts, 1958, 1962, 1963b, 1968; Roberts and Stokes, 1965; Roberts and Ricketts, 1979; Roberts and Neilson, 1981, 1982
	Poland	Lewandowska and Skapski, 1979
Cereals	Canada	Budd et al., 1954
	Czechoslovakia	Kropáč, 1966
	England	Brenchley and Warington, 1930, 1933, 1945
	Scotland	Warwick, 1984
Corn/soybean	Hungary	Fekete, 1975
	U.S.A.	Schweizer and Zimdahl, 1984a, b; Bridges and Walker, 1985; Burnside et al., 1986a, b
Root crops	U.S.A.	Dotzenko et al., 1969
Rice	Australia	McIntyre, 1985
	Morocco	Bouhache et al., 1983
Pineapple	Malaysia	Wee, 1974
Miscellaneous arable crops	England	Froud-Williams et al., 1983
	Morocco	Bouhache and Tanji, 1985
	U.S.A.	Williams and Egley, 1977; Conn et al. 1984
Fallow or cultivated land	Canada	Archibold and Hume, 1983
	England	Roberts, 1963a; Roberts and Dawkins, 1967; Roberts and Feast, 1973
Pasture/meadow	Canada	Dore and Raymond, 1942; Archibold, 1981
	Czechoslovakia	Dvořák and Krejčíř, 1980b
	England	Champness and Morris, 1948; Champness 1949a; Howe and Chancellor, 1983; Williams, 1984
	Japan	Hayashi and Numata, 1971
	USSR	Rabotnov, 1956, 1958

TABLE II. Summary of selected seed bank studies of various non-agricultural habitats.

Habitat	Country	References
Abandoned fields	U.S.A.	Livingston and Allesio, 1968
Prairie	Canada	Archibold, 1981
	U.S.A.	Lippert and Hopkins, 1950; Major and Pyott, 1966; Marlette and Anderson, 1986
Shrub woodland	Australia	Hodgkinson et al., 1980
Semi-desert	U.S.A.	Hassan and West, 1986
Forest	Britain	Hill and Stevens, 1981
	Canada	Kellman, 1970; Johnson, 1975; Moore and Wein, 1977; Archibold, 1979
	Poland	Piroznikow, 1983
	U.S.A.,	Olmsted and Curtis, 1947; Livingston and Allesio, 1968; Whipple, 1978; Pratt et al., 1984
Rainforest	Australia	Hopkins and Graham, 1984
	New Guinea	Enright, 1985
Tundra	U.S.A.	McGraw, 1980; Roach, 1983
Marsh	U.S.A.	Van der Valk and Davis, 1978; Leck and Graveline, 1979; Smith and Kadlec, 1983, Hopkins and Parker, 1984; Parker and Leck, 1985; Smith and Kadlec, 1985

TABLE III. List of the numbers of individual sampling units per plot (or site) used in selected seed bank studies.

Number of sampling units per plot (or site)	References
1, 2, 3	Lippert and Hopkins, 1950; Johnson, 1975; Zimmergren, 1980; Enright, 1985; Parker and Leck, 1985
4, 5	Olmsted and Curtis, 1947; Rabotnov, 1956; Hayashi and Numata, 1971; Hopkins and Graham, 1984; Panetta, 1985
8	Roberts and Stokes, 1965; Roberts, 1968; Hill and Stevens, 1981; Hopkins and Parker, 1984
10	Rabotnov, 1956; Major and Pyott, 1966; Hayashi and Numata, 1971; Fekete, 1975; Moore and Wein, 1977; Bridges and Walker, 1985
12, 13	Johnson, 1975; Dvořák and Krejčíř, 1980b; Smith and Kadlec, 1985; Marlete and Anderson, 1986
15, 16	Champness, 1949a; Roberts and Stokes, 1965; Kropáč, 1966; Whipple, 1978; Williams, 1984; Bridges and Walker, 1985
20	Kelley, 1977; Lewandowska and Skapski, 1979; Standifer, 1980; Goyeau and Fablet, 1982; Bouhache et al., 1983; Bouhache and Tanji, 1985; Hassan and West, 1986
24, 25, 28	Andrew and Mott, 1983; Howe and Chancellor, 1983; Smith and Kadlec, 1983; Smith and Kadlec, 1985; Burnside et al., 1986a,b; Marlette and Anderson, 1986
34, 36, 40	Kellman, 1970; Lewandowska and Skapski, 1979; McGraw, 1980; Roach, 1983; Marlette and Anderson, 1986
44, 45	Kellman, 1974b; Marlette and Anderson, 1986
48, 50	Milton, 1939; Rabotnov, 1956; Howe and Chancellor, 1983; Marlette and Anderson, 1986
60, 64	Kellman, 1974b; Nicholson and Keddy, 1983; Warwick, 1984; Marlette and Anderson, 1986
72, 78, 80, 84	Kellman, 1974a; Warwick, 1984; McIntyre, 1985; Marlette and Anderson, 1986
100	Rabotnov, 1958; Thompson and Grime, 1979; Piroznikow, 1983; Marlette and Anderson, 1986
200	Pavone and Reader, 1982

TABLE IV. List of the sampling methods used in selected seed bank studies.

Sampling method	References
Random	Milton, 1936; Major and Pyott, 1966; Dotzenko et al. 1969; Kellman, 1974a; Johnson, 1975; Van der Valk and Davis, 1978; Roberts and Ricketts, 1979; McGraw, 1980; Smith and Kadlec, 1983; Conn et al., 1984; Hopkins and Graham, 1984; Warwick, 1984; Williams, 1984; Bridges and Walker, 1985; Panetta, 1985; Smith and Kadlec, 1985; Burnside et al., 1986a, b; Hassan and West, 1986
Systematic	Rabotnov, 1958; Kropáč, 1966; Kellman, 1974b; Archibold, 1979; Hodgkinson et al. 1980; Bouhache et al., 1983; Pratt et al., 1984; Schweizer and Zimdahl, 1984 a, b; Bouhache and Tanji, 1985
Stratified random	Thompson and Grime, 1979
Multi-stage	Kellman, 1970; Goyeau and Fablet, 1982
Along transect	Johnston et al., 1969; Leck and Graveline, 1979
Regularly along transect	Olmsted and Curtis, 1947; Hayashi and Numata, 1971; Kellman, 1974b; Archibold, 1981; Archibold and Hume, 1983; Froud-Williams et al., 1983; Nicholson and Keddy, 1983; Piroznikow, 1983; Roach, 1983; Hopkins and Parker, 1984; Parker and Leck, 1985; Marlette and Anderson, 1986
Randomly along transect	Livingston and Allesio, 1968; Kelley, 1977; Pavone and Reader, 1982
Zig-zag	Brenchley and Warington, 1930, 1945; McIntyre, 1985
Representative (middle of plot)	Wee, 1974; Standifer, 1980; Hill and Stevens, 1981; Roberts and Neilson, 1981; Lewandowska and Skapski, 1979
Unidentified	Chippendale and Milton, 1934; Milton, 1939; Doré and Raymond, 1942; Champness and Morris, 1948; Champness, 1949a; Lippert and Hopkins, 1950; Budd et al., 1954; Rabotnov, 1956; Roberts, 1958, 1962, 1963a, b, 1968; Roberts and Stokes, 1965; Roberts and Dawkins, 1967; Roberts and Feast, 1973; Hurle, 1974; Fekete, 1975; Moore and Wein, 1977; Whipple, 1978; Dvořák and Krejčíř, 1980b; Zimmergren, 1980; Andrew and Mott, 1983; Howe and Chancellor, 1983; Warnes and Andersen, 1984; Bridges and Walker, 1985; Enright, 1985

TABLE 4. Summary of the dimensions of sampling units used in selected seed bank studies of arable land.

Sampling tool	Dimension* (cm)	Depth (cm)	Volume (ml)	Crop	Country	References
Auger	1.9	15	43	Corn	Canada	Benoit and Cavers, 1983
		20	57	Vegetables	U.S.A.	Standifer, 1980
		25	71	Corn	U.S.A.	Schweizer and Zimdahl, 1984a,b
		30	85	Corn-soybean Cereals	U.S.A.	Warnes and Andersen, 1984
	2.3-2.5†	10	49	Vegetables	England	Roberts, 1963a;
		10	49	Vegetables-cereals	England	Roberts and Ricketts, 1979
		15	74	Vegetables	England	Roberts, 1958, 1963b; Roberts and Stokes, 1965; Roberts, 1968
		15	74	Vegetables-cereals	England	Roberts and Neilson, 1981, 1982
		20	98	AR	England	Froud-Williams et al., 1983
		23	113	CULT	England	Roberts and Dawkins, 1967; Roberts and Feast, 1973
	3	15	106	Pineapple	Malaysia	Wee, 1974
	3.7-4†	8	101	CULT	Canada	Archibold and Hime, 1983
		10	126	Rice	Australia	McIntyre, 1985
	4	30	377	Corn-soybean-cereals	U.S.A.	Warnes and Andersen, 1984
	5	5	98	UN	Wales	Naylor, 1970
		15	299	UN	U.S.A.	Conn et al., 1984
		20	393	Rice	Morocco	Bouhache et al., 1983
		20	393	UN	U.S.A.	Williams and Egley, 1977
				Corn	U.S.A.	Burnside et al., 1986a, b
		30	589	Corn	France	Goyeau and Fablet, 1982
		60	1178	Corn-soybean	U.S.A.	Bridges and Walker, 1985
				AR	Morocco	Bouhache and Tinji, 1985
	6	4	113	UN	Belize	Kellman, 1974a
	7	46	1771	Corn-soybean-cereals	U.S.A.	Warnes and Andersen, 1984
	11	15	1426	Corn-soybean	U.S.A.	Bridges and Walker, 1985
Knife/ blade	7.6 x 10	15	11400	Wheat-barley	England	Brenchley and Warington, 1930, 1945
		15	11400	Wheat	Canada	Budd et al., 1954
	15 x 15	25-30†	6750	Cereals	Czechoslovakia	Kropáč, 1966
	20 x 20	25	10000	Wheat	Germany	Hurle, 1974

* Dimensions for the augers refer to the diameter; those for the blades refer to the side of a block of soil.
† Calculations for volume are rounded off to the nearest unit.
‡ The larger value is used for the required calculations.
AR - Arable crops; CULT - cultivated but no crops grown;
UN - unidentified crop

TABLE VI. Summary of the dimensions of sampling units used in selected seed bank studies of pastures, leys and meadows.

Sampling tool	Dimension* (cm)	Depth (cm)	Volume† (ml)	Country	References
Auger	2.3-2.5	15	74	England	Howe and Chancellor, 1983; Williams, 1984
	3	13-18≠	127	Wales	Milton, 1936
	5.6	5-11≠	271	England	Champness and Morris, 1948
		6-17≠	419	England	Champness, 1949a
	8	10	503	Canada	Archibold, 1981
Knife/ blade	10 x 10	10	1000	USSR	Rabotnov, 1956, 1958
				Japan	Hayashi and Numata, 1971
	15 x 15	2.5	563	Canada	Dore and Raymond, 1942
	23 x 23	36	19044	Wales	Chippendale and Milton, 1934

* Dimensions for the augers refer to the diameter; those for the blades refer to the side of a block of soil.

† Calculations for the volume are rounded off to the nearest unit.

≠ The larger value is used for the required calculations.

TABLE VII. Summary of the dimensions of sampling units used in selected seed bank studies of various habitats.

Habitat	Sampling tool	Dimension* (cm)	Depth (cm)	Volume† (ml)	Country	References
Abandoned fields	Auger	5	10	196	Canada	Pavone and Reader, 1982
	Auger	7	3	116	England	Thompson and Grime, 1979
	Knife/ blade	10 x 10	2	200	Sweden	Zimmergren, 1980
	NI#	NI	NI	40	Japan	Numata et al., 1964a, b
Chaparral	Knife/ blade	29 x 29	10-15	12615	U.S.A.	Keeley, 1977
Forest	Auger	8	10	503	Canada	Archibold, 1979
		10	10	785	Canada	Kellman, 1970, 1974b
					Canada	Johnson, 1975
	Auger	10	10-11	863	U.S.A.	Livingston and Allessio, 1968
	Knife/ blade	929	1.3-1.5	4645	U.S.A.	Olmsted and Curtis, 1947
	NI	10 x 10	NI	NI	Canada	Moore and Wein, 1977
		10 x 10	10	1000	U.S.A.	Pratt et al., 1984
		20 x 20	5	2000	U.S.A.	Whipple, 1978
		20 x 30	10	6000	Britain	Hill and Stevens, 1981
Marsh	Auger	3	18	127	Wales	Milton, 1939
			21	148	Canada	Nicholson and Keddy, 1983
	Knife/ blade	10 x 10	10	1000	U.S.A.	Leck and Graveline, 1979
	Knife/ blade	20 x 20	4	1600	U.S.A.	Smith and Kadlec, 1983, 1985
	Knife/ blade	20 x 20	5	2000	U.S.A.	Hopkins and Parker, 1984; Parker and Leck, 1985
	NI	675	4-5	3375	U.S.A.	Van der Valk and Davis, 1978
Prairie	NI	929	1.3	121	U.S.A.	Lippert and Hopkins, 1950
	Auger	10	2.5	196	Canada	Johnston et al, 1969
		15.2	6	1089	U.S.A.	Marlette and Anderson, 1986
Rainforest	Knife/ blade	25 x 50	5	6250	Australia	Hopkins and Graham, 1984
	NI	20 x 20	7.5	3000	New Guinea	Enright, 1985
Semi-desert	Auger	5.4	5	115	U.S.A.	Hassan and West, 1986
Tundra	Auger	5	35	687	U.S.A.	McGraw, 1980
	Auger	12.5	20	2454	U.S.A.	Roach, 1983
Savanna woodland	NI	1400	2.5	3500	Australia	Andrew and Mott, 1983
Shrub woodland	Knife/ blade	40 x 40	1	1600	Australia	Hopkinson et al., 1980

* Dimensions for the augers refer to the diameter; those for the blades refer to the side of a block of soil.
† Calculations for the volume are rounded off to the nearest unit.
\# NI - not identified
The larger value is used for the required calculations
The value refers to an area in cm^2

TABLE VIII. List of methods used to collect sampling units to selected seed bank studies.

Method of collecting sampling units (S.U.)	References
Subsampled	Chippendale and Milton, 1934; Dore and Raymond, 1942; Champness and Morris, 1948; Dotzenko et al., 1969; Hodgkinson et al., 1980
Bulked	Milton, 1936; Budd et al., 1954; Roberts, 1958, 1962, 1963a, b; Wee, 1974; Leck and Graveline, 1979; Hill and Stevens, 1981; Roberts and Neilson, 1981; Froud-Williams et al., 1983; Conn et al., 1984; Pratt et al., 1984; Warnes and Andersen, 1984; Smith and Kadlec, 1985
Subsampled, bulked S.U.	Livingston and Allesio, 1968; Johnston et al., 1969; Hurle, 1974; Roberts and Ricketts, 1979
S.U. made up of bulked cores	Brenchley and Warington, 1930, 1945; Roberts and Dawkins, 1967; Roberts and Feast, 1973; Archibold, 1979, 1981; Archibold and Hume, 1983; Williams, 1984; Bridges and Walker, 1985; Panetta, 1985; Burnside et al., 1986a, b
Subsampled S.U. made up of bulked cores	Van der Valk and Davis, 1978; Schweizer and Zimdahl, 1984 a, b

APPENDIX B

A MODIFIED MALONE'S TECHNIQUE TO EXTRACT SEEDS FROM SOIL SAMPLES.

Soil samples are soaked for a minimum of 30 minutes in a solution of sodium hexametaphosphate (Calgon) and sodium bicarbonate (baking soda). The solution is prepared by mixing in water 50 g of sodium hexametaphosphate and 25 g of sodium bicarbonate per liter of solution. The important characteristic of these compounds is to disperse soil particles. This suspension is poured over a set of sieves, the upper one with 2.0 mm mesh openings (No. 10 Canadian Standard) and the lower one with 0.5 mm mesh openings (No. 35 Canadian Standard). The material is washed through these sieves by a fine spray of water from a garden sprayer (Fig. I of Appendix E). The seeds as well as some debris are collected in the lower sieve.

This sieve is then inverted over a clay saucer (18 cm in diameter). By gently tapping, material is emptied upon a Whatman No. 1 qualitative filter paper in the bottom of the saucer. The samples were moved to a well-ventilated room and covered with a fine mesh nylon to prevent any contamination. They are left to dry for one or two days. The material is then gently brushed off the filter paper and placed in a labelled No. 1 coin envelope.

APPENDIX C

LISTING OF COMPUTER PROGRAMS FOR SAMPLING IN A 32 X 32 MATRIX AND THE SUMMARIES OF THE MATHEMATICAL FORMULAS USED IN THESE PROGRAMS

APPENDIX C

SECTION I. RAND.FOR - Fortran computer program for random sampling in a 32 x 32 matrix

```
C* THIS PROGRAM TAKES NN RANDOM SAMPLES OF SIZE M FROM
C* A SQUARE MATRIX OF DATA VALUES.
C PROGRAMMER - N. KENKEL
      DIMENSION N(32,32), REM(400), REV(400), RESV(400)
      OPEN(UNIT = 1, FILE = 'CALDAT.DAT')
      IDIM = 32
      NUM = 1024
      DO 20 I = 1, IDIM
   20 READ (I,25) (N(I, J), J =1, IDIM)
   25 FORMAT (12, 19I3,/,I2,11I3)
      CLOSE (UNIT = 1, FILE = 'CALDAT.DAT')
  904 WRITE (5,26)
   26 FORMAT ('SPECIFY RANDOM SEED VALUE')
      READ(5,27)IR
   27 FORMAT(I)
      CALL SETRAN(IR)
C * RANDOM SAMPLE; NN SAMPLES EACH OF SIZE M*
      WRITE(5,28)
   28 FORMAT(' RANDOM;SPECIFY # SAMPLES, AND SAMPLE SIZE')
      READ(5,30)NN,M
   30 FORMAT(2I)
      DO 100 L=1,NN
      IRS=0
      IRS2=0
      DO 80 K=1,M
      X=(RAN(Q)*IDIM)+1.0
      Y=(RAN(Q)*IDIM)+1.0
      I=IFIX(X)
      J=IFIX(Y)
      IF(X.GT.32.0)I=32
      IF(Y.GT.32.0)J=32
      IRS=IRS+N(I,J)
      IRS2=IRS2+N(I,J)**2
   80 CONTINUE
      QQ=FLOAT(IRS)
      QQ2=FLOAT(IRS2)
      REM(L)=QQ/M
      REV(L)=(QQ2-QQ**2/M)/(M-1)
      RESV(L)=(REV(L)/M)*(1-FLOAT(M)/NUM)
  100 CONTINUE
C RANDOM COMPUTE AVE OF THE NN MEAN AND VARIANCE VALUES
      TRM=0.0
      TRV=0.0
      TRS=0.0
      DO 110 I=1,NN
      TRM=TRM+REM(I)
      TRV=TRV+REV(I)
      TRS=TRS+RESV(I)
  110 CONTINUE
      RM=TRM/NN
```

```
      RV=TRV/NN
      RS=TRS/NN
C* FIND THE MAX. AND MIN VALUES
      RMMN=REM(1)
      RMMX=REM(1)
      RVMN=REV(1)
      RVMX=REV(1)
      RSMN=RESV(1)
      RSMX=RESV(1)
      DO 115 L=2,NN
      IF(REM(L).GT.RMMX)RMMX=REM(L)
      IF(REM(L).LT.RMMN)RMMN=REM(L)
      IF(REV(L).GT.RVMX)RVMX=REV(L)
      IF(REV(L).LT.RVMN)RVMN=REV(L)
      IF(RESV(L).GT.RSMX)RSMX=RESV(L)
      IF(RESV(L).LT.RSMN)RSMN=RESV(L)
 115  CONTINUE
C * MONTE CARLO SAMPLING VARIANCE
      RV1=0.0
      DO 120 I=1,NN
 120  RV1=RV1+(RM-REM(I))**2
      RS1=RV1/NN
C * COMPUTATION OF POPULATION PARAMETERS
      ISM=0
      ISM2=0
      DO 450 I=1,IDIM
      DO 450 J=1,IDIM
      ISM=ISM+N(I,J)
      ISM2=ISM2+(N(I,J)**2
 450  CONTINUE
      RR=FLOAT(ISM)
      RR2=FLOAT(ISM2)
      PM=RR/NUM
      PV=(RR2-RR**2/NUM)/(NUM-1)
      PSV=(PV/M)*(1-FLOAT(M)/NUM)
C * OUTPUT THE RESULTS
      WRITE(6,500)M,NN
 500  FORMAT(' RANDOM SAMPLING:SAMPLE SIZE=',I4,'  #SAMPLES=',I4)
      WRITE(6,505)
 505  FORMAT(/,' CALCULATED MEAN AND RANGE')
      WRITE(6,510)RM,RMMN,RMMX
 510  FORMAT(2X,F8.5,' (',F8.5,' - ',F8.5,' )')
      WRITE(6,515)
 515  FORMAT(/,' VARIANCE ESTIMATES AND RANGE')
      WRITE(6,510)
      WRITE(6,510)RV,RVMN,RVMX
      WRITE(6,525)
 525  FORMAT(/,' SAMPLING VARIANCE  ESTIMATES AND RANGE')
      WRITE(6,510)RS,RSMN,RSMX
      WRITE(6,530)RS1
 530  FORMAT(/,' MONTE CARLO ESTIMATE OF SAMPLING VARIANCE=',F8.5)
      WRITE(6,545)
 545  FORMAT(/,' POPULATION PARAMETERS')
```

```
      WRITE(6,550)PM,PV,PSV
550   FORMAT(' MEAN=',F8.5,' VAR=',F8.5,' SVAR=',F8.5)
      WRITE(5,923)
923   FORMAT(/,' TYPE 1 TO CONTINUE')
      READ(5,924)NAJ
924   FORMAT(I)
      IF (NAJ.EQ.1)GO TO 904
      STOP
      END
```

