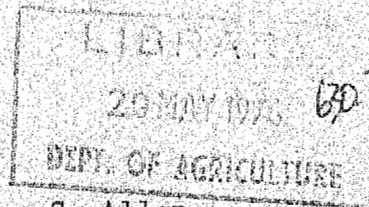


DEPARTMENT OF AGRICULTURE, SOUTH AUSTRALIA

Agronomy Branch Report

SEQUENTIAL SAMPLING FOR THE PASTURE COCKCHAFER,
Aphodius tasmaniae HOPE (COLEOPTERA: SCARABAEIDAE),
IN PASTURES IN SOUTH AUSTRALIA.



Peter G. Allen

Senior Research Officer, Entomology

Report No. 71

February, 1976.

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Senior Research Officer, Entomology

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SUMMARY

The larvae of Aphodius tasmaniae Hope are widespread pests of pasture in the higher rainfall areas of South Australia. At present, there is no reliable information on densities of larvae which are economic to treat or a method to estimate the mean density of a population of larvae in a pasture.

Sequential sampling was chosen as a technique to classify, with predetermined accuracy and with a minimum number of sample units, populations of A. tasmaniae into populations which were either economic or not to treat. The development of a sequential sampling plan depends on knowing the mathematical frequency distribution of larvae in a pasture and estimating realistic economic injury levels for larvae in pasture.

The spatial patterns of a number of populations of larvae in pastures were described by negative binomial distributions when a 108 cm² sample unit was used and the population was sampled by stratified random sampling (by area). The value of the dispersion parameter, k , of a negative binomial distribution is used to calculate a sequential plan. The value of k may vary with different ecological factors which may affect the dispersion of larvae, but the only factor which appeared to be correlated with k was mean larval density of the population. For the purpose of the sequential plan, it was necessary to assume there was a causal relation between these two parameters of the distribution and it was found that a significant linear regression was obtained when $\log k$ was plotted against the mean larval density. The slope of the regression could then be used to estimate the value of k for the value of the mean larval density that was chosen as the economic injury level in a particular sequential plan.

Field trials were conducted in naturally infested pasture to estimate the economic injury level of A. tasmaniae larvae in pastures. The initial trials were ungrazed by livestock and comparisons of pasture dry matter (D.M.) production were made between areas of pasture sprayed with lindane to control larvae and adjacent, untreated areas of pasture. There were no differences in pasture D.M. production which could be attributed to A. tasmaniae activity at any of the sites. The results suggested that the apparent damage caused by A. tasmaniae was a combined effect of grazing livestock and larval feeding and indicated the need for trials with grazing livestock. A trial similar to the ungrazed trial, except that both treatments were grazed evenly with wethers, was conducted at one site to mainly test the technique. Meaningful differences in available pasture D.M. after the winter and spring periods between the treatments showed that this technique could be expanded for future damage assessment trials, though the design of trials with a range of mean larval densities would have to allow for an estimate of pasture variability across the trial site.

The results from this thesis do not provide estimates of the economic injury levels for A. tasmaniae in pastures, however, a realistic range of economic injury levels were selected to test the practicability of sequential plans derived from the values of k estimated in the thesis. Depending on the predetermined accuracy set for the sequential plan, the use of a sequential plan appears to be a practical method to provide the necessary information for the economic control of A. tasmaniae larvae in pastures.

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I wish to thank my supervisors, Dr. D.A. Maelzer and Professor T.O. Browning, Waite Agricultural Research Institute, for their valuable guidance in the development of this study and helpful discussions and criticism during the study. Thanks are also due to Dr. D.A. Maelzer and Dr. R. Laughlin for criticism of the manuscript.

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The assistance and hospitality of farmers on whose properties the larval samplings were carried out was appreciated. Special thanks are due to Mr. A.B. Rowley and Mr. John Rowley, Meadows, on whose property the grazing trial was conducted and furthermore to John for his assistance during the trial period.

To my wife, Jill, I thank her for her interest and encouragement during the preparation of this thesis.

1. INTRODUCTION

Worldwide, little effort appears to be placed on insect damage assessment and, more particularly, determination of economic injury levels for different pest/crop interactions in agriculture. This was emphasized by Stern (1973), who pointed out that pesticides were applied against most of the world's pests as prophylactic measures or else were applied on the basis of vague criteria such as "when damaging numbers are present", "when heads are infested" and other similar expressions.