SECTION II. SYST.FOR - Fortran computer program for systematic sampling in a 32 x 32 matrix

```
C SYST.FOR- PROGRAM FINDS A SET OF SYSTEMATIC SAMPLES
C FROM A SQUARE MATRIX OF VALUES.
C PROGRAMMER - N. KENKEL
      DIMENSION N(32,32),YEM(400),YEV(400),YESV(400)
      OPEN(UNIT=1,FILE='CALDAT.DAT')
      IDIM=32
      NUM=1024
      DO 20 I=1,IDIM
   20 READ(1,25)(N(I,J),J=1,IDIM)
   25 FORMAT(I2,19I3,/,I2,11I3)
      CLOSE(UNIT=1,FILE='CALDAT.DAT')
  904 WRITE(5,26)
   26 FORMAT(' SPECIFY RANDOM SEED VALUE')
      READ(5,27)IR
   27 FORMAT(I)
      CALL SETRAN(IR)
C * SYSTEMATIC SAMPLE - NM SAMPLES EACH OF SIZE MM
      WRITE(5,121)
  121 FORMAT(' SYSTEMATIC: SPECIFY SAMPLING INTERVALS(X AND Y COORDS)')
      READ(5,122)NX,NY
  122 FORMAT(2I)
      NXX=IDIM/NX
      NYY=IDIM/NY
      MM=NXX*NYY
      WRITE(5,124)
  124 FORMAT(' SPECIFY # SYSTEMATIC SAMPLES TO TAKE')
      READ(5,125)NM
  125 FORMAT(I)
      DO 200 L=1,NM
      IYS=0
      IYS2=0
      X=(RAN(Q)*NX)+1.0
      Y=(RAN(Q)*NY)+1.0
      I=IFIX(X)
      J=IFIX(Y)
      IF(X.GT.NX)I=NX
      IF(Y.GT.NY)J=NY
      DO 140 KK=I,32,NX
      DO 140 LL=J,32,NY
      IYS=IYS+N(KK,LL)
      IYS2=IYS2+N(KK,LL)**2
  140 CONTINUE
      QQ=FLOAT(IYS)
      QQ2=FLOAT(IYS2)
      YEM(L)=QQ/MM
      YEV(L)=(QQ2-QQ**2/MM)/(MM-1)
      YESV(L)=(YEV(L)/MM)*(1-FLOAT(MM)/NUM)
  200 CONTINUE
C * SYSTEMATIC - COMPUTE AVE. OF NM MEAN AND VARIANCE VALUES
      TYM=0.0
      TYV=0.0
```

```
      TYS=0.0
      DO 210 I=1,NM
      TYM=TYM+YEM(I)
      TYV=TYV+YEV(I)
      TYS=TYS+YESV(I)
  210 CONTINUE
      YM=TYM/NM
      YV=TYV/NM
      YS=TYS/NM
C * FIND THE MAX AND MIN OF THESE VALUES
      YMMN=YEM(1)
      YMMX=YEM(1)
      YVMN=YEV(1)
      YVMX=YEV(1)
      YSMN=YESV(1)
      YSMX=YESV(1)
      DO 220 L=2,NM
      IF(YEM(L).GT.YMMX)YMMX=YEM(L)
      IF(YEM(L).LT.YMMN)YMMN=YEM(L)
      IF(YEV(L).GT.YVMX)YVMX=YEV(L)
      IF(YEV(L).LT.YVMX)YVMN=YEV(L)
      IF(YESV(L).GT.YSMX)YSMX=YESV(L)
      IF(YESV(L).LT.YSMN)YSMN=YESV(L)
  220 CONTINUE
C * MONTE CARLO SAMPLING VARIANCE
      YV1=0.0
      DO 225 I=1,NM
  225 YV1=YV1+(YM-YEM(I))**2
      YS1=YV1/NM
C * OUTPUT THE RESULTS
      WRITE(6,500)MM,NM
  500 FORMAT(' SYSTEMATIC SAMPLING:SAMPLE SIZE=',I4,' #SAMPLES=',I4)
      WRITE(6,505)
  505 FORMAT(/,' CALCULATED MEAN, AND RANGES')
      WRITE(6,510)YM,YMMN,YMMX
  510 FORMAT(2X,F8.5,' (',F8.5,' - ',F8.5,' )')
      WRITE(6,515)
  515 FORMAT(/,' VARIANCE ESTIMATES AND RANGE')
      WRITE(6,510)YV, YVMN, YVMX
      WRITE(6,525)
  525 FORMAT(/,' SAMPLING VARIANCE ESTIMATES AND RANGE')
      WRITE(6,510)YS,YSMN,YSMX
      WRITE(6,530)YS1
  530 FORMAT(/,' MONTE CARLO ESTIMATE OF SAMP VAR=',F8.5)
      WRITE(6,923)
  923 FORMAT(/,' TYPE 1 TO CONTINUE')
      READ(6,924)KZ
  924 FORMAT(I)
      IF (KZ.EQ.1)GO TO 904
      STOP
      END
```

SECTION III. STRAN.FOR - Fortran computer program for stratified random sampling in a 32 x 32 matrix.

```
C STRAN.FOR - PROGRAM TAKES A STRATIFIED RANDOM SAMPLE FROM A MATRIX.
C THE STRATA ARE OF THE SAME SIZE, AND RECTANGULAR (USER SPECIFIED).
C THE SAME NUMBER OF SAMPLES ARE TAKEN FROM EACH STRATA.
C PROGRAMMER - N. KENKEL
      DIMENSION N(32,32),SEM(400),SEV(400),SESV(400),
     *SAVE(16,16),VAR(16,16),SVAR(16,16)
      OPEN(UNIT=1,FILE='CALDAT.DAT')
      IDIM=32
      NUM=1024
      DO 20 I=1,IDIM
   20 READ(1,25)(N(I,J),J=1,IDIM)
   25 FORMAT(I2,19I3,/,I2,11I3)
      CLOSE(UNIT=1,FILE='CALDAT.DAT')
  904 WRITE(5,26)
   26 FORMAT(' SPECIFY RANDOM SEED VALUE')
      READ(5,27)IR
   27 FORMAT(I)
      CALL SETRAN(IR)
C * STRATIFIED SAMPLE . NL SAMPLES EACH OF SIZE MP
      WRITE(5,300)
  300 FORMAT(' SPECIFY STATA SIZE IN X, Y COORDS.
     + AND THE NUMBER OF SAMPLES TO TAKE W/I EACH STRATA')
      READ(5,305)NX,NY,NS
  305 FORMAT(3I)
C * TAKE NL STRATIFIED SAMPLES EACH OF SIZE MP
      NXX=IDIM/NX
      NYY=IDIM/NY
      NSTRA=NXX*NYY
      MP=NXX*NYY*NS
      QX=NX*NY
      QXX=(QX*(QX-NS))/NS
      QXX=QXX/(NUM**2)
      WRITE(5,306)
  306 FORMAT(' SPECIFY NUMBER OF STRATIFIED SAMPLES TO TAKE')
      READ(5,307)NL
  307 FORMAT(I)
      DO 400 L=1,NL
      ADX=1.0
      DO 320 K=1,NXX
      ADY=1.0
      DO 316 KK=1,NYY
      ISS=0
      ISS2=0
      DO 315 LL=1,NS
      X=(RAN(Q)*NX)+ADX
      Y=(RAN(Q)*NY)+ADY
      I=IFIX(X)
      J=IFIX(Y)
      XX=NX+ADX-1.0
      YY=NY+ADY-1.0
      IF(X.GT.XX)I=XX
```

```
      IF(Y.GT.YY)J=YY
      ISS=ISS+N(I,J)
      ISS2=ISS2+N(I,J)**2
315   CONTINUE
      QQ=FLOAT(ISS)
      QQ2=FLOAT(ISS2)
      SAVE(K,KK)=QQ/NS
      SVAR(K,KK)=(QQ2-QQ**2/NS)/(NS-1)
      ADY=ADY+NY
316   CONTINUE
      ADX=ADX+NX
320   CONTINUE
      TSA=0.0
      TSV=0.0
      DO 325 I=1,NXX
      DO 325 II=1,NYY
      TSA=TSA+SAVE(I,II)
      TSV=TSV+SVAR(I,II)
325   CONTINUE
      SEM(L)=TSA/NSTRA
      SEV(L)=TSV/NSTRA
      QQZ=0.0
      DO 350 K=1,NXX
      DO 350 KK=1,NYY
350   QQZ=QQZ+SVAR(K,KK)
      SESV(L)=QXX*QQZ
400   CONTINUE
C STRATIFIED. COMPUTE AVE OF THE MEAN AND VARIANCE VALUES
      TSM=0.0
      TSV=0.0
      TSS=0.0
      DO 410 I=1,NL
      TSM=TSM+SEM(I)
      TSV=TSV+SEV(I)
      TSS=TSS+SESV(I)
410   CONTINUE
      SM=TSM/NL
      SV=TSV/L
      SS=TSS/NL
C * FIND THE MAX AND MIN VALUES
      SMMN=SEM(1)
      SMMX=SEM(1)
      SVMN=SEV(1)
      SVMX=SEV(1)
      SSMN=SESV(1)
      SSMX=SESV(1)
      DO 415 L=2,NL
      IF(SEM(L).GT.SMMX)SMMX=SEM(L)
      IF(SEM(L).LT.SMMN)SMMN=SEM(L)
      IF(SEV(L).GT.SVMX)SVMX=SEV(L)
      IF(SEV(L).LT.SVMN)SVMN=SEV(L)
      IF(SESV(L).GT.SSMX)SSMX=SESV(L)
      IF(SESV(L).LT.SSMN)SSMN=SESV(L)
```

```
 415  CONTINUE
C MONTE CARLO ESTIMATE OF THE SAMPLING VARIANCE
      SV1=0.0
      DO 425 I=1,NL
 425  SV1=SV1+(SM-SEM(I))**2
      SS1=SV1/NL
 C OUTPUT RESULTS
      WRITE(6,500)MP,NL
 500  FORMAT(' STRATIFIED RANDOM: SAMPLE SIZE=',I4,' #SAMPLES=',I4)
      WRITE(6,505)
 505  FORMAT(/,' CALCULATED  MEANS, AND RANGE')
      WRITE(6,510)SM,SMMN,SMMX
 510  FORMAT(2X,F8.5,' (',F8.5,' - ',F8.5,' )')
      WRITE(6,515)
 515  FORMAT(/,' POOLED VARIANCE ESTIMATES AND RANGE')
      WRITE(6,510)SV,SVMN, SVMX
      WRITE(6,525)
 525  FORMAT(/,' SAMPLING VARIANCE ESTIMATES AND RANGE')
      WRITE(6,510)SS,SSMN,SSMX
      WRITE(6,530)SS1
 530  FORMAT(/,' MONTE CARLO ESTIMATE OF SAMPLING VARIANCE=',F8.5)
C POPULATION PARAMETERS
      IPQ=0
      IPR=0
      DO 680 I=1,NXX
      DO 670 K=1,NYY
      V=0
      VM=0
      DO 650 J=1,NX
      IJ=IPQ+J
      DO 650 JJ=1,NY
      IK=IPR+JJ
      V=V+FLOAT(N(IJ,IK)**2)
      VM=VM+FLOAT(N(IJ,IK))
 650  CONTINUE
      VAR(I,K)=(V-VM**2/QX)/(QX-1)
      IPR=IPR+NY
 670  CONTINUE
      IPR=0
      IPQ=IPQ+NX
 680  CONTINUE
      A=0
      B=0
      DO 700 I=1,NXX
      DO 700 K=1,NYY
      A=A+(QX-1)*VAR(I,K)
      B=B+QX*(QX-NS)*(VAR(I,K)/NS)
 700  CONTINUE
      PVX=FLOAT(NUM-NSTRA)
      PSVX=FLOAT(NUM**2)
      PV=(1/PVX)*A
      PSV=(1/PSVX)*B
      WRITE(6,750)
```

```
750   FORMAT(/,' POPULATION PARAMETERS')
      WRITE(6,751)PV
751   FORMAT(' POPULATION POOLED VARIANCE=',F8.4)
      WRITE(6,752)PSV
752   FORMAT(' POPN SAMPLING VARIANCE=',F8.4)
      WRITE(5,923)
923   FORMAT(/,' TYPE 1 TO CONTINUE')
      READ(5,924)NAJ
924   FORMAT(I)
      IF (NAJ.EQ.1)GO TO 904
      STOP
      END
```

SECTION IV. CLUSR.FOR - Fortran computer program for cluster sampling in a 32 x 32 matrix.

```
C* THIS PROGRAM TAKES A SET OF CLUSTER SAMPLES FROM A GRID POPN.
C PROGRAMMER - N. KENKEL
      DIMENSION NA(32,32),VW(400),VB(400),VAR(K400),VSAMP(400),XMEAN(400
      IDIM=32
      NUM=1024
      OPEN(UNIT=1,FILE='CALDAT.DAT')
      DO 20 I=1,IDIM
      READ(1,25)(NA(I,J),J=1,IDIM)
 25   FORMAT (I2,19I3,/,I2,11I3)
 20   CONTINUE
      CLOSE(UNIT=1,FILE='CALDAT.DAT')
940   WRITE(5,26)
 26   FORMAT(' SPECIFY RANDOM SEED VALUE')
      READ(5,27)IR
 27   FORMAT(I)
      CALL SETRAN(IR)
      WRITE(5,100)
100   FORMAT(' SPECIFY # OF CLUSTERS TO SAMPLE')
      READ(5,110)N
110   FORMAT(I)
      WRITE(5,120)
120   FORMAT(' SPECIFY X AND Y COORDS OF EACH CLUSTER')
      READ(5,130)NX,NY
130   FORMAT(2I)
      M=NX*NY
      NM=N*M
      WRITE(5,140)NM
140   FORMAT(' TOTAL SAMPLE SIZE IS=',I)
      NN=NUM/M
      WRITE(5,150)NN
150   FORMAT(' TOTAL # POSSIBLE CLUSTERS =',I)
      WRITE(5,160)
160   FORMAT(' SPECIFY # SAMPLES TO TAKE')
      READ(5,170)NK
170   FORAMT(I)
      XM1=0.0
      XM2=0.0
      DO 300 L=1,NK
      SW=0.0
      VIT=0.0
      SSW=0.0
      DO 250 JK=1,N
      X=(RAN(Q)*32.0)+1.0
      Y=(RAN(Q)*32.0)+1.0
      I=IFIX(X)
      J=IFIX(Y)
      XNX=FLOAT(NX)
      YNY=FLOAT(NY)
      IF(X.GT.32.0)I=32
      IF(Y.GT.32.0)J=32
      GO TO 180
```

```
175   I=I+1
180   IF(INT(I/XNX).EQ.(I/XNX)) GO TO 190
      GO TO 175
 185  J=J+1
 190  IF(INT(J/YNY).EQ.(J/YNY)) GO TO 200
      GO TO 185
 200  NT=0
      NSS=0
      K1=I-(NX-1)
      K2=I
      KK1=J-(NY-1)
      KK2=J
      DO 220 K=K1,K2
      DO 220 KK=KK1,KK2
      NT=NT+NA(K,KK)
 220  NSS=NSS+NA(K,KK)**2
      QQ1=FLOAT(NT)
      QQ2=FLOAT(NSS)
      VIT=VIT+(QQ2-QQ1**2/M)/(M-1)
      SW=SW+QQ1/M
      SSW=SSW+(QQ1/M)**2
 250  CONTINUE
      VW(L)=VIT/N
      VB(L)=(SSW-SW**2/N)/(N-1)
      VAR(L)=(M*(NN-1)*VB(L)+NN*(M-1)*VW(L))/(NN*M-1)
      VSAMP(L)=(FLOAT(NN-N)/FLOAT(NN*N))*VB(L)
      XMEAN(L)=SW/N
      XM1=XM1+SW/N
      XM2=XM2+(SW/N)**2
 300  CONTINUE
      SVEST=(XM2-XM1**2/NK)/NK
      XMEST=XM1/NK
      VI=0.0
      UR=0.0
      TOT=0.0
      JQ=1
      ID1=IDIM/NY
      ID2=IDIM/NX
      DO 400 I=1,ID1
      IQ=1
      JJQ=JQ+NY-1
      DO 420 J=1,ID2
      NT=0
      NT2=0
      IIQ=IQ+NX-1
      DO 140 K=IQ,IIQ
      DO 410 KK=JQ,JJQ
      NT=NT+NA(K,KK)
      NT2=NT2+(NA(K,KK)**2)
 410  CONTINUE
      UQ=FLOAT(NT)
      UQQ=FLOAT(NT2)
      TOT=TOT+UQ
```

```
      VI=VI+((UQQ-UQ**2/M)/(M-1))
      UR=UR+(UQ/M)**2
  420 IQ=IQ+NX
  400 JQ=JQ+NY
      VIB=(UR-((TOT/M)**2)/NN)/(NN-1)
      VIW=VI/NNNN*M)
      VSPOP=(FLOAT(NN-N)/FLOAT(NN*N))*VIB
C FIND MAX AND MIN VALUES
      VWMN=VW(1)
      VWMX=VW(1)
      VBMN=VB(1)
      VBMX=VB(1)
      VRMN=VAR(1)
      VRMX=VAR(1)
      VSMN=VSAMP(1)
      VSMX=VSAMP(1)
      XMMN=XMEAN(1)
      XMMX=XMEAN(1)
      DO 500 I=2,NK
      IF(VW(I).GT.VWMX)VWMX=VW(I)
      IF(VW(I).LT.VWMN)VWMN=VW(I)
      IF(VB(I).GT.VBMX)VBMX=VB(I)
      IF(VB(I).LT.VBMN)VBMN=VB(I)
      IF(VAR(I).GT.VRMX)VRMX=VAR(I)
      IF(VAR(I).LT.VRMN)VRMN=VAR(I)
      IF(VSAMP(I).GT.VSMX)VSMX=VSAMP(I)
      IF(VSAMP(I).LT.VSMN)VSMN=VSAMP(I)
      IF(XMEAN(I).GT.XMMX)XMMX=XMEAN(I)
      IF(XMEAN(I).LT.XMMN)XMMN=XMEAN(I)
  500 CONTINUE
C CALCULATE MEANS FOR THESE
      TVW=0.0
      TVB=0.0
      TVR=0.0
      TVS=0.0
      TXM=0.0
      DO 550 I=1,NK
      TVW=TVW+VW(I)
      TVB=TVB+VB(I)
      TVR=TVR+VAR(I)
      TVS=TVS+VSAMP(I)
  550 TXM=TXM+XMEAN(I)
      TVW=TVW/NK
      TVB=TVB/NK
      TVR=TVR/NK
      TVS=TVS/NK
      TXM=TXM/NK
C OUTPUT RESULTS
      WRITE(6,600)
  600 FORMAT(' THE FOLLOWING ARE POPULATION PARAMETERS')
      WRITE(6,605)VIB,VIW
  605 FORMAT(' BETWEEN VARIANCE=',F,'  WITHIN VARIANCE='F)
      WRITE(6,610)VARI,XME
```

```
610   FORMAT(' POPN VARIANCE=',F,'  POPN MEAN=',F)
      WRITE(6,612)VSPOP
612   FORMAT(' POPN SAMPLING VARIANCE=',F)
      WRITE(6,615)
615   FORMAT(//,' THESE ARE THE MONTE PYTHON ESTIMATES')
      WRITE(6,620)
620   FORMAT(' WITHIN VARIANCE AND RANGE')
      WRITE(6,630)TVW,VWMN,VWMX
630   FORMAT(2X,F8.5,'   ( ',F8.5,' TO ',F8.5,' )')
      WRITE(6,635)
635   FORMAT(' BETWEEN VARIANCE AND RANGE')
      WRITE(6,630)TVB,VBMN,VBMX
      WRITE(6,640)
640   FORMAT(' VARIANCE AND RANGE')
      WRITE(6,630)TVR,VRMN,VRMX
      WRITE(6,645)
645   FORMAT(' SAMPLING VARIANCE AND RANGE')
      WRITE(6,630)TVS,VSMN,VSMX
      WRITE(6,650)
650   FORMAT(' MEAN VALUES AND RANGE')
      WRITE(6,630)TXM,XMMN,XMMX
      WRITE(6,660)SVEST
660   FORMAT(//,' MONTE CARLO SAMPLING VARIANCE ESTIMATE=',F)
      WRITE(6,670)XMEST
670   FORMAT(/,' VERIFICATION OF MONTE CARLO ESTIMATE OF MEAN =',F)
      WRITE(5,680)
680   FORMAT(' DO YOU WISH TO DO ANOTHER RUN?IF YES,TYPE 12,ELSE 0')
      READ(5,690)NOR
690   FORMAT(I)
      IF(NOR.EQ.12) GO TO 940
      STOP
      END
```

Section V Summary of the mathematical formulas used in the RAND.FOR program for random sampling.

Statistics	Formula
population mean	$\frac{\sum x_{ij}}{N}$
	where N = population size
population variance	$\frac{\sum (x_{ij} - \bar{x})^2}{N-1}$
population sampling variance	$\frac{S_x^2}{n}(1-F)$
	where n = sample size $F = n/N$
calculated mean (RM) for all 400 samples (i)	$RM = \frac{\sum_{i=1}^{400} REM_i}{400}$
	where $REM_i = \frac{\sum x_{ij}}{n}$
variance estimate (RV) for all 400 samples (i)	$RV = \frac{\sum_{i=1}^{400} REV_i}{400}$
	where $REV_i = \frac{\sum (x_{ij} - \bar{x}_{i.})^2}{n-1}$
	$\bar{x}_{i.}$ = mean of sample i
sampling variance estimate (RS) for all 400 samples (i)	$RS = \frac{\sum_{i=1}^{400} RESV_i}{400}$
	where $RESV_i = \frac{REV_i}{n}(1-F)$
Monte Carlo estimate of sampling variance (RSI)	$RSI = \frac{RVI}{400}$
	where $RVI = \sum_{i=1}^{400} (RM - REM_i)^2$

Section VI Summary of the mathematical formulas used in the SYST.FOR program for systematic sampling.

Statistics	Formula
calculated mean (YM) for all 400 samples (i)	YM $\frac{\sum_{i=1}^{400} YEM_i}{400}$
i	where $YEM_i = \frac{\sum x_{i,j}}{n}$
	n = sample size
variance estimate (YV) for all 400 samples (i)	YV $\frac{\sum_{i=1}^{400} YEV_i}{400}$
	where $YEV_i = \frac{\sum x_{i,j}^2 - \frac{(\sum x_{i,j})^2}{n}}{n-1}$
sampling variance estimate (YS) for all 400 samples (i)	YS $\frac{\sum_{i=1}^{400} YESV_i}{400}$
	where $YESV_i = \frac{YEV}{n}\left(\frac{1-n}{N}\right)$
	N population size
Monte Carlo estimate of sampling variance (YSI)	YSI $\frac{\sum_{i=1}^{400} (YM - YEM_i)^2}{400}$

Section VII Summary of the mathematical formulas used in the STRAN.FOR program for stratified random sampling.

Statistics	Formula
population pooled variance (PV)	$PV = \frac{1}{N-K}\left[\sum_{h=1}^{K}(N_h - 1)VAR_h\right]$
	where N = total no. of sampling units
	K = total no. of strata
	N_h = total no. of sampling units per stratum
	$VAR_h = \frac{\sum x_{ij}^2 - \frac{(\sum x_{ij})^2}{N_h}}{N_h - 1}$
	= true variance per stratum
population sampling variance (PSV)	$PSV = \frac{1}{N^2}\left[\sum_{h=1}^{K} N_h\left(N_h - n_h\right)\frac{VAR_h}{n_h}\right]$
	where n_h = no. of sampling units per stratum
calculated mean (SM) for all 400 samples (i)	$SM = \frac{\sum_{i=1}^{400} SEM_i}{400}$
	where $SEM_i = \frac{\sum_{i=1}^{K} SAVE_i}{K}$
	= mean of all stratal means
	$SAVE_i = \frac{\sum x_{ij}}{n_h}$
	= mean per stratum or stratal mean
pooled variance estimate (SV) for all 400 samples (i)	$SV = \frac{\sum_{i=1}^{400} SEV_i}{400}$
	where $SEV_i = \frac{\sum_{i=1}^{K} SVAR_i}{K}$
	= mean of all stratal variances per sample
	$SVAR_i = \frac{1}{n_h}\sum^{n_h}(x_{ij} - \bar{x}_i)^2$
	= variance per stratum or stratal variance
	$\bar{x}_i$ = mean for stratum i

Statistics	Formula
sampling variance estimate (SS) for all 400 samples (1)	$SS = \frac{\sum_{i=1}^{400} SESV_i}{400}$
	where $SESV_1 = \frac{1}{N^2}\left(\frac{N_h\,(N_h-n_h)}{n_h}\right)\sum_{i=1}^{k} SVAR_i$
	sampling variance per sample
Monte Carlo estimate of sampling variance (SS1)	$SS1 \quad \frac{SV1}{400}$
	where $SV1 \quad \sum_{i=1}^{400} (SM - SEM_i)^2$

Section VIII Summary of the mathematical formulas used in the CLUSR. FOR program for cluster sampling.

Statistics	Formula
between cluster variance (VIB)	$VIB = \frac{UR - \left[\frac{\left(\frac{TOT}{M}\right)^2}{NN}\right]}{NN-1}$
	where NN = total no. of possible clusters in matrix for that cluster size
	M = total no. of sampling units per cluster
	$UR = \sum^{NN} \left(\frac{NT_1}{M}\right)^2$
	= summation of all clusters in the matrix
	$NT_1 = \sum x_{ij}$
	= all possible sampling units in one cluster
	$TOT = \sum^{NN} NT_i$
within cluster variance (VIW)	$VIW = \frac{VI}{NN}$
	where $VI = \sum^{NN} \frac{NT2 - \frac{NT_i^2}{M}}{M-1}$
	= summation of all clusters
	$NT2 = \sum x_{ij}^2$
population variance (VARI)	$VARI = \frac{M\,(NN-1)\,(VIB + NN)\,(ii - 1)\,VIW}{(NN)(M) - 1}$
population mean (XME)	$XME = \frac{TOT}{NN(M)}$
population sampling variance (VSPOP)	$VSPOP = \left(\frac{NN-N}{NN(N)}\right) VIB$
	where N = no. of clusters to be sampled

Statistics	Formula
between cluster variance (TVB)	$TVB = \frac{\sum_{i=1}^{400} VB_i}{400}$
	where $VB_i = \frac{SSW_i - \frac{SW_i^2}{N}}{N-1}$
	$SSW_i = \sum^{N} \left(\frac{\sum x_{ij}}{M}\right)^2$
	$\sum x_{ij}$ = summation of all sampling units in one cluster
	$SW_i = \sum^{N} \left(\frac{\sum x_{ij}}{M}\right)$
within cluster variance (TVW)	$TVW = \frac{\sum_{i=1}^{400} VW_i}{400}$
	where $VW_i = \frac{VIT_i}{N}$
	$VIT_i = \sum^{N} \left[\frac{\sum x_{ij}^2 - \frac{(\sum x_{ij})^2}{M}}{M-1}\right]$
variance (TVR)	$TVR = \frac{\sum_{i=1}^{400} VAR_i}{400}$
	where $VAR_i = \frac{M(NN-1)(VB_i + NN)(M-1)VW_i}{[NN(M)]-1}$
Monte Carlo estimate of sampling variance (TVS)	$TVS = \frac{\sum_{i=1}^{400} VSAMP_i}{400}$
	where $VSAMP_i = \left[\frac{NN-N}{NN(N)}\right] VB_i$
Monte Carlo estimate of mean (TXM)	$TXM = \frac{\sum_{i=1}^{400} XMEAN_i}{400}$
	where $XMEAN_i = \frac{SW_i}{N}$
Monte Carlo sampling variance estimate (SVEST)	$SVEST = \frac{XM2 - \frac{XM1^2}{400}}{400}$
	where $XM2 = \sum^{400} \left(\frac{SW_i}{N}\right)^2$
	$XM1 = \sum^{400} \frac{SW_i}{N}$
Verification of Monte Carlo estimate of mean (XMEST)	$XMEST = \frac{XM1}{400}$

APPENDIX D

RAW DATA AND STATISTICAL ANALYSIS TESTING THE EFFICIENCY OF DIFFERENT SAMPLING METHODS IN A 32 X 32 MATRIX

APPENDIX D

INTRODUCTION

A sampling event consisted in drawing a sample of "n" sampling units "where "n" is the sample size" according to the sampling method under investigation and calculating the required statistics. These data were then stored temporarily. A second sample was drawn and the procedure was repeated until a total of 400 samples had been drawn and their related statistics calculated. The mean, the variance, the sampling variance of the mean and the Monte Carlo estimate of the sampling variance of the mean for the population (or matrix) were then calculated based on all 400 samples. This whole sequence of operations is called a sampling sequence. The mathematical formulas used to calculate the required statistics varied with the different sampling method under investigation. They are summarized in section V to VIII of Appendix C. If the sample size under investigation was 400 or less, then three sampling sequences were made and their results averaged. It is these averaged values which are reported in the figures in Section 2.8. If the sample size was greater than 400, then only one such sampling sequence was made.

TABLE II. Summary of the sample mean ($\bar{X}$), the Monte Carlo estimate of sampling variance (M.C.$S^2\bar{x}$) and the population sampling variance ($S^2\bar{x}$) calculated for various sample sizes by RAND.FOR computer program for random sampling of a 32 x 32 matrix.

Sample size	Statistics		
	Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance (M.C.$S^2\bar{x}$)	Population sampling† variance $S^2\bar{x}$)
4	2.434	1.876	1.643
5	2.278	1.371	1.313
8	2.312	1.685	0.818
10	2.337	0.691	0.653
15	2.381	0.440	0.433
16	2.357	0.397	0.406
20	2.412	0.348	0.323
25	2.404	0.303	0.257
30	2.350	0.223	0.213
32	2.357	0.178	0.200
35	2.395	0.176	0.182
40	2.346	0.170	0.159
45	2.374	0.165	0.140
50	2.380	0.146	0.126
55	2.402	0.137	0.114
60	2.367	0.116	0.104
64	2.381	0.096	0.097
65	2.363	0.098	0.095
70	2.362	0.091	0.088
75	2.358	0.075	0.082
80	2.372	0.063	0.076
90	2.371	0.067	0.067
100	2.370	0.072	0.060
120	2.373	0.058	0.049
128	2.366	0.049	0.045
150	2.371	0.042	0.038
200	2.376	0.037	0.027
256	2.384	0.025	0.019
300	2.364	0.022	0.016
400	2.379	0.018	0.010
500	2.382	0.015	0.007
512	2.378	0.012	0.006

* The values given are averaged over three sampling sequences if the sample size is ≤ 400; otherwise the values given represent one sampling sequence if the sample size is > 400.

† The calculation of the population sampling variance ($S^2\bar{x}$) is not related to the sampling event. It is obtained from formula $S^2\bar{x} = 1/n\ S^2\bar{x}\ (I-F)$, where $F = n/N$; $S^2\bar{x}$ = population variance; n = sample size; N = population size.

TABLE III. Summary of the sample mean ($\bar{X}$), the Monte Carlo estimate of sampling variance ($M.C.S^2_{\bar{x}}$) calculated for various sample sizes by SYST.FOR computer program for systematic sampling of a 32 x 32 matrix.

Sample size	Sampling* Interval	Statistics†	
		Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance ($M.C.S^2_{\bar{x}}$)
4	16-16	2.431	1.863
8	16-8	2.449	0.545
	8-16	2.283	1.111
	32-4	2.423	0.589
	4-32	2.452	2.421
16	8-8	2.341	0.204
	16-4	2.387	0.281
	4-16	2.277	1.110
	32-2	2.386	0.268
	2-32	2.318	1.927
32	8-4	2.378	0.116
	4-8	2.354	0.160
	16-2	2.348	0.104
	2-16	2.283	1.017
64	4-4	2.379	0.088
	8-2	2.394	0.027
	2-8	2.377	0.094
128	4-2	2.374	0.017
	2-4	2.374	0.047
256	2-2	2.378	0.006

* Sampling interval refers to the distance between the selected sampling units as represented by the elements (ij) of the matrix. The first number corresponds to the interval between the i rows of the matrix and the second number corresponds to the interval between the j columns of the matrix.

† The values given are averaged over three sampling sequences if the sample size is ≤ 400.

TABLE IV. Summary of the sample mean ($\bar{X}$), the Monte Carlo estimate of sampling variance (M.C.$S^2_{\bar{x}}$) calculated for various sample sizes by STRAN.FOR computer program for stratified random sampling of a 32 x 32 matrix.

Sample size	Strata orientation*	No. of strata in matrix	No. of sampling units sampled /stratum	Statistics†	
				Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance (M.C.$S^2_{\bar{x}}$)
4	32 x 16	2	2	2.341	1.499
	16 x 32	2	2	2.412	1.904
8	16 x 16	4	2	2.413	0.785
	32 x 8	4	2	2.328	0.624
	8 x 32	4	2	2.388	0.906
	32 x 16	2	4	2.385	0.741
	16 x 32	2	4	2.442	0.861
16	32 x 4	8	2	2.356	0.339
	4 x 32	8	2	2.373	0.392
	16 x 8	8	2	2.381	0.349
	8 x 16	8	2	2.384	0.400
	16 x 16	4	4	2.339	0.395
	32 x 8	4	4	2.427	0.382
	8 x 32	4	4	2.395	0.413
	32 x 16	2	8	2.401	0.353
	16 x 32	2	8	2.366	0.457
32	8 x 8	16	2	2.312	0,150
	32 x 2	16	2	2.369	0,144
	2 x 32	16	2	2.369	0.211
	16 x 4	16	2	2.343	0.128
	4 x 16	16	2	2.354	0.204
	32 x 4	8	4	2.374	0.179
	4 x 32	8	4	2.370	0.225
	16 x 8	8	4	2.330	0.163
	8 x 16	8	4	2.352	0.195
	16 x 16	4	8	2.369	0.200
	32 x 8	4	8	2.387	0.153
	8 x 32	4	8	2.380	0.199
	32 x 16	2	16	2.364	0.195
	16 x 32	2	16	2.389	0.212
64	16 x 2	32	2	2.369	0.080
	2 x 16	32	2	2.376	0.101
	8 x 4	32	2	2.369	0.086
	4 x 8	32	2	2.370	0.075
	8 x 8	16	4	2.372	0.085
	32 x 2	16	4	2.379	0.080
	2 x 32	16	4	2.355	0.108

TABLE IV. (Cont'd)

Sample size	Strata orientation*	No. of strata in matrix	No. of sampling units sampled /stratum	Statistics†	
				Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance (M.C.$S^2_{\bar{x}}$)
64	16 x 4	16	4	2.390	0.078
	4 x 16	16	4	2.346	0.095
	32 x 4	8	8	2.382	0.081
	4 x 32	8	8	2.387	0.096
	16 x 8	8	8	2.382	0.078
	8 x 16	8	8	2.380	0.102
	16 x 16	4	16	2.371	0.101
	32 x 8	4	16	2.382	0.082
	8 x 32	4	16	2.369	0.105
	32 x 16	2	32	2.361	0.097
	16 x 32	2	32	2.376	0.118
128	4 x 4	64	2	2.374	0.033
	8 x 2	64	2	2.365	0.031
	2 x 8	64	2	2.388	0.039
	16 x 2	32	4	2.375	0.038
	2 x 16	32	4	2.381	0.050
	8 x 4	32	4	2.384	0.039
	4 x 8	32	4	2.360	0.036
	8 x 8	16	8	2.375	0.042
	32 x 2	16	8	2.358	0.039
	2 x 32	16	8	2.360	0.045
	16 x 4	16	8	2.365	0.035
	4 x 16	16	8	2.376	0.048
	32 x 4	8	16	2.388	0.042
	4 x 32	8	16	2.381	0.050
	16 x 8	8	16	2.367	0.041
	8 x 16	8	16	2.386	0.045
	16 x 16	4	32	2.370	0.047
	32 x 8	4	32	2.386	0.040
	8 x 32	4	32	2.397	0.051
	32 x 16	2	64	2.371	0.047
	16 x 32	2	64	2.380	0.057
256	4 x 2	128	2	2.373	0.014
	2 x 4	128	2	2.369	0.018
	4 x 4	64	4	2.372	0.018
	8 x 2	64	4	2.363	0.017
	2 x 8	64	4	2.376	0.019
	16 x 2	32	8	2.379	0.017
	2 x 16	32	8	2.385	0.029
	8 x 4	32	8	2.370	0.020
	4 x 8	32	8	2.375	0.020
	8 x 8	16	16	2.378	0.022
	32 x 2	16	16	2.371	0.019

TABLE IV. (Cont'd)

Sample size	Strata orientation*	No. of strata in matrix	No. of sampling units sampled /stratum	Statistics†	
				Sample mean ($\bar{x}$)	Monte Carlo estimate of sampling variance (M.C.$S^2_{\bar{x}}$)
256	2 x 32	16	16	2.360	0.024
	16 x 4	16	16	2.371	0.019
	4 x 16	16	16	2.370	0.025
	32 x 4	8	32	2.366	0.021
	4 x 32	8	32	2.370	0.028
	16 x 8	8	32	2.358	0.021
	8 x 16	8	32	2.355	0.024
	16 x 16	4	64	2.359	0.029
	32 x 8	4	64	2.368	0.021
	8 x 32	4	64	2.373	0.024
	32 x 16	2	128	2.380	0.025
	16 x 32	2	128	2.370	0.028
512	2 x 2	256	2	2.371	0.005
	4 x 2	128	4	2.377	0.006
	2 x 4	128	4	2.372	0.008
	8 x 2	64	8	2.377	0.008
	2 x 8	64	8	2.379	0.010
	4 x 4	64	8	2.369	0.009
	16 x 2	32	16	2.368	0.009
	2 x 16	32	16	2.375	0.010
	8 x 4	32	16	2.369	0.008
	4 x 8	32	16	2.374	0.011
	32 x 2	16	32	2.376	0.009
	2 x 32	16	32	2.380	0.013
	16 x 4	16	32	2.371	0.008
	4 x 16	16	32	2.370	0.011
	8 x 8	16	32	2.371	0.010
	32 x 4	8	64	2.378	0.012
	4 x 32	8	64	2.372	0.014
	16 x 8	8	64	2.371	0.010
	8 x 16	8	64	2.376	0.013
	32 x 8	4	128	2.390	0.010
	8 x 32	4	128	2.372	0.013
	16 x 16	4	128	2.370	0.011
	32 x 16	2	256	2.375	0.011
	16 x 32	2	256	2.371	0.013

* Strata orientation refers to the way the matrix is subdivided. Each stratum incorporates i successive rows and j successive columns of the matrix.

† The values given are averaged over three sampling sequences if the sample size is ≤ 400; otherwise, the values given represent one sampling sequence if the sample size is > 400.

TABLE V. Summary of the sample mean ($\bar{X}$) and the Monte Carlo estimate of sampling variance (M.C.S^2x) calculated for various sample sizes by CLUSR.FOR computer program for cluster sampling of a 32 x 32 matrix.

Sample size	Cluster* shape	No. of clusters sampled in matrix	No. of sampling unit/cluster	Statistics†	
				Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance (M.C.$S^2\bar{x}$)
8	2 x 2	2	4	2.364	2.158
16	2 x 2	4	4	2.266	0.792
	4 x 2	2	8	2.319	1.559
	2 x 4	2	8	2.418	1.159
32	2 x 2	8	4	2.327	0.492
	4 x 2	4	8	2.325	0.680
	2 x 4	4	8	2.350	0.526
	4 x 4	2	16	2.399	1.083
	8 x 2	2	16	2.410	1.259
	2 x 8	2	16	2.317	0.781
64	2 x 2	16	4	2.376	0.248
	4 x 2	8	8	2.403	0.379
	2 x 4	8	8	2.418	0.357
	4 x 4	4	16	2.368	0.537
	8 x 2	4	16	2.435	0.686
	2 x 8	4	16	2.379	0.438
	8 x 4	2	32	2.352	0.912
	4 x 8	2	32	2.381	0.769
	16 x 2	2	32	2.387	1.062
	2 x 16	2	32	2.405	0.249
128	2 x 2	32	4	2.389	0.122
	4 x 2	16	8	2.377	0.186
	2 x 4	16	8	2.367	0.142
	4 x 4	8	16	2.403	0.263
	8 x 2	8	16	2.362	0.296
	2 x 8	8	16	2.397	0.213
	8 x 4	4	32	2.408	0.465
	4 x 8	4	32	2.355	0.380
	16 x 2	4	32	2.383	0.526
	2 x 16	4	32	2.364	0.111
	8 x 8	2	64	2.398	0.642
	16 x 4	2	64	2.368	0.833
	4 x 16	2	64	2.386	0.182
	32 x 2	2	64	2.369	0.820
	2 x 32	2	64	2.392	0.040
256	2 x 2	64	4	2.379	0.066
	4 x 2	32	8	2.368	0.103

Sample size	Cluster* shape	No. of clusters sampled in matrix	No. of sampling unit/cluster	Statistics†	
				Sample mean ($\bar{X}$)	Monte Carlo estimate of sampling variance (M.C.$S^2_{\bar{x}}$)
256	2 x 4	32	8	2.385	0.070
	4 x 4	16	16	2.374	0.140
	8 x 2	16	16	2.314	0.165
	2 x 8	16	16	2.377	0.103
	8 x 4	8	32	2.343	0.219
	4 x 8	8	32	2.368	0.179
	16 x 2	8	32	2.347	0.250
	2 x 16	8	32	2.370	0.053
	8 x 8	4	64	2.379	0.326
	16 x 4	4	64	2.377	0.424
	4 x 16	4	64	2.379	0.090
	32 x 2	4	64	2.355	0.392
	2 x 32	4	64	2.377	0.019
	16 x 8	2	128	2.478	0.658
	8 x 16	2	128	2.376	0.172
	32 x 4	2	128	2.380	0.664
	4 x 32	2	128	2.374	0.017
512	2 x 2	128	4	2.348	0.032
	4 x 2	64	8	2.377	0.045
	2 x 4	64	8	2.391	0.041
	4 x 4	32	16	2.358	0.060
	8 x 2	32	16	2.380	0.083
	2 x 8	32	16	2.379	0.055
	8 x 4	16	32	2.377	0.116
	4 x 8	16	32	2.383	0.098
	16 x 2	16	32	2.367	0.119
	2 x 16	16	32	2.383	0.028
	8 x 8	8	64	2.414	0.160
	16 x 4	8	64	2.393	0.196
	4 x 16	8	64	2.377	0.042
	32 x 2	8	64	2.402	0.213
	2 x 32	8	64	2.369	0.010
	16 x 8	4	128	2.342	0.271
	8 x 16	4	128	2.375	0.079
	32 x 4	4	128	2.407	0.353
	4 x 32	4	128	2.368	0.008
	16 x 16	2	256	2.354	0.116
	32 x 8	2	256	2.428	0.526
	8 x 32	2	256	2.371	0.016

* Cluster shape is identified by the number of i rows and j columns it encompasses

† The values given are averaged over three sampling sequences if the sample size is ≤ 400; otherwise the values given represent one sampling sequence if the sample size is >400.

TABLE VI. Multiple pairwise comparisons of the Monte Carlo estimates of sampling variance for each sampling method with fixed sample size of 64 and 128 units.