A clear understanding of the economic aspects of pest control is a fundamental necessity for any crop protection scheme (Smith, 1971). The need for economic considerations in crop protection and provision of economic injury levels or similar quantitative information has been stressed many times (Chiarappa *et al* 1972, Cramer 1967, Hurtig 1964, Ordish 1962, Smith 1969, Stern 1966, Sylven 1968). In 1967, FAO convened the "Symposium on Crop Losses" to emphasize the need for the development and use of experimental methods to obtain quantitative estimates of crop losses due to pests that could be used for the determination of economic injury levels. As a result of a recommendation from this symposium, FAO have now produced a manual on "Crop Loss Assessment Methods" (FAO 1971). In America, the "International Biological Program" (IBP) has been initiated recently to enable an interdisciplinary approach to pest control, and one of the basic guidelines is to establish realistic pest injury levels (Huffaker 1972).

Damage assessment studies in Australia are practically non-existent and decisions to treat a particular infestation rely mainly on subjective opinion rather than reliable objective estimates. Treatment of agronomic pests is usually confined to obvious pest infestations known to cause extensive damage; losses which may be caused by lower densities of the pest are not fully realised. With greater economic and environmental pressures exerted on primary production, a more rational approach is necessary. Decisions resulting in excessive use of pesticide are not only uneconomic but can accentuate the adverse effects pesticides may have on the environment (Anon 1972) and can increase the risk of jeopardising export markets because of pesticide residues in produce (Proude 1971, Snelson 1971). Insufficient use of pesticides may be uneconomic where infestations are greater than the economic injury level but are not recognised by the producer. (Everly 1960).

While economic injury levels for pest/crop interactions are most important to assess the need for treatment, they can often be used inefficiently because of difficulties in reliably estimating pest densities in a crop. Most pests have a contagious or "patchy" distribution in a crop (Evans 1953) and reasonably accurate estimates of density using conventional sampling methods involve a large number of sample units which are usually impractical for landowners to assess because of the time involved. For this reason, the use of economic injury levels in the field would be more efficient with sequential sampling. Sequential sampling is a technique which can be used to classify the density of a pest infestation with predetermined accuracy from a minimum number of sample units (Waters 1955).

This project is designed to study the feasibility of using economic injury levels and sequential sampling for pest density to determine the economics of treating populations of Aphodius tasmaniae Hope larvae damaging pastures in South Australia.

2. THE PEST STATUS AND BIOLOGY OF A. tasmaniae

A. tasmaniae, a univoltine species, is indigenous to south-eastern Australia and has been recognised as a pest of semi-improved and improved pastures for at least the last 40 years (Swan 1934) and more recently a pest of cereals (Allen 1968) in South Australia. Madge (1952) considered that its range extended inland as far as the 450mm rainfall isohyet but it has been found also along the west coast of Eyre Peninsula where the average annual rainfall is as low as 375mm.

Its emergence as a pest resulted mainly from increased food made available by the application of superphosphate and sowing of subterranean clovers associated with pasture improvement. In improved pastures carrying more than five sheep per hectare, the surface organic matter can support a much larger number of early-instar larvae than can be supported in native, unimproved pastures (Maelzer 1962). Also, improved pastures provide lush growth suitable for older larvae after the "break" of the season. It takes at least three to four years after sowing of an improved pasture before there is sufficient surface organic matter to support large numbers of early-instar larvae (Maelzer 1962). Maelzer also considered that pasture development increased shelter for A. tasmaniae larvae in the lower South-East regions of South Australia because hundreds of hectares were artificially drained. Much of the drained area was previously flooded during part of the winter every year and caused a high mortality of larvae.

In South Australia, A. tasmaniae first caused damage in the South-East (Swan 1934) but by 1952 it was known to cause damage on Kangaroo Island, southern Eyre Peninsula and in the southern Adelaide Hills (Madge 1952). By 1960 it was affecting pastures and cereal crops on southern Yorke Peninsula (P.R. Birks, personal communication). Now, it is found also in the central and northern Adelaide Hills and its presence is gradually extending towards the Barossa Valley. The known occurrence of A. tasmaniae in South Australia in 1974 is shown in Figure 1.