Sampling method	Total no. of sampling units									
	n = 64					n = 128				
	Pattern	M.C.$S^2_{\bar{x}}$	Comparison order	F*	Accept/ reject†	Pattern	M.C.$S^2_{\bar{x}}$	Comparison order	F*	Accept/ reject
Random	-	0.096	-	-	-	-	0.049	-	-	-
Systematic	8-2	0.027	1-2	3.300	R	4-2	0.017	1-2	2.762	R
	4-4	0.088	1-3	3.514	R	2-4	0.047			
	2-8	0.094	2-3	1.065	A					
Stratified random	16x2	0.080	1-2	1.066	A	16x2	0.038	1-2	1.032	A
	8x4	0.086	1-3	1.072	A	8x4	0.039	1-3	1.058	A
	4x8	0.075	1-4	1.262	R	4x8	0.036	1-4	1.331	R
	2x16	0.101	2-3	1.143	A	2x16	0.050	2-3	1.091	A
			2-4	1.183	A			2-4	1.290	R
			3-4	1.352	R			3-4	1.408	R
Cluster	16x2	1.062	1-2	1.165	A	16x2	0.526	1-2	1.131	A
	8x4	0.912	1-3	1.381	R	8x4	0.465	1-3	1.383	R
	4x8	0.769	1-4	4.258	R	4x8	0.380	1-4	4.753	R
	2x16	0.249	2-3	1.186	A	2x16	0.111	2-3	1.223	A
			2-4	3.657	R			2-4	4.202	R
			3-4	3.084	R			3-4	3.436	R

* Test of equality of variance $F = M.C.S^2_{\bar{x}_1} / M.C.S^2_{\bar{x}_2}$

† H_o: The two Monte Carlo estimates of sampling variance are equal

H_a: The two Monte Carlo estimates of sampling variance are not equal

For 2 comparisons the rejection level is $F_{(2)0.05, 399, 399} = 1.16$

For 3 comparisons the rejection level is $F_{(2)0.02, 399, 399} = 1.23$

For 4 comparisons the rejection level is $F_{(2)0.01, 399, 399} = 1.26$

TABLE VII. Multiple pairwise comparisons of the Monte Carlo estimates of sample variance of two sample sizes (64 and 128 units) for stratified random sampling.

Sample size	Pattern	M.C.$S^2_{\bar{x}}$	Comparison order	F*	Accept/ reject†
64	16 x 16	0.101	1-2	1.235	A
	32 x 8	0.082	1-3	1.040	A
	8 x 32	0.105	1-4	2.144	R
128	16 x 16	0.047	1-5	2.522	R
	32 x 8	0.040	1-6	1.983	R
	8 x 32	0.051	2-3	1.284	A
			2-4	1.736	R
			2-5	2.042	R
			2-6	1.606	R
			3-4	2.229	R
			3-5	2.622	R
			3-6	2.062	R
			4-5	1.176	A
			4-6	1.081	A
			5-6	1.272	A

* Test of equality of variance $F = M.C.S^2_{\bar{x}_1} / M.C.S^2_{\bar{x}_2}$

† H_o: The two Monte Carlo estimates of sampling variance are equal

H_a: The two Monte Carlo estimates of sampling variance are not equal

For 6 comparisons the rejection level is $F_{(2)0.003, 399, 399} = 1.318$

TABLE VIII. Multiple pairwise comparisons of the Monte Carlo estimates of sampling variance of different sampling methods for a sample size of 64 units.

Sampling method	Pattern	$S^2_{\bar{x}}$	12 pairwise comparisons								
			Comparison order	F*	Accept/ reject†	Comparison order	F*	Accept/ reject	Comparison order	F*	Accept/ reject
Random	-	0.096	1-2	3.597	R	3-5	1.095	A	5-12	3.102	R
			1-3	1.089	A	3-6	1.027	A	6-7	1.143	A
Systematic	8-2	0.027	1-4	1.023	A	3-7	1.173	A	6-8	1.183	A
	4-4	0.088	1-5	1.193	A	3-8	1.152	A	6-9	12.388	R
	2-8	0.094	1-6	1.119	A	3-9	12.064	R	6-10	10.637	R
			1-7	1.278	A	3-10	10.359	R	6-11	8.971	R
Stratified random	16x2	0.080	1-8	1.058	A	3-11	8.737	R	6-12	2.909	R
	8x4	0.086	1-9	11.074	R	3-12	2.833	R	7-8	1.352	A
	4x8	0.075	1-10	9.509	R	4-5	1.166	A	7-9	14.155	R
	2x16	0.101	1-11	8.020	R	4-6	1.094	A	7-10	12.155	R
			1-12	2.601	R	4-7	1.250	A	7-11	10.251	R
Cluster	16x2	1.062	2-3	3.230	R	4-8	1.082	A	7-12	3.324	R
	8x4	0.912	2-4	3.514	R	4-9	11.328	R	8-9	10.470	R
	4x8	0.769	2-5	3.013	R	4-10	9.727	R	8-10	8.990	R
	2x16	0.249	2-6	3.213	R	4-11	8.204	R	8-11	7.582	R
			2-7	2.812	R	4-12	2.660	R	8-12	2.459	R
			2-8	2.802	R	5-6	1.066	A	9-10	1.165	A
			2-9	39.806	R	5-7	1.072	A	9-11	1.381	R
			2-10	34.180	R	5-8	1.262	A	9-12	4.258	R
			2-11	28.828	R	5-9	13.209	R	10-11	1.186	A
			2-12	9.348	R	5-10	11.342	R	10-12	3.656	R
			3-4	1.065	A	5-11	9.566	R	11-12	3.084	R

* Test of equality of variance $F = M.C.S^2_{\bar{x}_1} / M.C.S^2_{\bar{x}_2}$

† H_o: The two Monte Carlo estimates of sampling variance are equal

H_a: The two Monte Carlo estimates of sampling variance are not equal

For 12 comparisons the rejection level is $F(2)\ 0.001, 399, 399 = 1.365$

TABLE IX. Comparison of the equality of two regression coefficient using a Student's t test.

$H_o: \beta_1 = \beta_2$ $\quad b_1 = -0.9942$

$H_a: \beta_1 \neq \beta_2$ $\quad b_2 = -1.11372$

$$Sb_1 - b_2 = \sqrt{\left(S^2_{y.x}\right)_p \left[\frac{1}{\sum x_1^2} + \frac{1}{\sum x_2^2}\right]} \left(S^2_{y.x}\right)_p = 1.83145$$

$Sb_1 - b_2 = 0.0819$

$$\left(S^2_{y.x}\right)_p = \frac{(\text{residual SS})_1 + (\text{residual SS})_2}{(\text{residual DF})_1 + (\text{residual DF})_2} \qquad \nu = n_1 + n_2 - 4 = 60$$

$$t = \frac{b_1 - b_2}{Sb_1 - b_2} = \frac{-0.9942 - (-1.11372)}{0.08019} = 1.42537$$

$t_{0.05(2)60} = 2.000$

H_o is accepted

The two regression coefficients came from the same population

TABLE X. Comparison of the equality of two elevations using a Student's t test.

Regresssion	Σx^2	Σxy	Σy^2	n	b	residual SS	residual DF
Monte Carlo regression	569.369	-49.046	196.528	32	-0.999	192.303	30
Population regression	569.369	-54.654	226.847	32	-1.114	221.600	30
Pooled regression						413.904	60
"Common" regression	1,138.737	-103.700	423.375		-0.091	413.931	61

$H_o: \alpha_1 = \alpha_2$ $\quad \bar{Y}_1 - \bar{Y}_2 = 0.1302$

$H_s: \alpha_1 \neq \alpha_2$ $\quad \bar{x}_1 - \bar{x}_2 = 0$

$\left(S^2_{y.x}\right)_c = SS_c/DF_c$ $\quad 1/n_1 = 1/n_2 = .0316$

$$b_c = \frac{(\Sigma xy)_1 + (\Sigma xy)_2}{(\Sigma x^2)_1 + (\Sigma x^2)_2} \qquad \left(S^2_{y.x}\right)_c = 6.7858$$

$$\nu = n_1 + n_2 - 3 = 61$$

$$t = \frac{(\bar{Y}_1 - \bar{Y}_2) - b_c(\bar{x}_1 - \bar{x}_2)}{\left[\left(S^2_{y.x}\right)_c \left[\frac{1}{n_1} + \frac{1}{n_2} + \frac{(\bar{x}_1 - \bar{x}_2)^2}{(\Sigma x_1^2) + (\Sigma x_2^2)}\right]\right]^{1/2}} = \frac{0.1302}{\left[6.7858(0.0425)\right]^{1/2}} = 0.632$$

$t_{0.05(2),\,61} = 1.995$

H_o is accepted

The two regression lines have the same elevation

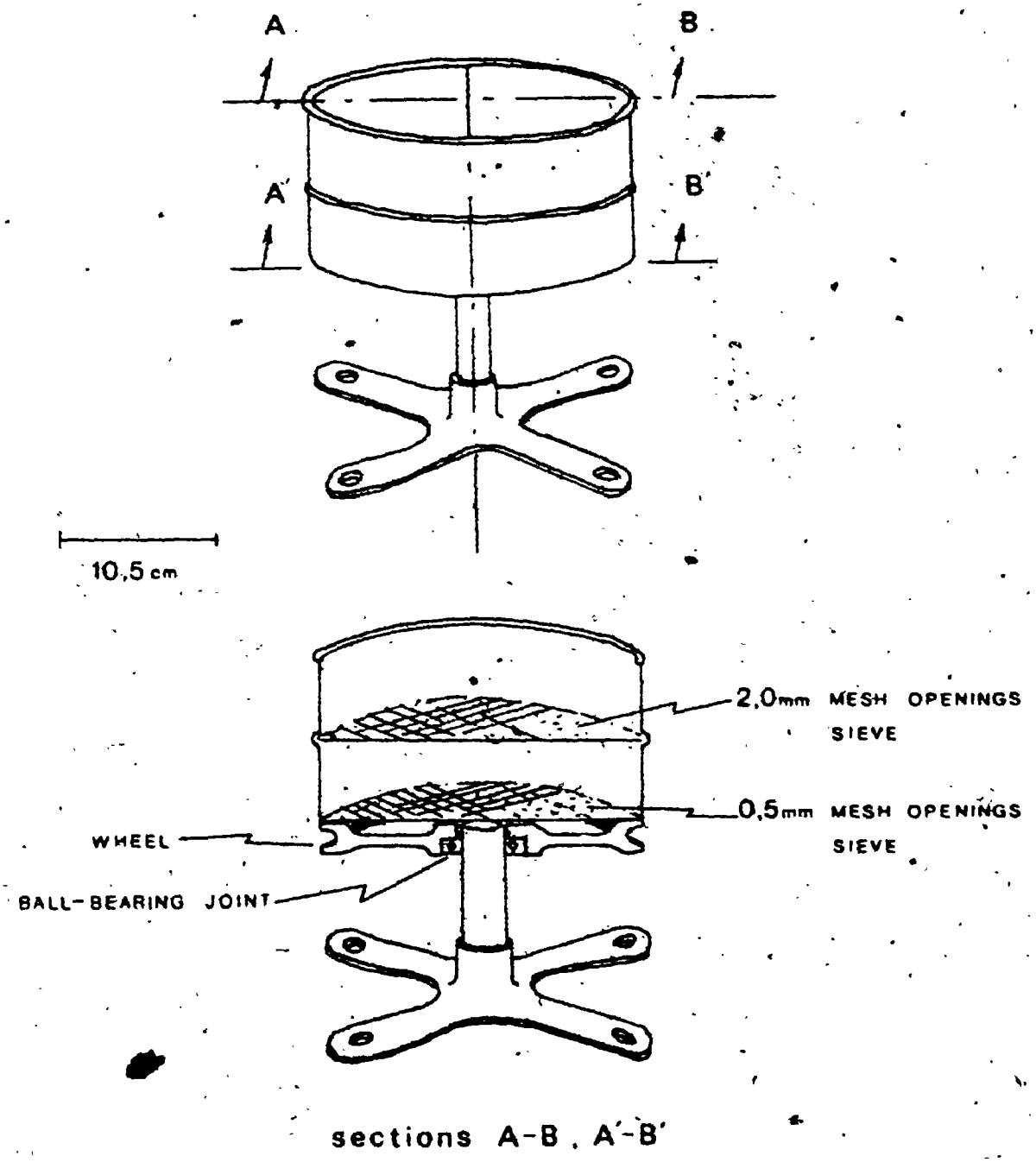
APPENDIX E

SUPPLEMENTAL SCHEMATIC REPRESENTATIONS

APPENDIX E

APPENDIX E

Figure I Diagram of equipment used to wash soil samples.



sections A-B , A'-B'

Figure II. Plotting of the residuals $(Y-\hat{Y})$ as a function of their corresponding sample sizes. a) The residuals of the population sampling variance (Ln); b) The residuals of the Monte Carlo estimate of sampling variance (Ln).

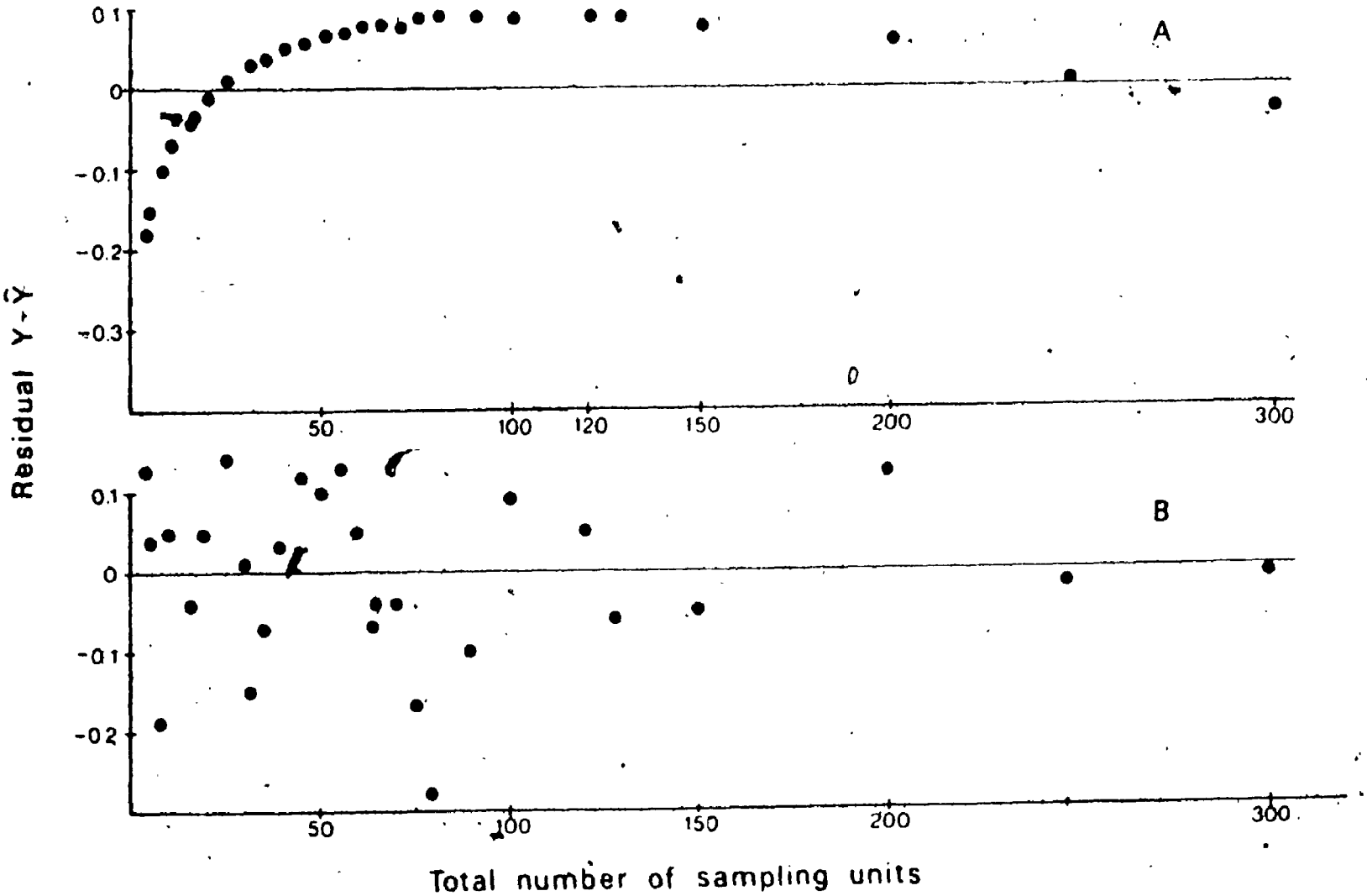

Residual Y-Ŷ
0.1
0
-0.1
-0.2
-0.3
A
50
100
120
150
200
300
0.1
0
-0.1
-0.2
B
50
100
150
200
300
Total number of sampling units

Figure III. Schematic diagram of fields 1, 2, 3 and 4 on Mr. Tucsok's farm, Oxford County, Ontario. Numbers refer to field identification codes. Strata are delineated by thick lines —— and clusters are drawn with thin lines ——. The location of the randomly chosen clusters from each field are illustrated by ⬚.

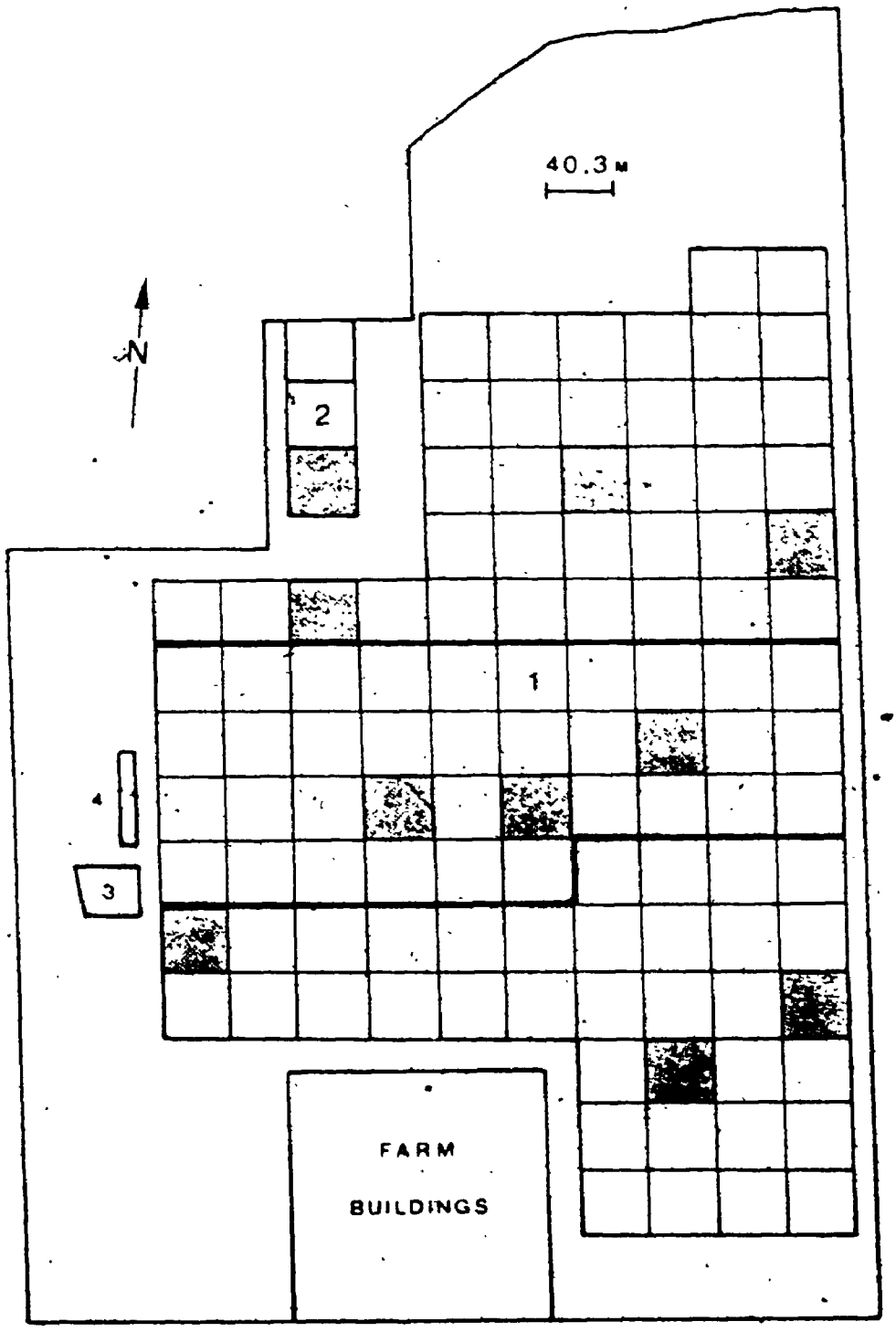

40.3 M
N
2
1
4
3
FARM
BUILDINGS

Figure IV. Schematic diagram of fields 5, 6 and 7 on Mr. Tuesok's farm, Oxford County, Ontario. Numbers refer to field identification codes. Strata are delineated by thick lines —— and clusters are drawn with thin lines ——. The location of the randomly chosen clusters from each field are illustrated by  .

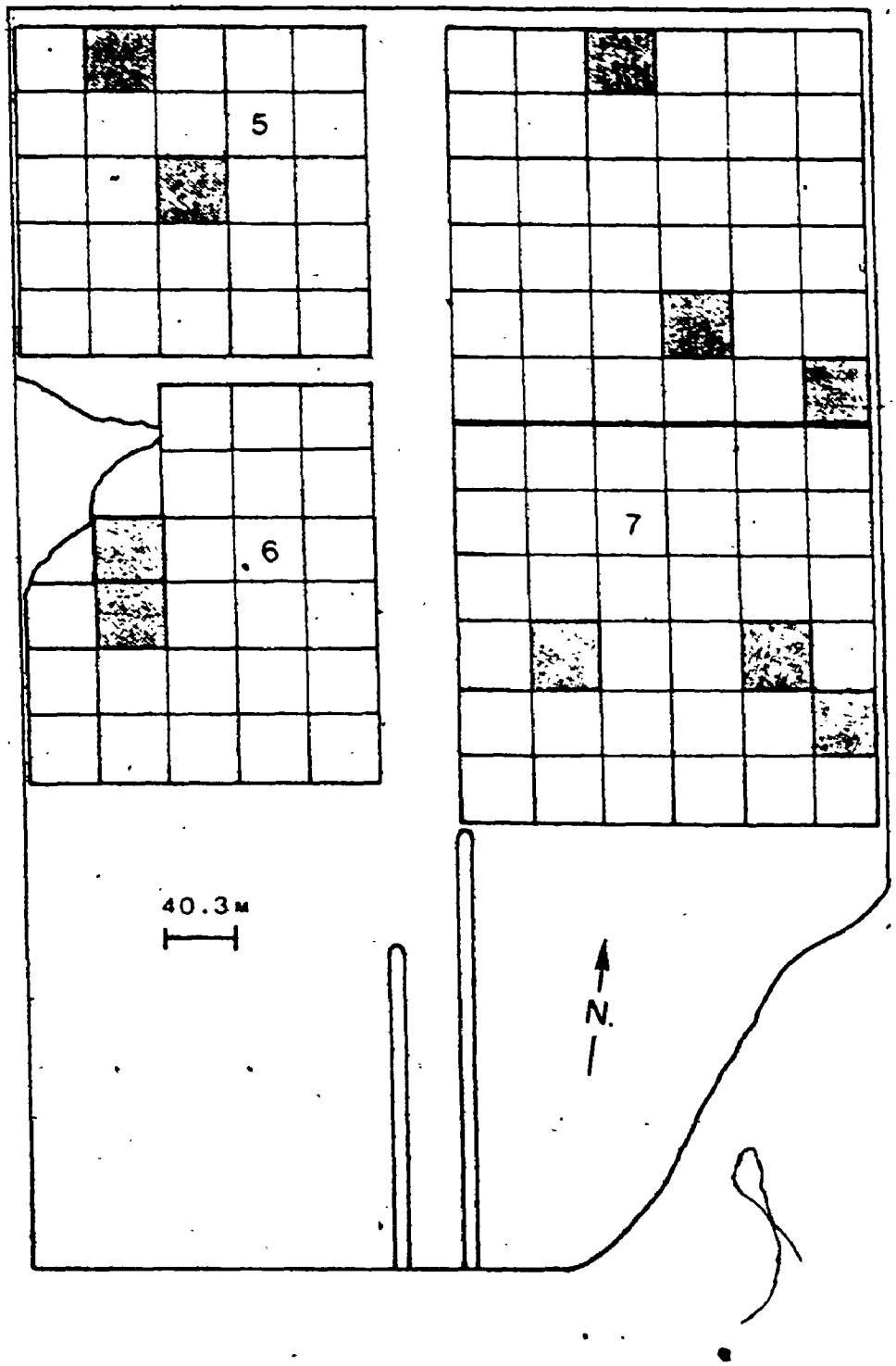

5
6
7
40.3M
N.

Figure V. Schematic diagram of field-8 on Mr. Tucsok's farm, Oxford County, Ontario. Numbers refer to field identification codes. Strata are delineated by thick lines — and clusters are drawn with thin lines ——. The location of the randomly chosen clusters from each field are illustrated by ⊡.

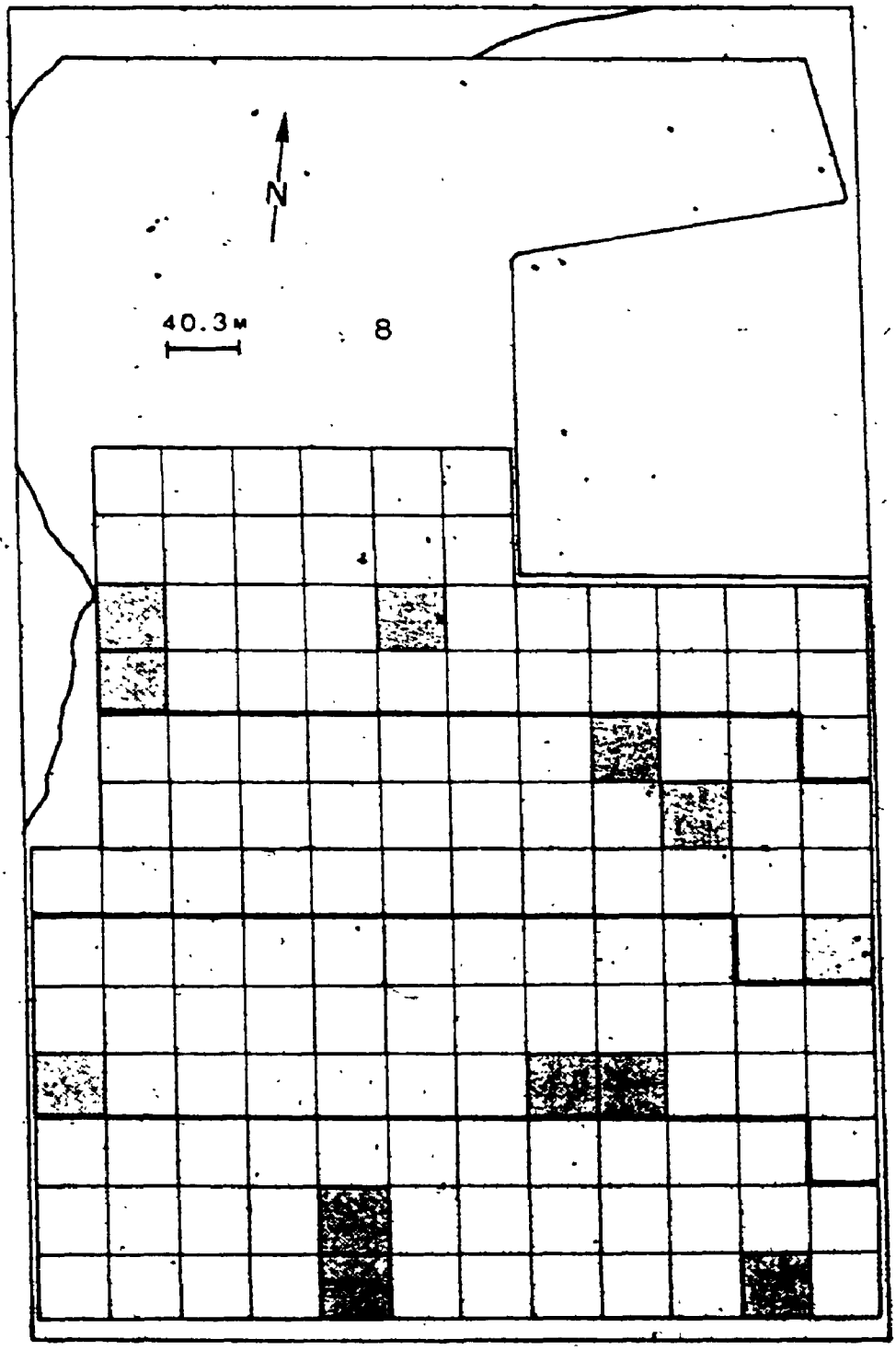

N
40.3м
8

Figure VI. Plotting of the residuals $(Y - \hat{Y})$ of the total number of Chenopodium spp. seeds/m^2 ($\sqrt{x + 0.5}$). A) as a function of the corresponding fields and B) as a function of the corresponding clusters of field 1. There are 87 hidden observations in figure VI-A. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.

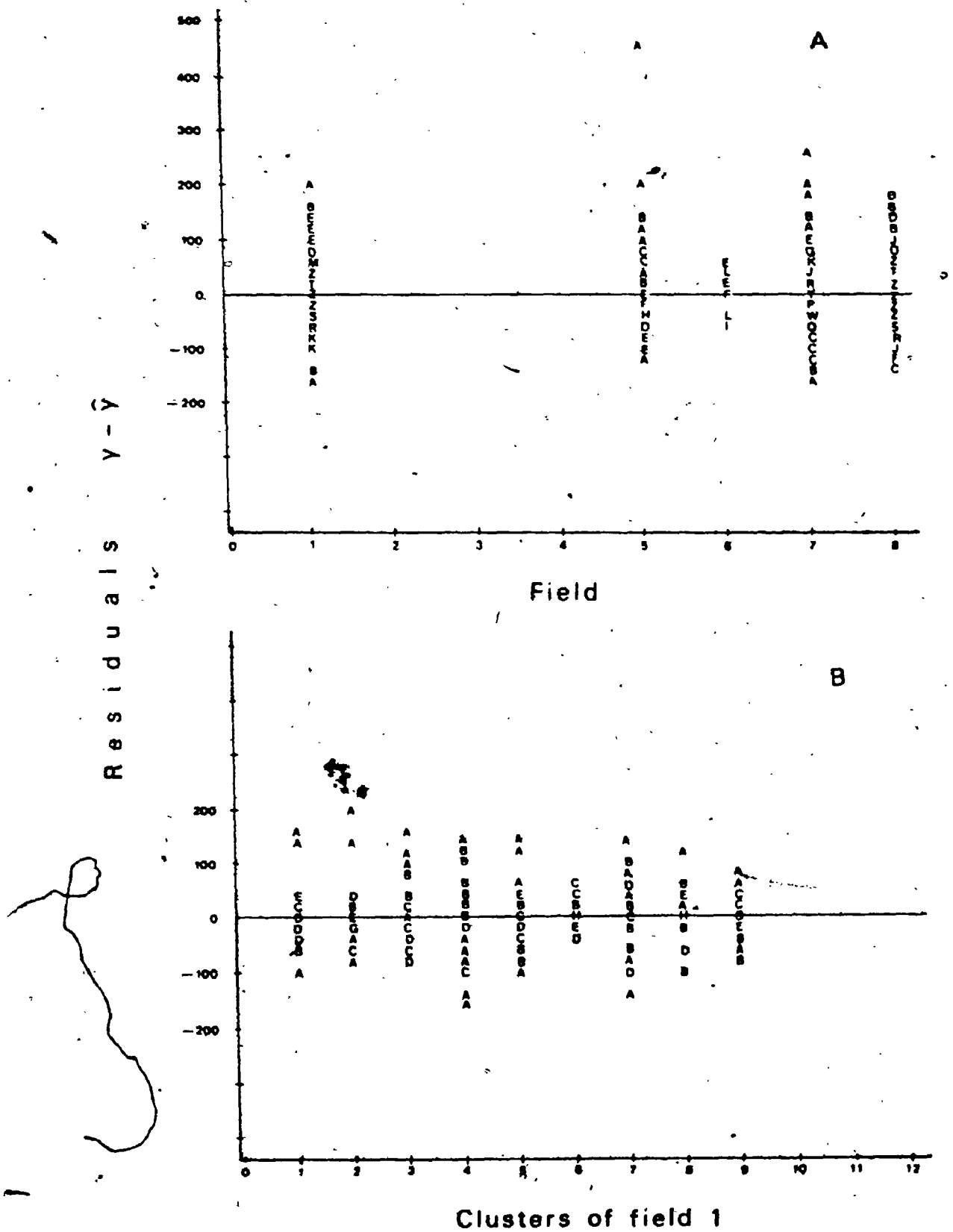

A
B
Residuals $y - \hat{y}$
Field
Clusters of field 1

Figure VII. Plotting of the residuals $(Y - \hat{Y})$ of the total number of Chenopodium spp. seeds/m^2 $(\sqrt{x + 0.5})$. A) as a function of the corresponding clusters of field 5 and B) as a function of the corresponding clusters of field 6. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.

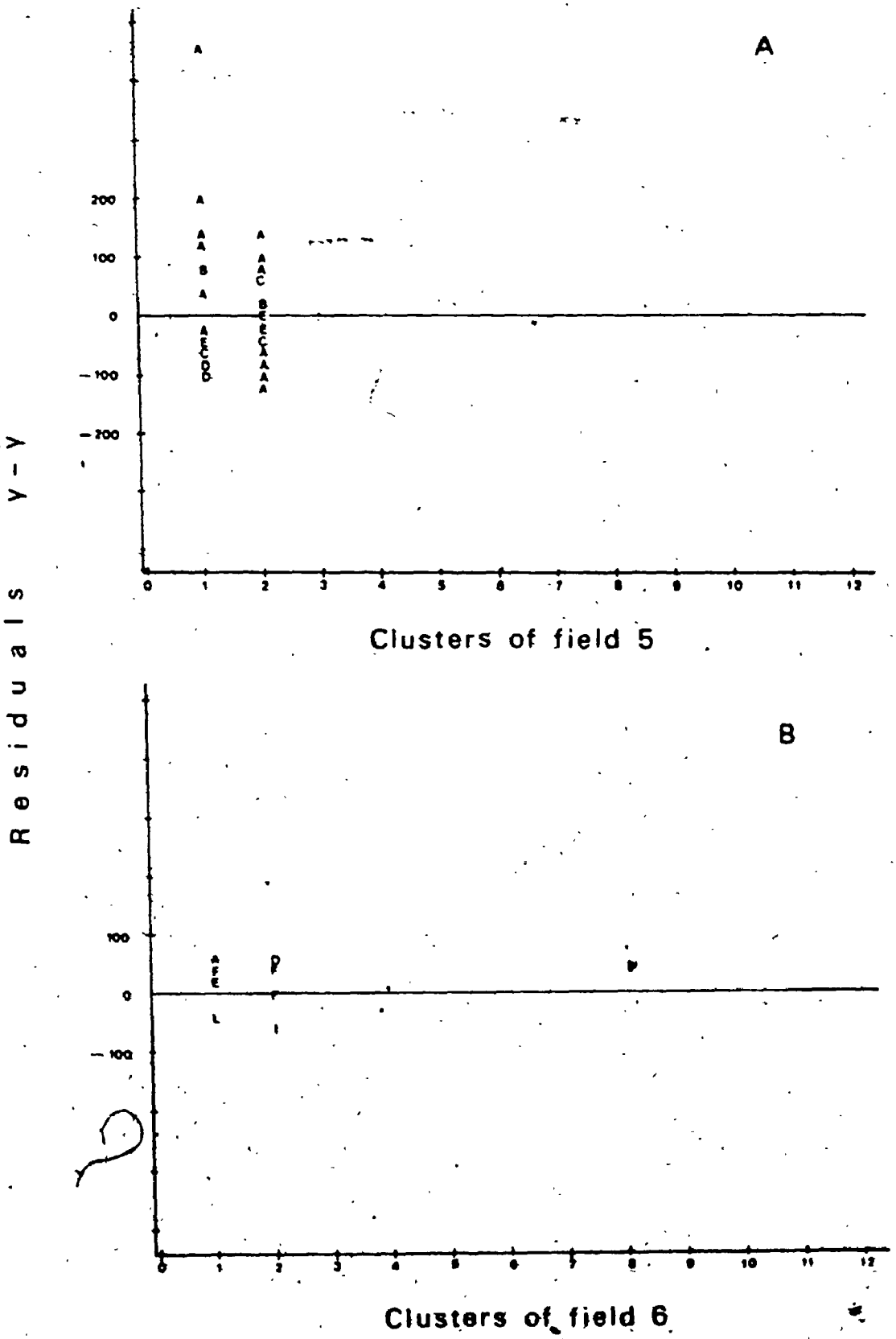
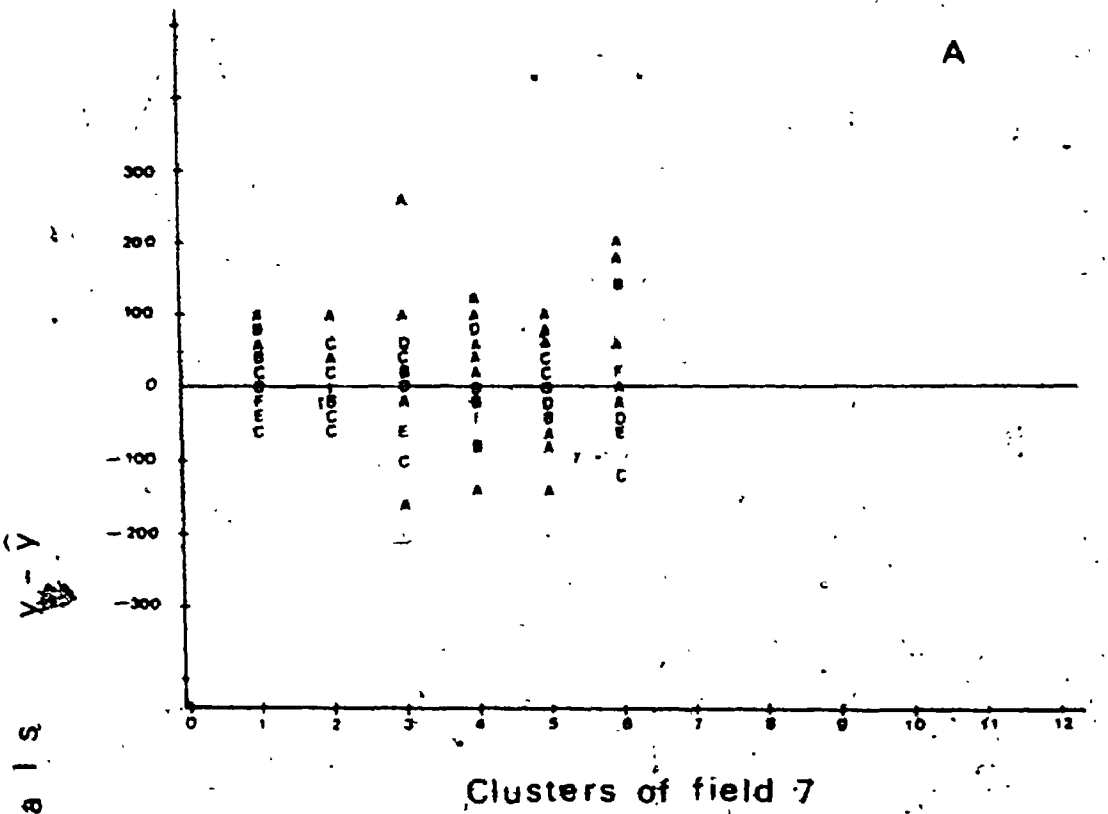
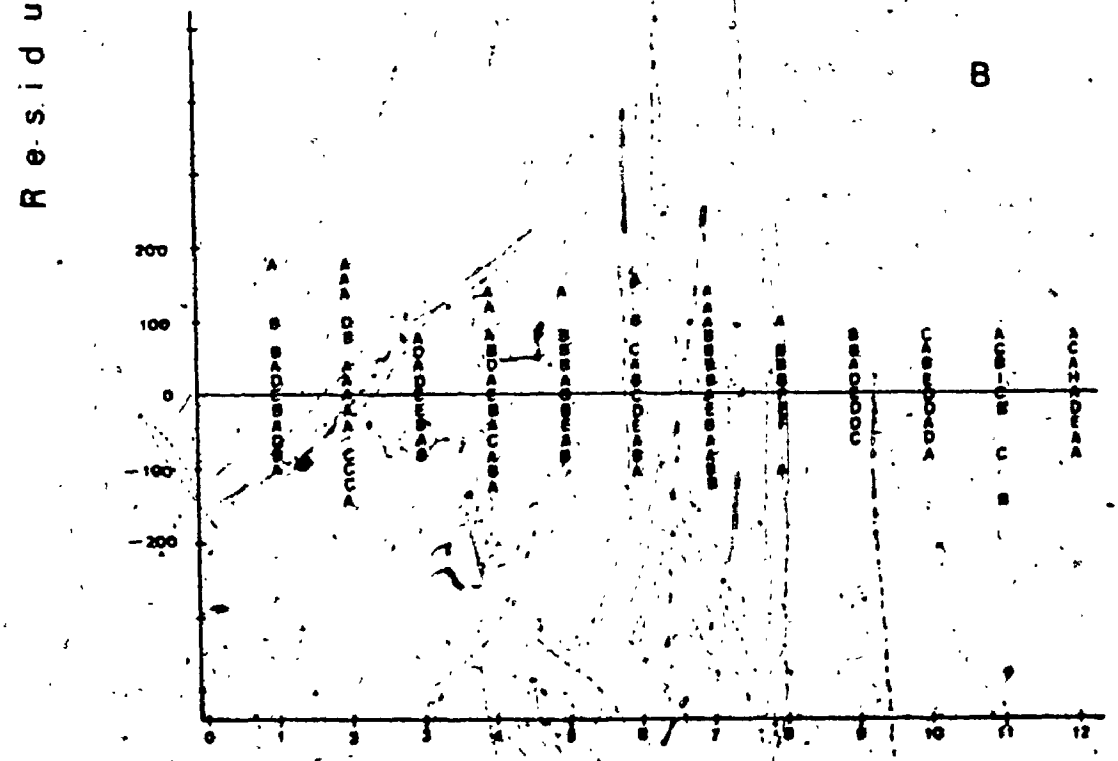

A
200
100
0
−100
−200
0 1 2 3 4 5 6 7 8 9 10 11 12
Clusters of field 5
B
100
0
−100
0 1 2 3 4 5 6 7 8 9 10 11 12
Clusters of field 6
Residuals y − ŷ

Figure VIII. Plotting of the residuals $(Y - \hat{Y})$ of the total number of Chenopodium spp. seeds/m^2 $(\sqrt{x + 0.5})$. A) as a function of the corresponding clusters of field 7 and B) as a function of the corresponding clusters of field 8. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.