2.1 Damage to Pastures

The larvae are soil dwelling but come to the surface for food. First and early-second instar larvae feed on decaying organic matter on the surface of the soil and may occasionally eat the thinnest shoots of pasture grasses. However, the majority of older larvae feed on the vegetation of annual pasture plants, though some larvae are always found feeding in dung pads. Older larvae seem to "prefer" leguminous rather than graminaceous plants (Maelzer 1962),

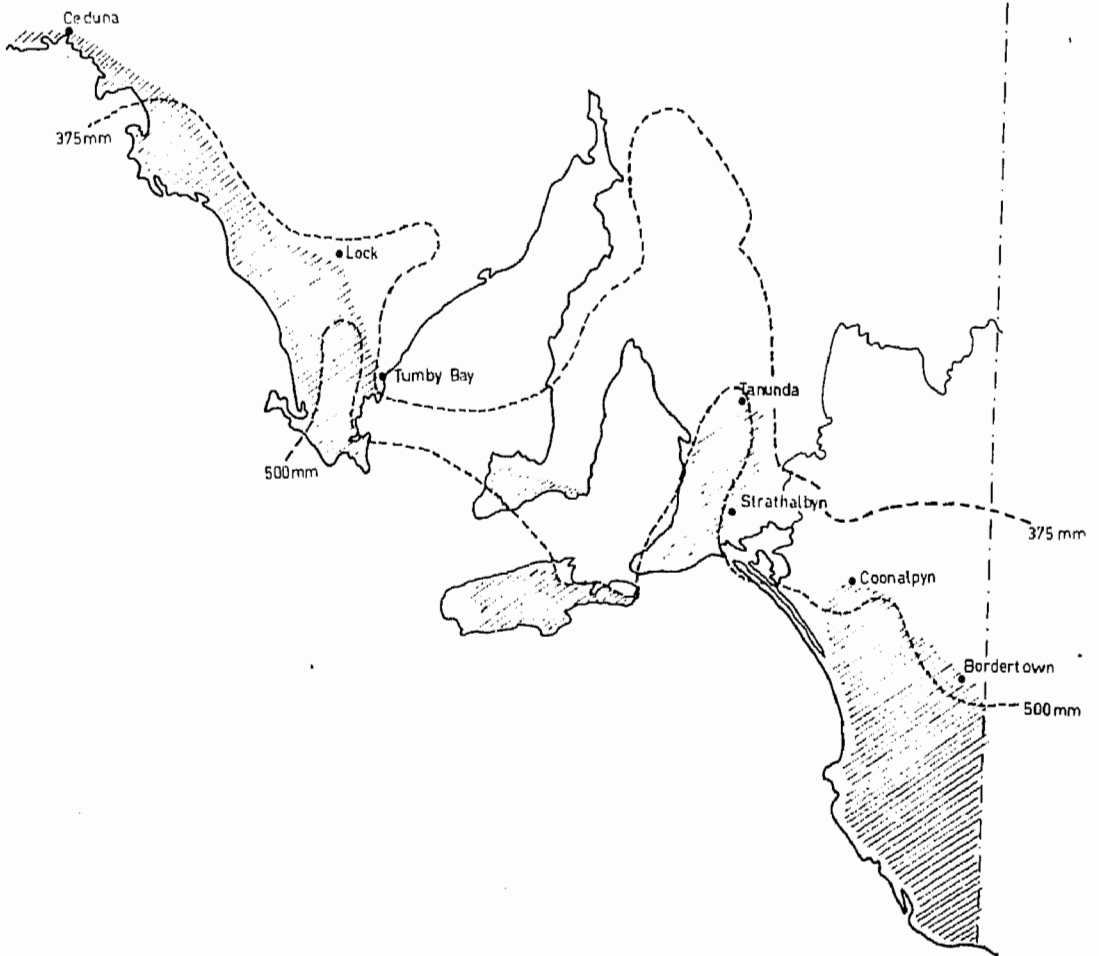


Figure 1 : The known occurrence of *A. tasmaniae* in South Australia, 1974, and the 375 mm and 500 mm average annual rainfall isohyets.

but both will be eaten. Broad-leaf, annual weeds will be eaten also, especially in the absence of clovers and annual grasses. Feeding on pasture plants normally begins in early winter (May) and is usually completed by the beginning of spring (September).

Depending on larval density, damage can result in bare or thinned patches in the pasture (Plate 1). In addition to the heavy losses in pasture dry matter which can occur, damage may reduce the quality of pasture due to invasion by winter annual weeds and may increase the risk of soil erosion.

Two weeds commonly invading damaged areas are capeweed (Arctotheca calendula Levyns) and crowfoot (Erodium spp.). These annual weeds have a very high moisture content and when they die-off in late spring the plant residues have little feed-value for livestock and are usually broken up and blown away by mid-summer. The bare areas left in the paddock are then susceptible to reinfestation by the next generation of A. tasmaniae (Section 2.2.), which further accentuates the pest problem. Reduced pasture production also occurs where soil, which is pushed out from the larval tunnels, smothers heavily grazed pasture plants.