Clusters of field 7



Clusters of field 8

Residuals $y - \hat{y}$

Figure IX. Plotting of the residuals $(Y - \hat{Y})$ of the total number of black Chenopodium spp. seeds/m^2 $(\sqrt{x + 0.5})$. A) as a function of the corresponding fields and B) as a function of the corresponding clusters of field 1. There are 98 hidden observations in figure IX-A. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.

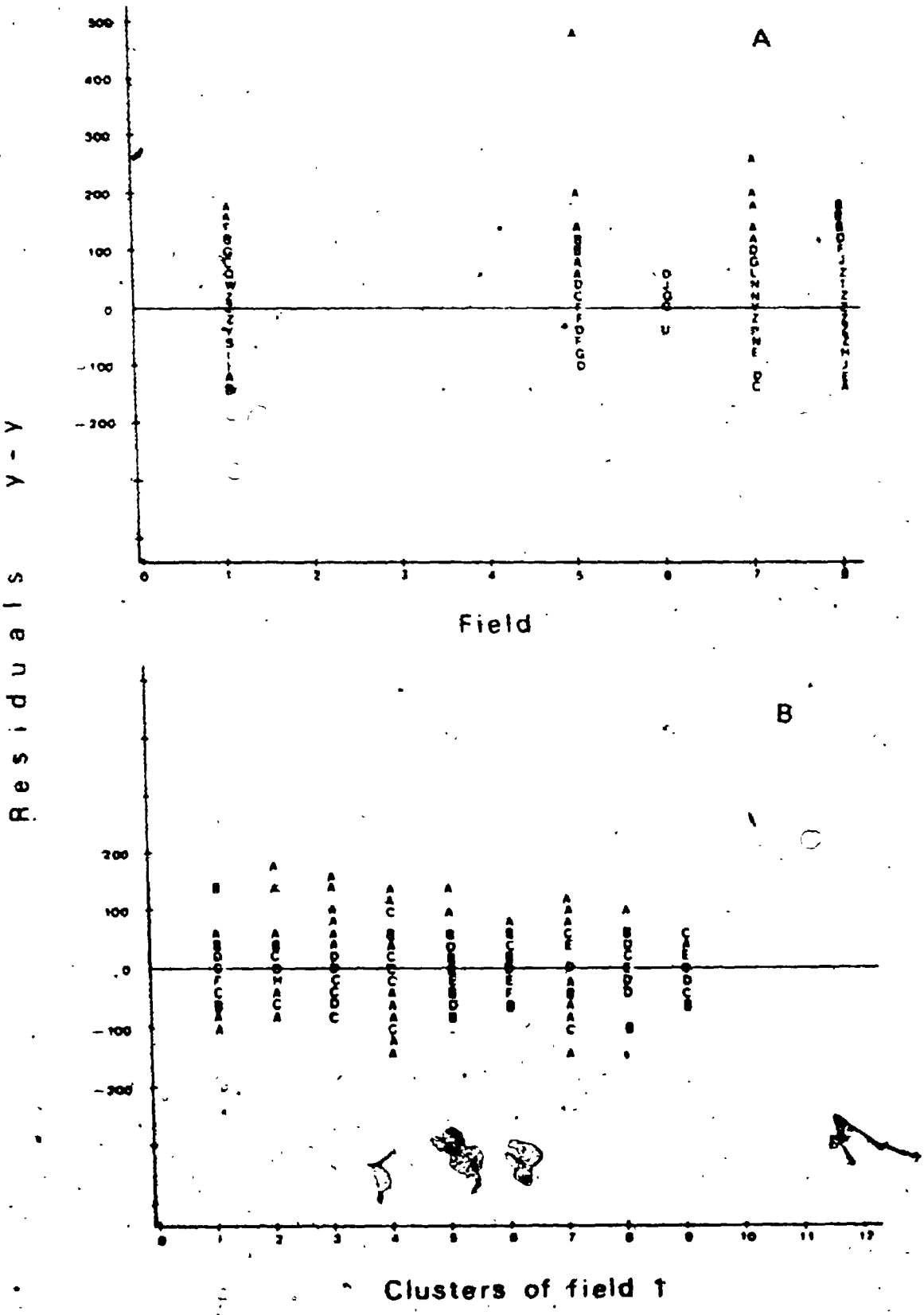
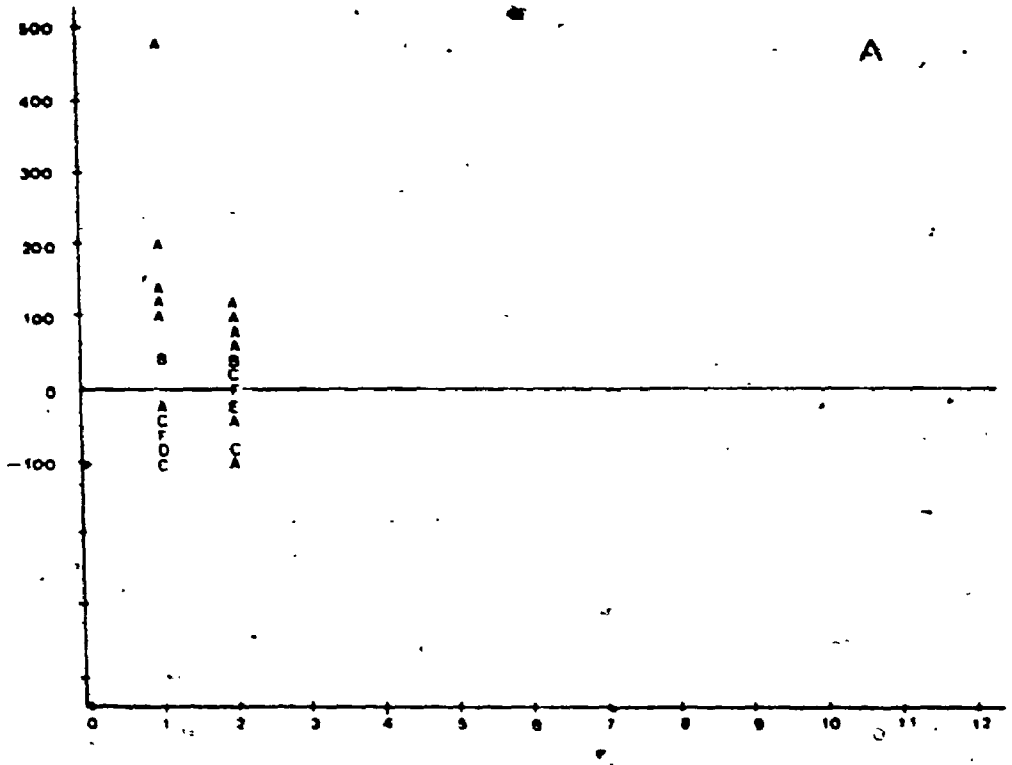
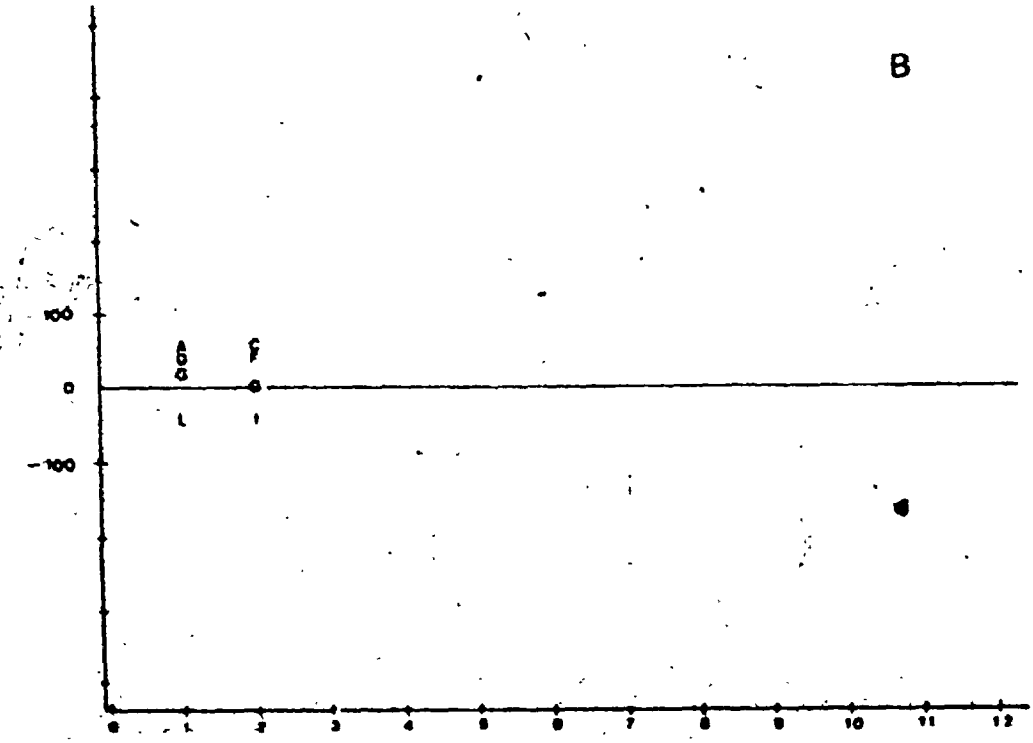

A
B
Residuals y - ŷ
Field
Clusters of field 1

Figure X. Plotting of the residuals $(Y - \hat{Y})$ of the total number of black Chenopodium spp. seeds/m^2 ($\sqrt{x + 0.5}$). A) as a function of the corresponding clusters of field 5 and B) as a function of the corresponding clusters of field 6. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.



Clusters of field 5



Clusters of field 6

Residuals $y - \hat{y}$

Figure XI. Plotting of the residuals $(Y - \hat{Y})$ of the total number of black Chenopodium spp. seeds/m^2 $(\sqrt{x + 0.5})$. A) as a function of the corresponding clusters of field 7 and B) as a function of the corresponding clusters of field 8. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.

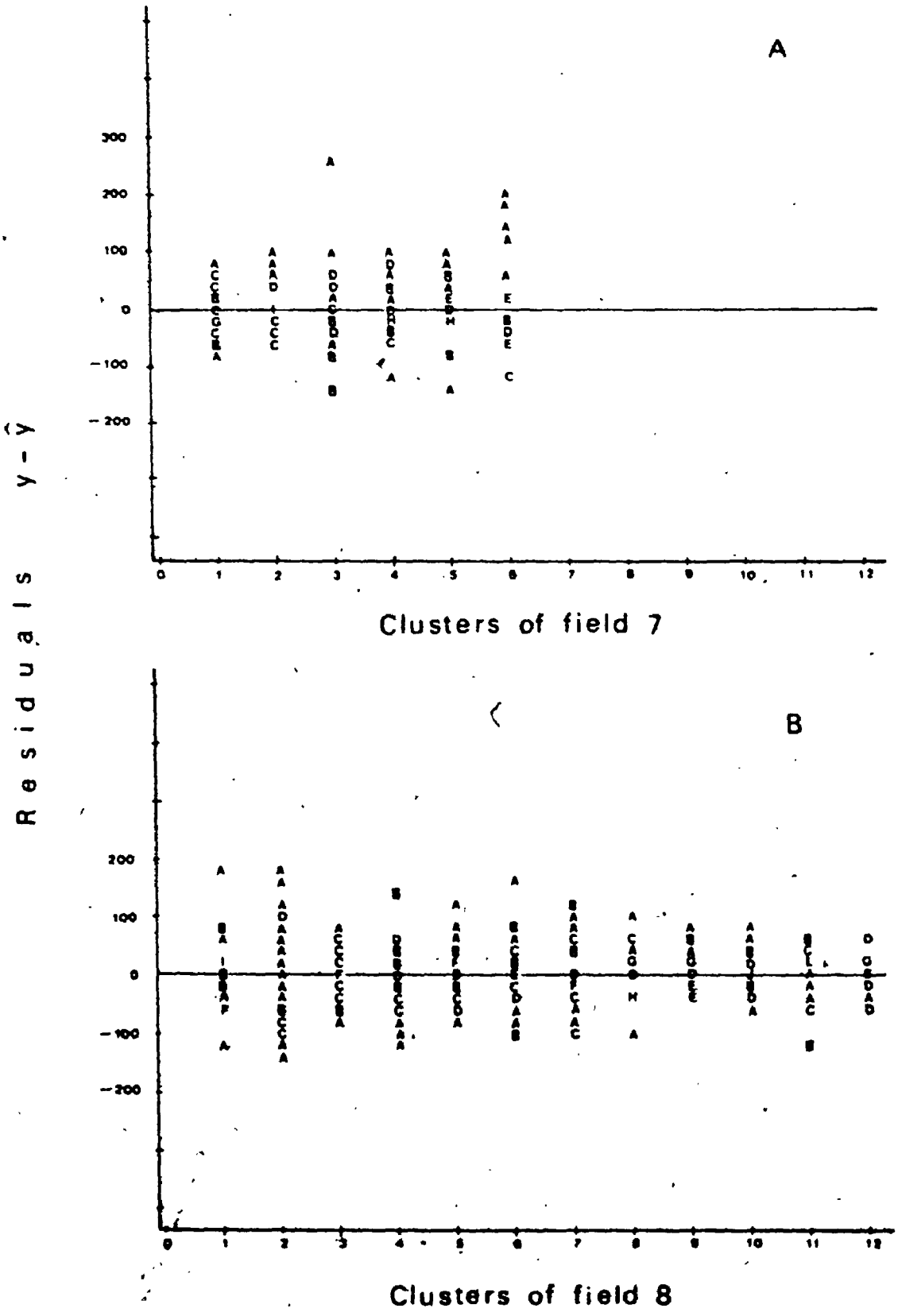

A
B
Residuals $y - \hat{y}$
Clusters of field 7
Clusters of field 8

Figure XII. Plotting of the residuals $(Y - \hat{Y})$ of the total number of brown Chenopodium spp. seeds/m^2 $(\sqrt{x + 0.5})$. A) as a function of the corresponding fields and B) as a function of the corresponding clusters of field 1. There are 51 hidden observations in figure XII-A. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.

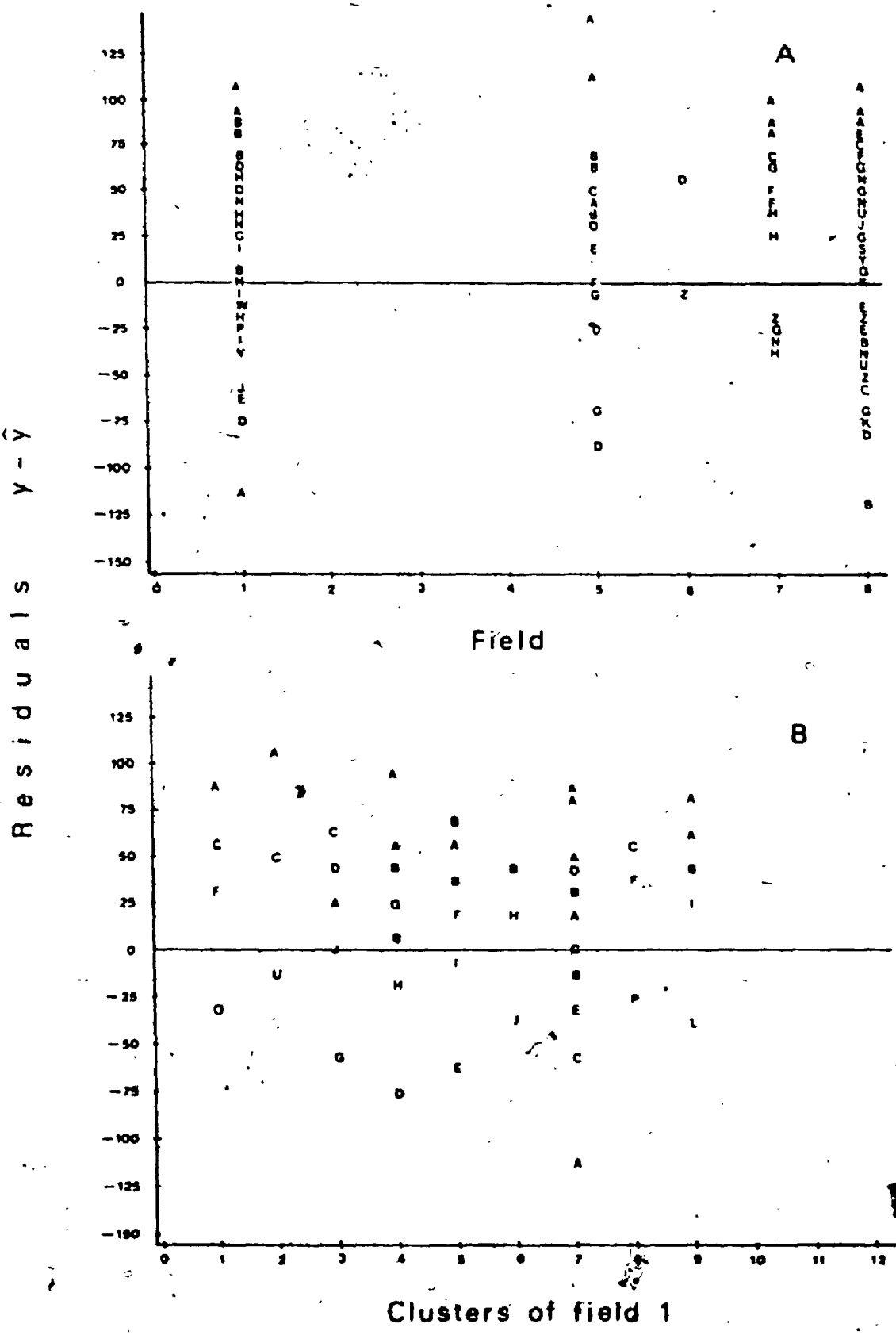
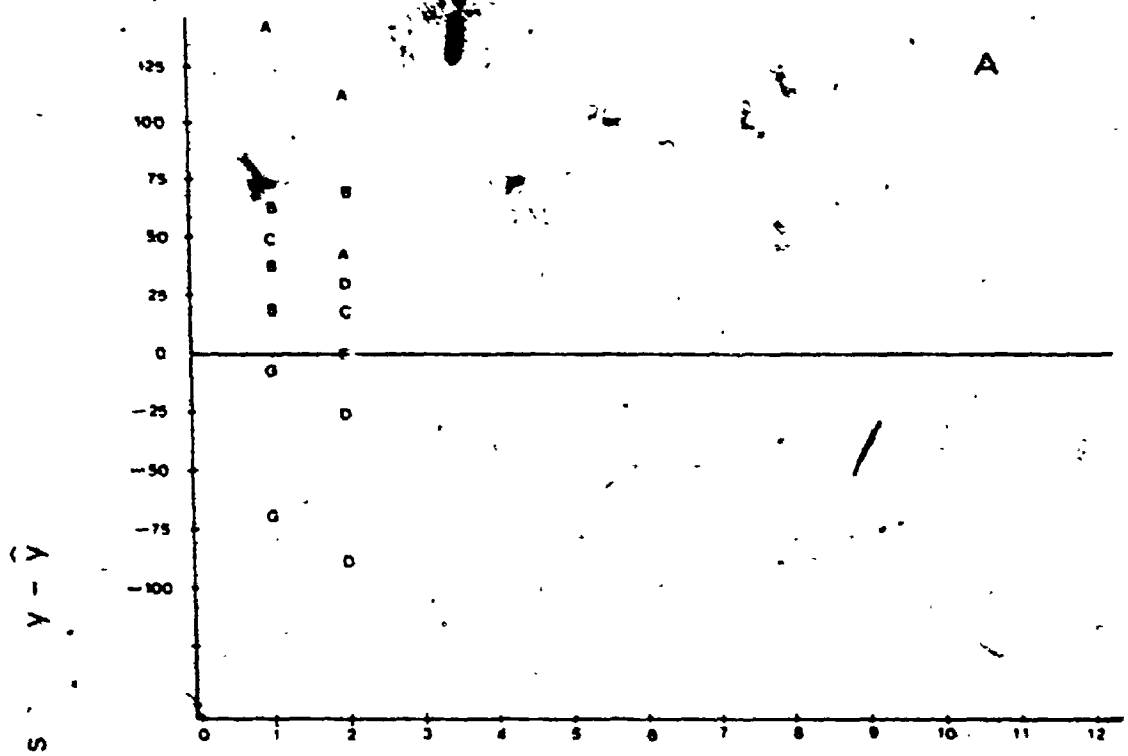
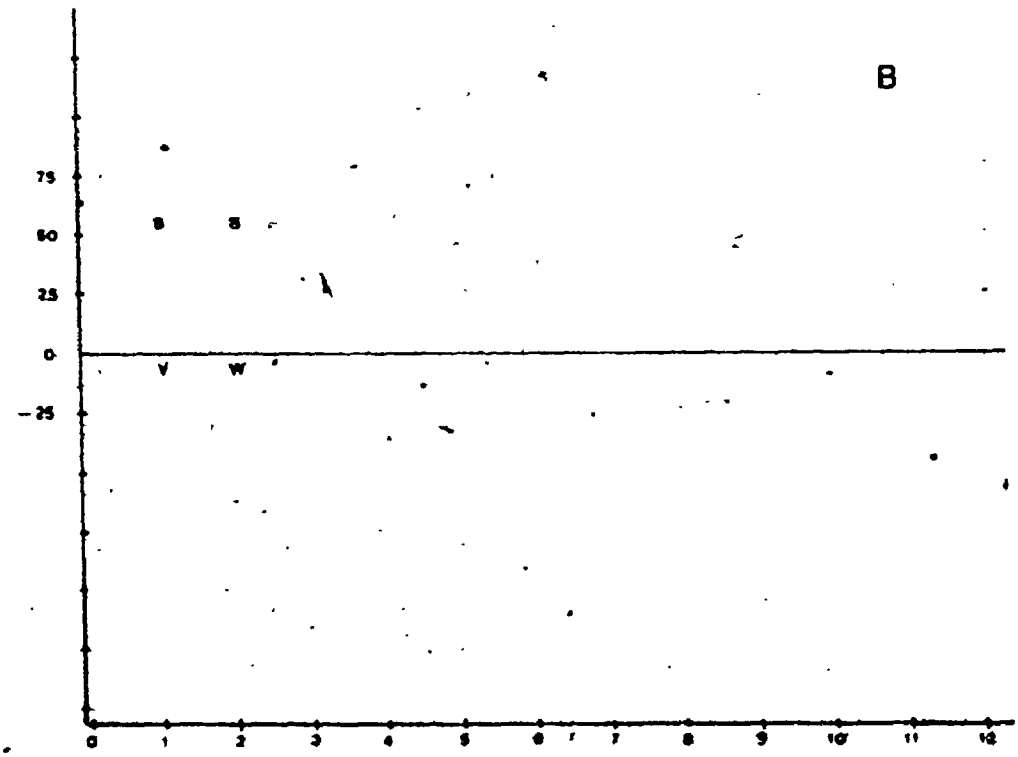

A
B
Residuals y - ŷ
Field
Clusters of field 1

Figure XIII. Plotting of the residuals $(Y - \hat{Y})$ of the total number of brown Chenopodium spp. seeds/m^2 ($\sqrt{x + 0.5}$). A) as a function of the corresponding clusters of field 5 and B) as a function of the corresponding clusters of field 6. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.



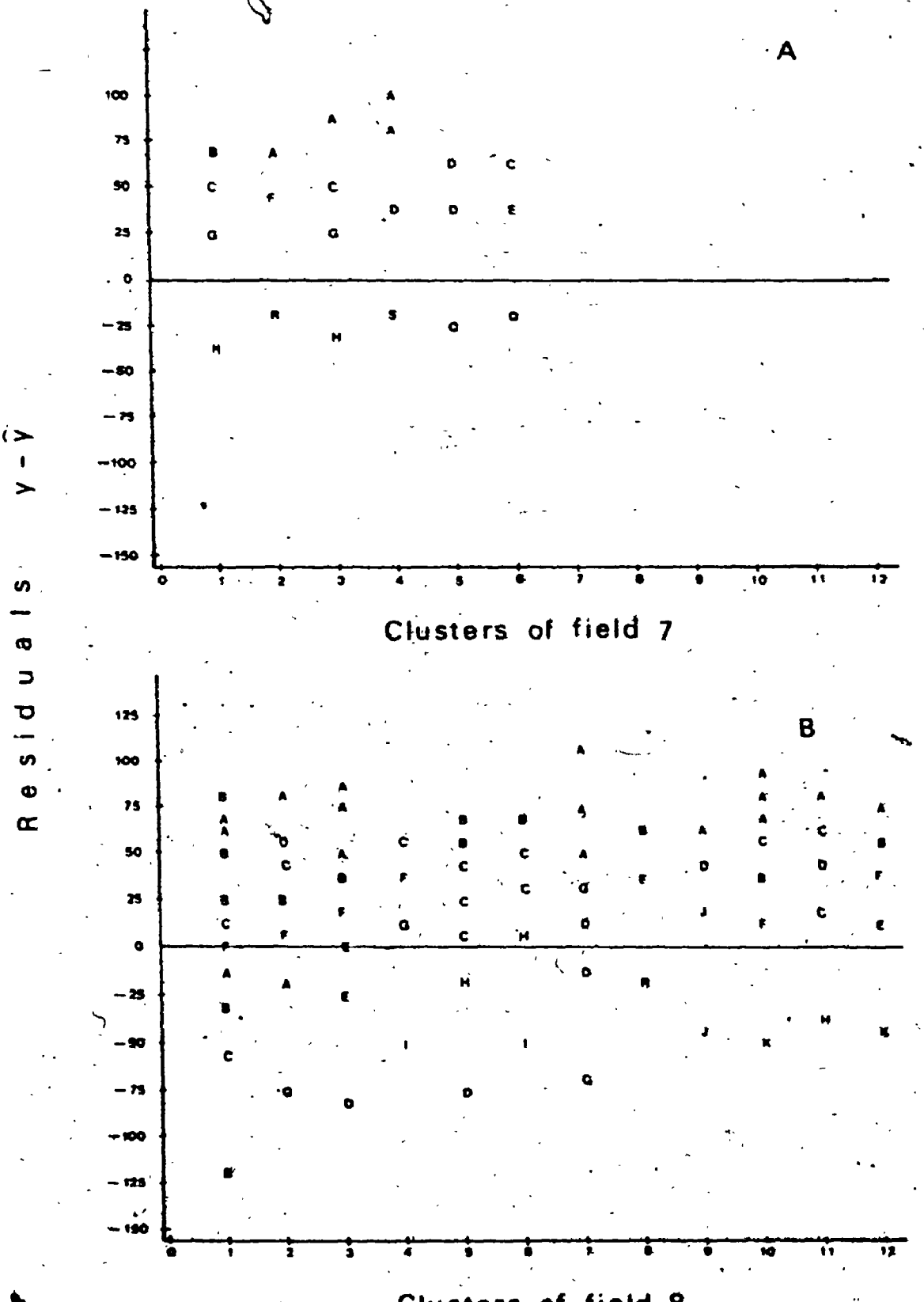
Residuals $y - \hat{y}$

Clusters of field 5



Clusters of field 6

Figure XIV. Plotting of the residuals $(Y - \hat{Y})$ of the total number of brown Chenopodium spp. seeds/m^2 ($\sqrt{x + 0.5}$). A) as a function of the corresponding clusters of field 7 and B) as a function of the corresponding clusters of field 8. Letters of the alphabet represent increasing number of observations: A=1, B=2, C=3, ..., Z=26.


A
B
Residuals y - ŷ
Clusters of field 7
Clusters of field 8

APPENDIX F

MULTIPLE PAIRWISE COMPARISONS OF SAMPLING VARIANCE

Bartlett's test for homogeneity of variance is based on the M statistic which approximates the chi-square distribution with n - 1 degrees of freedom (Snedecor and Cochran, 1980, p. 252). However, it is affected adversely by non-normal populations (Zar, 1974; Snedecor and Cochran, 1980). In this case the underlying distribution of sampling variance is assumed to be normal since a minimum of 400 random sampling events were conducted to calculate the Monte Carlo estimate of sampling variance (see Snedecor and Cochran, 1980 for further explanations). It is these estimates which were tested for homogeneity with the Bartlett's test.

If the null hypothesis (H_o) for Bartlett's test (H_o: the variance are equal) is rejected, then pairwise comparisons of variance using an F test follows. However, it should be remembered that several comparisons are usually considered invalid to test a multisample hypothesis (Snedecor and Cochran, 1980, p. 130).

As the number of items to be compared increases so does the chance of making a Type I error (i.e. rejecting a true H_o) (Snedecor and Cochran, 1980, p. 130). The probability of such an error is α (the level at which H_o is rejected). If the level of probability of any such error is to be maintained, the probability of a Type I error for any of all possible pairs of comparisons (α') must be so small that their summation does not exceed the desired α. This results in a conservative

test since the small α' give very few significant differences between individual pairwise comparisons (Sokal and Rohlf, 1981, p. 243).

$$\alpha' = \alpha' \frac{k(k-1)}{2}$$

where α = desired probability level

α' = probability level of any pairwise comparison

$\frac{k(k-1)}{2}$ = number of all possible comparisons of k items

The α' was calculated for each number of the different Monte Carlo estimates of sampling variance to be compared.

Total number of Monte Carlo estimates of sampling variance to be compared	Rejection level for each pairwise comparisons (α')
3	0.02
4	0.01
5	0.005
6	0.003
8	0.002
10,11,12	0.001

Using the desired α' as the probability of rejection of any null hypothesis (H_0: the sampling variances are equal), the critical F value to be used for the F test was calculated using the 'FPROBS' program (Orloci and Kenkel, 1985).

APPENDIX G

SUMMARIES OF THE ANALYSIS OF VARIANCE ON THE MEAN NUMBER OF *Chenopodium* spp. SEEDS/m^2 AND THE RATIOS OF THE VARIOUS SEED CATEGORIES IN DIFFERENT FIELDS ON TUCSOK'S FARM, OXFORD COUNTY, ONTARIO, IN JULY, 1982

APPENDIX C

Table I. A summary of analyses of variance on the mean number of *Chenopodium* spp. seeds/m^2 in different cultivated fields on Tucsok's farm, Oxford County, Ontario, in July 1982 †

Seed ‡ category (Mean number/m^2)	Source of variation			
	Model	Field	Stratum within field	Cluster within field and stratum
	F value	F value	F value	F value
Seed total	41.53****	5.11**	2.29 NS	22.99****
Black seeds	41.11****	4.86**	2.28 NS	23.24****
Brown seeds	13.4 ****	5.14**	2.02 NS	7.43****
Whole seeds	15.19****	8.37***	2.02 NS	6.95****
Damaged seeds	39.75****	4.93**	2.42 NS	22.00****
Underdeveloped seeds	20.71****	3.69*	2.25 NS	12.88****
Whole black seeds	14.56****	7.83***	2.09 NS	6.84****
Whole brown seeds	3.16****	7.8 ***	0.93 NS	1.67*

† The analysis of variance was done on the transformed variables. The transformation was $(x + 0.5)^{1/2}$ for all variables except for the number of whole brown seeds/m^2. This latter variable was ranked and an analysis of variance was performed on the ranks. The degrees of freedom were distributed as follows: model = 30, field = 4, stratum within field = 6, cluster within stratum and field = 20, error = 740,

* = significant at the 0.05 level
** = significant at the 0.01 level
*** = significant at the 0.001 level
**** = significant at the 0.0001 level
NS = non significant

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa.

Table 11. A summary of the mean number of Chenopodium spp. seeds/m^2 in different cultivated fields on Tucsok's farm, Oxford County, Ontario, in July 1982 †

Field Number	Seed category ‡ (Mean number/m^2)							
	Seed. Total	Black seeds	Brown seeds	Whole seeds	Damaged seeds	Underdeveloped seeds	Whole black seeds	Whole brown seeds
1	39 309ab§	35 365ab	2 553	2 621b	23 966ab	9 268ab	2 569ab	63b
5	80 312a	71 850a	6 022	11 829a	43 613a	22 354a	10 790a	792a
6	2 056b	1 888b	30	0b	664b	668b	0b	0b
7	19 761ab	18 196ab	625	802b	10 951ab	5 370ab	715b	47b
8	42 540a	37 361ab	3 562	2 917b	25 108a	10 751ab	2 747ab	224b

† Data represents the retransformed values $[(x')^2 - 0.5]$ of all variables except for the number of whole brown seeds/m^2 which are given as the original values.
Field 1 = mean of 224 soil samples
Fields 5 and 6 = mean of 49 soil samples
Field 7 = mean of 150 soil samples
Field 8 = mean of 299 soil samples

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

§ Numbers of seeds in the same column followed by different letters are significantly different at 0.05 level using Scheffé's multiple contrasts test.

Table III. A summary of an analysis of variance on the mean number of *Chenopodium* spp. seeds/m^2 in two fallow fields (fields 3 and 4) on Tucsok's farm, Oxford County, Ontario, in July 1982 †

Seed ‡ category (Mean number/m^2)	Source of variation: Field	
	MS	F value
Total number of seeds	110305	3.09 NS
Black seeds	181792	6.16 *
Brown seeds	9649	0.95 NS
Whole seeds	3440	0.5 NS
Damaged seeds	87886	4.97 *
Underdeveloped seeds	55433	3.55 NS
Whole black seeds	555	0.09 NS
Whole brown seeds	7965	-5.04 *

† The analysis of variance was done on the transformed variables. The transformation was $(x + 0.5)^{\frac{1}{2}}$. The degrees of freedom were distributed as follows: model = 1, field = 1, error = 39.
* = significant at the 0.05 level
NS = non significant

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

Table IV. A summary of the mean number of Chenopodium spp. seeds/m^2 in two fallow fields (fields 3 and 4) on Tucsok's farm, Oxford County, Ontario, in July 1982 †

Field Number	Seed category ‡ (Mean number/m^2)							
	Seed Total	Black seeds	Brown seeds	Whole seeds	Damaged seeds	Underdeveloped seeds	Whole black seeds	Whole brown seeds
3	134 360	94 655a §	34 832	21 512	59 792a	48 811	16 826	3 124a
4	223 619	197 283b	24 082	16 357	115 218b	87 799	14 926	746b

† Data represents the retransformed values $[(x')^2 - 0.5]$ of all variables
Field 3 = mean of 25 soil samples
Field 4 = mean of 16 soil samples

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed testa around the embryo but with no visible damage to the testa

§ Numbers of seeds in the same column followed by different letters are significantly different at 0.05 level.

Table V. A summary of analyses of variance on the ratios of different Chenopodium spp. seed categories in different cultivated fields on Tucsok's farm, Oxford County, Ontario, in July 1982†

Seed category‡	Source of variation			
	Model	Field	Stratum within field	Cluster within field and stratum
	F value	F value	F value	F value
Ratio to total number of seeds				
Total number of black seeds	3.49****	4.63**	1.08NS	2.31***
Total number of brown seeds	3.49****	4.63**	1.08NS	2.31***
Total number of whole seeds	4.38****	13.08****	2.48NS	1.51NS
Total number of damaged seeds	1.91**	2.89NS	5.28**	0.92NS
Total number of underdeveloped seeds	2.14***	1.81NS	2.22NS	1.56NS
Ratio to total number of black seeds				
Number of whole black seeds	4.04****	12.59****	2.50NS	1.42NS
Number of damaged black seeds	1.87**	3.22*	7.43***	0.72NS
Number of underdeveloped black seeds	2.40****	2.70NS	4.99**	1.16NS
Ratio to total number of brown seeds				
Number of whole brown seeds	2.44****	4.98**	1.11NS	1.51NS
Number of damaged brown seeds	2.19***	1.05NS	1.36NS	2.09**
Number of underdeveloped brown seeds	2.16***	0.71NS	0.55NS	2.58***
Ratio to total number of whole seeds				
Number of whole black seeds	2.18***	5.12**	0.88NS	1.47NS
Number of whole brown seeds	2.18***	5.12**	0.88NS	1.47NS
Ratio to total number of damaged seeds				
Number of damaged black seeds	3.23****	3.[illegible]7*	2.42NS	2.02**
Number of damaged brown seeds	3.23****	3.[illegible]7*	2.42NS	2.02**
Ratio to total number of underdeveloped seeds				
Number of underdeveloped black seeds	3.29****	2.72NS	1.07NS	2.70****
Number of underdeveloped brown seeds	3.29****	2.72NS	1.07NS	2.70****

† The analysis of variance was done on the ranked values of the dependent variable. The degrees of freedom were distributed as follows: model = 30, field = 4, stratum within field = 6, cluster within stratum and field = 20, error = 748.

NS = non significant
* = significant at the 0.05 level
** = significant at the 0.01 level
*** = significant at the 0.001 level
**** = significant at the 0.0001 level

‡ Whole seed = plump seed with no visible damage to the testa
Damaged seed = plump seed with visible damage to the testa
Underdeveloped seed = seed with wrinkled or collapsed around the embryo but with no visible damage to the testa

REFERENCES

Alex, J.F. 1964. Weeds of tomato and corn fields in two regions of Ontario. Weed Res. 4: 308-318.

Alex, J.F. and McLaren, R.D. 1983. Triazine resistance: the occurrence and increase in resistance among Ontario weed species previously susceptible to triazine herbicides. Weed Science Soc. Amer: Abstr. Poster Session.

Alex, J.F., Cayouette, R. and Mulligan, G.A. 1980. Common and botanical names of weeds in Canada. Expert Committee on Weeds. Canadian Agricultural Services Coordinating Committee Research Branch, Agriculture Canada, Publ. 1397.

Allott, D.J. 1970. Non-cultivation a success in 10-year raspberry soil trial. The Grower 3: 35-36.

Andrew, M.H. and Mott, J.J. 1983. Annuals with transient seed banks: the population biology of indigenous Sorghum species of tropical north-west Australia. Aust. J. Ecol. 8: 265-276.

Anonymous. 1973. Aatrex tolerance pigweed in Washington. Weeds Today 4: 17.

Anonymous. 1982. SAS user's guide: statistics, 1982 edition. SAS Institute Inc. Cary, North Carolina.

Archibold, O.W. 1979. Buried viable propagules as a factor in postfire regeneration in northern Saskatchewan. Can. J. Bot. 57: 54-58.

Archibold, O.W. 1981. Buried viable propagules in native prairie and adjacent agricultural sites in central Saskatchewan. Can. J. Bot. 59: 701-706.

Archibold, O.W. and Hume, L. 1983. A preliminary survey of seed input into fallow fields in Saskatchewan. Can. J. Bot. 61: 1216-1221.

Bandeen, J.D. and McLaren, R.D. 1976. Resistance of Chenopodium album to triazine herbicides. Can. J. Plant Sci. 56: 411-412.

Bandeen, J.D., Stephenson, G.R. and Cowett, E.R. 1982. Discovery and distribution of herbicide-resistant weeds in North America. In Herbicide Resistance in Plants. H.M. LeBaron and J. Gressel (eds.). pp. 9-30. John Wiley and Sons, New York.

Barralis, G. 1973. Survie des semences de mauvaises herbes dans les terres cultivées. Phytoma Def. Cult. 25: 25-30.

Bassett, I.J. And Crompton, C.W. 1978. The biology of canadian weeds. 32. Chenopodium album L. Can. J. Plant Sci. 58: 1061-1072.

Bassett, I.J. and Crompton, C.W. 1982. The genus Chenopodium in Canada. Can. J. Bot. 60: 586-610.

Böhm, W. 1979. Methods of studying root systems. Ecological studies 33. Springer-Verlag, Berlin.

Benoit, D.L. and Cavers, P.B. 1983. A comparison of sampling techniques for estimating seed populations in arable soil. Ontario Pesticide Advisory Committee. Ministry of the Environment. 9th annual pesticide symposium. Jan. 25-26, 1983. Toronto, Ont. Abstract.

Bouhache, M. et Tanji, A. 1985. Evaluation du stock en semences de la morelle jaune (Solanum elaeagnifolium Cav.) dans le sol du Tadla (Maroc). Weed Res. 25: 11-14.

Bouhache, M., Boulet, C. et Hammouni, M. 1983. Etude du stock en semences d'Echinochloa crus-galli (L.) Beauv. dans le sol des rizières du Gharb (Maroc). Weed Res. 23: 385-390.

Brenchley, W.E. and Warington, K. 1930. The weed seed population of

arable soil. I. Numerical estimation of viable seeds and observations on their natural dormancy. J. Ecol. 18: 235-272.

Brenchley, W.E. and Warington, K. 1933. The weed seed population of arable soil. II. Influence of crop, soil and methods of cultivation upon the relative abundance of viable seeds. J. Ecol. 21: 101-127.

Brenchley, W.E. and Warington, K. 1936. The weed seed population of arable soil. III. The re-establishment of weed species after reduction by fallowing. J. Ecol. 24: 479-501.

Brenchley, W.E. and Warington, K. 1945. The influence of periodic fallowing on the prevalence of viable weed seeds in arable soil. Ann. Appl. Biol. 32: 285-296.

Bridges, D.C. and Walker, R.H. 1985. Influence of weed management and cropping systems on sicklepod (Cassia obtusifolia) seed in the soil. Weed Sci. 33: 800-804.

Budd, A.C., Chepil, W.S. and Dougherty, J.L. 1954. Germination of weed seeds. III. The influence of crops and fallow on the weed seed population of the soil. Can. J. Agric. Sci. 34: 18-27.

Burnside, O.C., Moomaw, R.S., Roeth, F.W., Wicks, G.A. and Wilson, R.G. 1986a. Weed seed demise in soil in weed-free corn (Zea mays) production across Nebraska. Weed Sci. 34: 248-251.

Burnside, O.C., Wilson, R.G., Wicks, G.A., Roeth, F.W. and Moomaw, R.S. 1986b. Weed seed decline and buildup in soil under various corn management systems across Nebraska. Agron. J. 78: 451-454.

Cavers, P.B. and O'Toole, J.J. 1981. Variations in numbers of dormant viable seeds from different soil samples taken from a single arable field. Proc. 13th Int. Bot. Congr. 13: 111.

Champness, S.S. 1949a. Notes on the buried seed populations beneath different types of ley in their seeding year. Ecology 37: 51-56.

Champness, S.S. 1949b. Notes on the technique of sampling soil to determine the content of buried viable seeds. J. Brit. Grassl. Soc. 4: 115-118 (non vide). Cited in Major and Pyott 1966.

Champness, S.S. and Morris, K. 1948. The population of buried viable seeds in relation to contrasting pasture and soil types. J. Ecol. 36: 149-173.

Chancellor, R.J. 1979. The long-term effects of herbicides on weed populations. Ann. Appl. Biol. 91: 141-144.

Chippendale, H.G. and Milton, W.E.J. 1934. On the viable seeds present in the soil beneath pastures. J. Ecol. 22: 508-531.

Cochran, W.G. 1977. Sampling techniques. John Wiley and Sons, Inc., New York. 3rd Edition.

Conn, J.S., Cochrane, C.L. and Delapp, J.A. 1984. Soil seed bank changes after forest clearing and agricultural use in Alaska. Weed Sci. 32: 343-347.

Conover, W.J. and Iman, R.L. 1981. Rank transformations as a bridge between parametric and nonparametric statistics. The American Statistician 35: 124-129.

Cook, R. 1980. The biology of seeds in the soil. In Demography and evolution in plant populations. O.T. Solbrig (ed.). Bot. Monogr. 15: 107-129. University of California Press, Berkeley and Los Angeles.

Dore, W.G. and Raymond, L.C. 1942. Pasture studies. XXIV. Viable seeds in pasture soil and manure. Scientific Agriculture 23: 69-79.

Dospekhov, B.A. and Chekryzhov, A.D. 1972. Counting weed seeds in the

soil by the method of small samples. Izv. Timiryazev. S. Kh. Akad. 2: 213-215. [Ru., Translated].

Dotzenko, A.D., Ozkan, M. and Storer, K.R. 1969. Influence of crop sequence, nitrogen fertilizer and herbicides on weed seed populations in sugar beet fields. Agron. J. 61: 34-37.

Doyon, D. 1984. Importance du chiendent dans les cultures au Québec. Rapport. Journée d'information en malherbologie. 6 mars 1984. Conseil des Productions Végétales du Québec.

Doyon, D. et Bouchard, C.J. 1981. Inventaire des mauvaises herbes dans les champs de maïs-grain du comté de Saint-Hyacinthe, Québec. Phytoprotection 62: 1-10.

Dvořák, J. and Krejčíř, J. 1980a. Changes in the potential and actual weediness of soil in crop rotations with different proportions of cereals. Zeszyty Naukowe Akademii Rolniczo Technicznej w Olsztynie, Rolnictwo 29: 101-110. [Pl, translated].

Dvořák, J. and Krejčíř, J. 1980b. Inventory of weed seeds and fruits in topsoil under different crop rotations and herbicide applications. Acta Univ. Agric. Fac. Agron. 28: 9-23. [Cs, translated].

Dvořák, J. and Krejčíř, J. 1980c. Effects of crop rotation and herbicide application on weed seeds and their distribution in topsoil. Acta Univ. Agric. Fac. Agron. 28: 25-34. [Cs, translated].

Dvořák, J. and Krejčíř, J. 1974. On a study of weed seeds in the ploughed horizon. Acta Universitatis Agriculturae, A 22: 453-461. [Cs, ru, de]. (Abstract - Weed Abstr. 25: 1682, 1976).

Dyer, F.C. 1938. Analysis of soil for seeds. A method of concentrating the seeds from soil for the purpose of counting and naming the seeds in a soil survey. Sci. Agric. (Ottawa) 18: 641-646.

Elliott, J.M. 1977. Some methods for the statistical analysis of samples of Benthic invertebrates. Freshwater biological association scientific publication No. 25. Titus Wilson and Son Ltd., Kendal. 2nd. Edition.

Enright, N. 1985. Existence of a soil seed bank under rainforest in New Guinea. Aust. J. Ecol. 10: 67-71.

Erichsen-Brown, C. 1979. Use of plants for the past 500 years. Breezy Creeks Press, Aurora, Ontario.

Fay, P.K. and Olson, W.A. 1978. Technique for separating weed seed from soil. Weed Sci. 26: 530-533.

Feast, P.M. and Roberts, H.A. 1973. Note on the estimation of viable weed seeds in soil samples. Weed Res. 13: 110-113.

Fekete, R. 1975. Comparative weed-investigations in traditionally-cultivated and chemically-treated wheat and maize crops. IV. Study of the weed-seed contents of the soils of maize crops. Acta Biologica Szegep 21: 9-20.

Fleischman, B. 1951. Preliminary studies on the germination responses of damaged seeds of some Chenopodium species. Proc. Assoc. Offic. Seed Analysts 41: 119-122.

Fletcher, W.W. (ed.). 1983. Recent advances in weed research. Commonwealth Agricultural Bureaux. Farnham. England.

Forcella, F. 1984. A species-area curve for buried viable seeds. Aust. J. Agric. Res. 35: 645-652.

Froud-Williams, R.J., Chancellor, R.J. and Drennan, D.S.H. 1983. Influence of cultivation regime upon buried weed seeds in arable cropping systems. J. Appl. Ecol. 20: 199-208.

Goyeau, H. et Fablet, G. 1982. Etude du stock de semences de mauvaises

herbes dans le sol: le problème de l'échantillonnage. Annales (Paris) 2: 545-552.

Greig-Smith, P. 1964. Quantitative plant ecology. Butterworth and Co. (Publishers) Ltd., London. 2nd edition.

Harper, J.L. 1977. Population biology of plants. Academic Press Inc., London.

Hassan, M.A. and West, N.E. 1986. Dynamics of soil seed pools in burned and unburned sagebrush semi-deserts. Ecology 67: 269-272.

Hayashi, I. 1975. The special method of inventory of buried seed population of weeds. Workshop on Research Methodology in Weed Science, Bandung 1, paper no. 4 (non vide). Cited in Roberts 1981.

Hayashi, I. and Numata, M. 1971. Viable buried-seed population in the Miscanthus and Zoysia type grassland in Japan - Ecological studies on the buried-seed population in the soil related to plant succession VI. Jpn. J. Ecol. 20: 243-252.

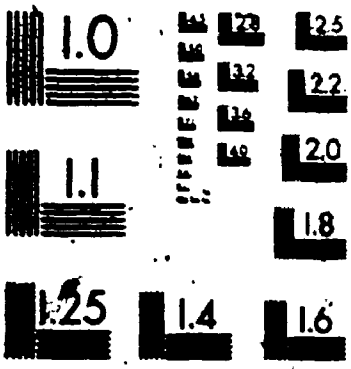
Hill, M.O. and Stevens, P.A. 1981. The density of viable seed in soils of forest plantations in upland Britain. J. Ecol. 69: 693-709.

Hodgkinson, K.C., Harrington, G.N. and Mills, G.F. 1980. Composition, spatial and temporal variability of the soil seed pool in a Eucalyptus populnea shrub woodland in central New South Wales. Aust. J. Ecol. 5: 23-29.

Holm, L.G., Pluckett, D.L., Pancho, J.V. and Herberger, J.P. 1977. The world's worst weeds. The University Press of Hawaii, Honolulu, Hawaii.

Hopkins, D.R. and Parker, V.T. 1984. A study of the seed bank of a salt marsh in northern San Francisco bay. Am. J. Bot. 71: 168-355.

Hopkins, M.S. and Graham, A.W. 1986. Viable soil seed banks in



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

disturbed lowland tropical rainforest sites in North Queensland. Aust. J. Ecol. 9: 71-79.

Howe, C.D. and Chancellor, R.J. 1983. Factors affecting the viable seed content of soils beneath lowland pastures. J. Appl. Ecol. 20: 915-922.

Hurle, K. 1974. Effect of long-term weed control measures on viable weed seeds in the soil. Proc. 12th British Weed Control Conf. 3: 1145-1152.

Johnson, E.A. 1975. Buried seed populations in the subarctic forest east of Great Slave Lake, Northwest Territories. Can. J. Bot. 53: 2933-2941.

Johnston, A., Smoliak, S. and Stringer, P.W. 1969. Viable seed populations in Alberta prairie topsoils. Can. J. Plant Sci. 49: 75-82.

Keeley, J.E. 1977. Seed production, seed populations in soil, and seedling production after fire for two congeneric pairs of sprouting and nonsprouting chaparral shrubs. Ecology 58: 820-829.

Kellman, M.C. 1970. The viable seed content of some forest soil in coastal British Columbia. Can. J. Bot. 47: 1383-1385.

Kellman, M.C. 1974a. The viable weed seed content of some tropical agricultural soils. J. Appl. Ecol. 11: 669-677.

Kellman, M.C. 1974b. Preliminary seed budgets for two plant communities in coastal British Columbia. J. Biogeogr. 1: 123-133.

Kenkel, N. 1981. Sampling theory in quantitative plant ecology. Unpublished manuscript. 77 pp.

Kershaw, K.A. 1973. Quantitative and dynamic plant ecology. Arnold (Publishers) Ltd., London. 2nd edition.

Kropač, Z. 1966. Estimation of weed seeds in arable soil. Pedobiologia 6: 105-128.

Leck, M.A. and Graveline, K.J. 1979. The seed bank of a freshwater tidal marsh. Am. J. Bot. 66: 1006-1015.

Lewandowska, A. and Skapski, H. 1979. Evaluation de l'envahissement potentiel des champs par les mauvaises herbes après la culture de l'oignon dans six régions de Pologne. Biul. Warzywniczy 23: 285-305. [Pl, translated].

Lippert, R.D. and Hopkins, H.H. 1950. Study of viable seeds in various habitats in mixed prairie. Trans. Kans. Acad. of Sci. 53: 355-364.

Livingston, R.B. and Allessio, M.L. 1968. Buried viable seed in successional field and forest stand, Harvard Forest, Massachusetts. Bull. Torrey Bot. Club 95: 58-69.

Major, J. and Pyott, W.T. 1966. Buried viable seeds in two California bunchgrass sites and their bearing on the definition of a flora: Vegetatio 13: 253-282.

Malone, C.R. 1967 A rapid method for enumeration of viable seeds in in soil. Weeds 15: 381-382.

Marlette, G.M. and Anderson, J.E. 1986. Seed banks and propagule dispersal in crested-wheatgrass stands. J. Appl. Ecol. 23: 161-175.

McGraw, J.B. 1980. Seed bank size and distribution of seeds in cottongrass tussock tundra, Eagle Creek, Alaska. Can. J. Bot. 58: 1607-1611.

McIntyre, S. 1985. Seed reserves in temperate australian rice fields following pasture rotation and continuous cropping. J. Appl. Ecol. 22: 875-884.

McMahon, D.J. and Mortimer, A.M. 1980. The prediction of couch infestations - a modelling approach. Proc. 15th British Weed Control Conf. 15: 601-608.

Milton, W.E.J. 1936. The buried viable seeds of enclosed and unenclosed hill land. Bull. Welsh Plant Breeding Station, Series H 14: 58-84.

Milton, W.E.J. 1939. The occurrence of buried viable seeds in soils at different elevations and on a salt marsh. J. Ecol. 27: 149-159.

Moore, J.M. and Wein, R.W. 1977. Viable seed populations by soil depth and potential site recolonization after disturbance. Can. J. Bot. 55: 2408-2412.

Moore, P.D. 1980. Soil seed banks. Nature (Lond.) 284: 123-124.

Mortimer, A.M., Putwain, P.D. and McMahon, D.J. 1978. A theoretical approach to the prediction of weed population sizes. Proc. 14th British Weed Control Conf. 14: 467-475.

Mueller-Dombois, D. and Ellenberg, H. 1974. Aims and methods of vegetation ecology. John Wiley and Sons, Inc., New York.

Muenscher, W.C. 1980. Weeds. Cornell University Press Ltd. London, England. 2nd edition.

Naylor, R.E.L. 1970. The prediction of blackgrass infestations. Weed Res. 10: 296-299.

Nicholson, A. and Keddy, P.A. 1983. The depth profile of a shoreline seed bank in Matchedash Lake, Ontario. Can. J. Bot. 61: 3293-3296.

Nie, N.H., Hull, C.H., Jenkins, J.G., Steinbrenner, K. and Bent, D.H. 1975. SPSS statistical package for the social sciences. McGraw-Hill Book Company, New York. 2nd edition.

Numata, M., Aoki, K. and Hayashi, E. 1964b. Ecological studies on the

buried-seed population in the soil as related to plant succession. II - Particularly on the pioneer stage dominated by Ambrosia elatior. Jpn. J. Ecol. 14: 224-227. [Jap., en.].

Numata, M., Hayashi, I., Komura, T. and Oki, K. 1964a. Ecological studies on the buried-seed population in the soil as related to plant succession. I. Jpn. J. Ecol. 14: 207-215. [Jap., en.].

Ødum, S. 1965. Germination of ancient seeds. Floristical observations and experiments with archeologically dated soil samples. Dan. Bot. Ark. 24, 70 pp. (Abstract - Weed Abstr. 15: 575 1966).

Olmsted, N.W. and Curtis, J.D. 1947. Seeds of the forest floor. Ecology 28: 49-52.

Orloci, L. and Kenkel, N.C. 1985. Introduction to data analysis. International Co-operative Publishing House, Fairland, Maryland.

Paatela, J. and Erviö, L.A. 1971. Weed seed in cultivated soils in Finland. Ann. Agric. Fenn. 10: 144-152 (non vide). Cited in Dvořák and Krejčíř 1980b.

Panetta, F.D. 1985. Population studies on Pennyroyal Mint (Mentha pulegium L.). II. Seed banks. Weed Res. 25: 311-315.

Parker, V.T. and Leck, M.A. 1985. Relationships of seed banks to plant distribution patterns in a freshwater tidal wetland. Amer. J. Bot. 72: 161-174.

Pavone, L.V. and Reader, R.J. 1982. The dynamics of seed bank size and seed state of Medicago lupulina. J. Ecol. 70: 537-547.

Peabody, D. 1974. Herbicide tolerant weeds appear in Western Washington. Weeds Today 5: 14.

Piroznikow, E. 1983. Seed bank in the soil of stabilized ecosystem of a deciduous forest (tilio-carpinetum) in the bialowieza national

park. Ekol. pol. 31: 145-172.

Poole, R.W. 1974. An introduction to quantitative ecology. McGraw-Hill Book Company, New York.

Pratt, D.W., Black, R.A. and Zamora, B.A. 1984. Buried viable seed in a ponderosa pine community. Can. J. Bot. 62: 44-52.

Rabotnov, T.A. 1956. Quelques données concernant la teneur en graines viables des sols des communautés prairiales. Akademiku V.N. Sukachevu K 75-letiyu so dnya rozhdeniya. 481-499. [Ru., translated].

Rabotnov, T.A. 1958. On methods of studying the supply of living seeds in soils of meadows. Bot. Zh. (Leningr.) 43: 1572-1581. [Ru., translated].

Roach, D.A. 1983. Buried seed and standing vegetation in two adjacent tundra habitats, northern Alaska. Oecologia (Berl.) 60: 359-364.

Roberts, H.A. 1958. Studies on the weeds of vegetable crops. I. Initial effects on cropping on the weed seeds in the soil. J. Ecol. 46: 759-768.

Roberts, H.A. 1962. Studies on the weeds of vegetable crops. II. Effect of six years of cropping on the weed seeds in the soil. J. Ecol. 50: 803-813.

Roberts, H.A. 1963a. Studies on the weeds of vegetable crops. IV. Further observations on the effects of different primary cultivations. J. Ecol. 51: 323-332.

Roberts, H.A. 1963b. The problem of weed seeds in the soil. In Crop Production in a Weed-free Environment. E.K. Woodford (ed.). pp. 73-82. Blackwell Scientific Publications. Oxford Symposium of the British Weed Control Council No. 2.

Roberts, H.A. 1963c. Studies on the weeds of vegetable crops. III.

Effect of different primary cultivations on the weed seeds in the soil. J. Ecol. 51: 83-95.

Roberts, H.A. 1966. The seed population of the soil and its implications for weed control. Proc. Irish Crop Prot. Conf. (1966): 14-22.

Roberts, H.A. 1968. The changing population of viable weed seeds in an arable soil. Weed Res. 8: 253-256.

Roberts, H.A. 1970. Viable weed seeds in cultivated soils. Rep. Natn. Veg. Res. Stn (1969): 25-38.

Roberts, H.A. 1981. Seed banks in soils. Adv. in Appl. Ecol. 6: 1-55.

Roberts, H.A. 1983. Weed seeds in horticultural soils. Sci. Hortic. 34: 1-11.

Roberts, H.A. and Dawkins, P.A. 1967. Effect of cultivation on the numbers of viable weed seeds in soil. Weed Res. 7: 290-301.

Roberts, H.A. and Feast, P.M. 1973a. Changes in the numbers of viable seeds in soil under different regimes. Weed Res. 13: 298-303.

Roberts, H.A. and Neilson, J.E. 1981. Changes in the soil seed bank of four long-term crop/herbicide experiments. J. Appl. Ecol. 18: 661-668.

Roberts, H.A. and Neilson, J.E. 1982. Seed banks of soils under vegetable cropping in England. Weed Res. 22: 13-16.

Roberts, H.A. and Ricketts, M.E. 1979. Quantitative relationships between the weed flora after cultivation and the seed population in the soil. Weed Res. 19: 269-275.

Roberts, H.A. and Stokes, F.G. 1965. Studies on the weeds of vegetable crops. V. Final observations on an experiment with different primary cultivations. J. Appl. Ecol. 2: 307-315.

Ryan, Jr., T.A., Joiner, B.L. and Ryan, B.F. 1976. Minitab student handbook. Wadsworth Publishing Company, Inc., Belmont, California.

Sampford, M.R. 1962. An introduction to sampling theory. Oliver and Boyd Ltd., Edinburgh.

Schweizer, E.E. and Zimdahl, R.L. 1984a. Weed seed decline in irrigated soil after six years of continuous corn (Zea mays) and herbicides. Weed Sci. 32: 76-83.

Schweizer, E.E. and Zimdahl, R.L. 1984b. Weed seed decline in irrigated soil after rotation of crops and herbicides. Weed Sci. 32: 84-89.

Smith, Jr., J.P. 1977. Vascular plant families. Mad River Press Inc., Eureka, California.

Smith, L.M. and Kadlec, J.A. 1983. Seed banks and their role during drawdown of a North American marsh. J. Appl. Ecol. 20: 673-684.

Smith, L.M. and Kadlec, J.A. 1985. The effects of disturbance on marsh seed banks. Can. J. Bot. 63: 2133-2137.

Snedecor, G.W. and Cochran, W.G. 1980. Statistical methods. The Iowa State University Press, Ames, Iowa. 7th edition.

Sokal, R.R. and Rohlf, F.J. 1981. Biometry. W.H. Freeman and Company, San Francisco. 2nd edition.

Standifer, L.C. 1980. A technique for estimating weed seed populations in cultivated soil. Weed Sci. 28: 134-138.

Steel, R.G.D., and Torrie, J.H. 1960. Principles and procedures of statistics. McGraw-Hill Book Company, Inc., New York.

Stuart, A. 1976. Basic ideas of scientific sampling. Charles Griffin and Company Ltd, London. 2nd edition.

Thomas, A.G. 1977. 1977 weed survey of cultivated land in

Saskatchewan. Agric. Can. Res. Sta. Regina, Sask. Mimeo. 103 pp.

Thompson, K. and Grime, J.P. 1979. Seasonal variation in the seed banks of herbaceous species in ten contrasting habitats. J. Ecol. 67: 893-921.

Thorsen, J.A. and Crabtree, G. 1977. Washing equipment for separating weed seed from soil. Weed Sci. 25: 41-42.

Tulikov, A.M., Frolova, T.N. and Chibotar, V.V. 1981. A comparative evaluation of sample sizes for calculating the number of weed seeds in soil. Izv. Timiryazev. S. Kh. Akad. 5: 190-193. [Ru., translated].

Van der Valk, A.G. and Davis, C.B. 1978. The role of seed banks in the vegetation dynamics of prairie glacial marshes. Ecology 59: 322-335.

Warnes, D.D. and Andersen, R.N. 1984. Decline of wild mustard (Brassica kaber) seeds in soil under various cultural and chemical practices. Weed Sci. 32: 214-217.

Warwick, M.A. 1984. Buried seeds in arable soils in Scotland. Weed Res. 24: 261-268.

Warwick, S.I. and Black, L. 1981. The relative competitiveness of atrazine susceptible and resistant populations of Chenopodium album and C. strictum. Can. J. Bot. 59: 689-693.

Warwick, S.I. and Marriage, P.B. 1982a. Geographical variation in populations of Chenopodium album resistant and susceptible to atrazine. I. Between- and within-population variation in growth and response to atrazine. Can. J. Bot. 60: 483-493.

Warwick, S.I. and Marriage, P.B. 1982b. Geographical variation in populations of Chenopodium album resistant and susceptible to

atrazine. II. Photoperiod and reciprocal transplant studies. Can. J. Bot. 60: 494-504.

Wee, Y.C. 1974. Viable seeds and spores of weed species in peat soil under pineapple cultivation. Weed Res. 14: 193-196.

Whipple, S.A.. 1978. The relationship of buried, germinating seeds to vegetation in an old-growth Colorado subalpine forest. Can. J. Bot. 56: 1505-1509.

Wicklund, R.E. and Richards, N.R. 1961. The soil survey of Oxford County. Report No. 28 of the Ontario Soil Survey, Research Branch, Canada Department of Agriculture and the Ontario Agricultural College, Guelph, Ontario.

Williams, E.D. 1984. Changes during 3 years in the size and composition of the seed bank beneath a long-term pasture as influenced by defoliation and fertilizer regime. J. Appl. Ecol. 21: 603-615.

Williams, J.T. 1963. Biological flora of the British Isles. Chenopodium album L. J. Ecol. 51: 711-725.

Williams, J.T. and Harper, J.L. 1965. Seed polymorphism and germination. I. The influence of nitrates and low temperatures on the germination of Chenopodium album. Weed Res. 5: 141-150.

Williams, R.D. and Egley, G.H. 1977. Comparison of standing vegetation with the soil seed population. Weed Sci. Soc. Amer. Abstr.: 79. (Abstract - Weed Abstr. 28: 2391 1979).

Yarnell, R.A. 1964. Aboriginal relationships between culture and plant life in the upper Great Lakes region. Anthrop. Pap. 23. Mus. Anthrop. Univ. of Mich. Ann. Arbor (non vide). Cited in Erichsen-Brown 1979.

Yates, F. 1960. Sampling methods for censuses and surveys. Charles

Griffin and Company Ltd., London, 3rd edition.

Zanin, G., Vecchio, V. and Gasquez, J. 1981. Experimental research on on atrazine-resistant populations of broad-leaved weed. Riv. Agron. 15: 196-207. [It.] (Abstract - Weed Abstr. 31: 3286 1982).

Zar, J.H. 1974. Biostatistical analysis. Prentice-Hall Inc., Englewood Cliffs, N.J.

Zawislak, K. 1980. The degree of specialization of crop rotations in relation to actual and potential weediness of crop stands. Zeszyty Naukowe Akademii RolniczoTechnicznet w Olsztynie, Rolnictwo 29: 283-293. [Pl, ru, en]. (Abstract - Weed Abstr. 30: 2133 1981).

Zimmergren, D. 1980. The dynamics of seed banks in an area of sandy soil in southern Sweden. Bot. Not. 133: 633-641.