The extent and severity of damage depends mainly on the frequency and amount of rainfall during the period January to April. Rainfall in this period affects oviposition by adults and survival of newly-hatched larvae (Section 2.2.). The area treated with insecticide during the last decade probably varied between 100,000 and 200,000 hectares annually. In most years, it is almost certain that a greater area could have been treated economically. Failure to treat infestations which caused economic damage would have resulted mainly from insufficient knowledge of the pest by landowners and no sound information on densities worth treating.

2.2 Biology and Ecology of *A. tasmaniae*

To develop sequential sampling for use at the optimum time for insecticidal treatment of *A. tasmaniae*, an understanding of adult behaviour prior to oviposition, preferred oviposition sites and survival and activity of newly-hatched larvae is essential. This information is available from previous studies on the biology and ecology of *A. tasmaniae* by Carne (1956) and Maelzer (1961, 1961a, 1962, 1962a, 1964).

Adult behaviour

By the end of December, adults are found in pupal cells approximately 10 to 15 cm deep in the soil. They emerge from the soil two to four days after the soil around them is wetted by rain during January to March. The quantity of

rain required to stimulate emergence of adults depends on the penetration of rain into the soil which varies with soil type. Mated females lay their first batch of eggs in the soil three to six days after emergence; this usually accounts for more than 70 percent of eggs laid. If females then feed on dung, a second batch of eggs is developed and laid. Adults live for about two weeks.

The adults are crepuscular and their behaviour following emergence is influenced by weather conditions at the time of a potential flight. In South Australia, summer rainfall develops either from cold fronts or thunderstorm activity. At dusk, on the days on which adults emerge after cold frontal rain, wind velocity is usually above 8 km/hr and the temperature is less than 15°C. Therefore, adults usually do not fly for 3-4 days and they tend to congregate and lay the first batch of eggs in the places from which they emerged, hence reinfesting areas damaged by larvae in the previous winter. However, after thunderstorm activity, temperatures at the time of potential flight are above 15°C and there is little wind, and adults then fly before laying their first batch of eggs. Eggs may be laid over a wide area after these flights, though generally within about 3 km from emergence sites.

Oviposition sites

During oviposition, there appears to be a strong aggregation of adults which is reflected by the "patchy" or contagious distribution of larvae in pastures and crops. Swan (1934) suggested that beetles were attracted to the accumulation of dung which was often present in areas where eggs were apparently laid. Carne (1956) postulated that beetles were attracted to paddocks containing recently germinated clover, which facilitated burrowing, and that adults in flight were attracted to other adults in the soil. Maelzer (1961) associated the aggregation of larvae with areas in pasture which had a very thin cover of "stubble" or no cover in later summer. H.G. Andrewartha suggested that the bareness of pasture surfaces was a "token stimulus" and that beetles aggregated in these areas in relation to soil moisture which was usually higher under a bare surface than under a cover of "stubble" (Maelzer 1961).

Maelzer (1961) tested the response of newly-emerged adults to soil moisture and found that most females preferred, and laid eggs in, soils with pF values in the range 2.8 to 3.2. Also, he showed that the water content under a relatively bare surface was higher than under a cover of stubble; this substantiated Andrewartha's suggestion. These differences in soil moisture were measured in a perennial rye-grass pasture in the South-East of South Australia during summer (D.A. Maelzer, personal communication). If these measurements had been made in annual pasture during summer, the level of soil moisture under the dry pasture residue probably would have been higher than under bare surfaces. (J.E. Schultz, personal communication). This may be due to loss of soil

moisture being less under the annual pasture residue than under the tussocks of perennial rye-grass because the former acts as a better mulch and does not transpire. Although the soil moisture regime under annual and perennial pastures may differ, there is still an apparent aggregation of adults on bare or sparsely covered areas in annual pasture during oviposition. It appears that Andrewartha's "token stimulus" may still be operating but under different conditions.

In "wet" summers, when there is not a meaningful difference in soil moisture under bare or sparsely covered surfaces compared to surfaces covered with pasture residue, the stimulus for adults to aggregate on bare or sparsely covered surfaces is not as strong.

In these years, pasture residues or other types of "shelter" appear to be a secondary stimulus determining where the beetles will burrow, and eggs will be laid under surfaces with shelter (Maelzer 1961).

Adults also aggregate and lay eggs in sheep "camps", especially the second batch of eggs. They take advantage of the loose surface for burrowing and there is the added attraction of dung on which to feed. Females that have laid the first batch of eggs move upwind to reach dung, often resulting in larval infestations on the leeward slopes of hills. Usually, these infestations are less dense and not as common as those on the windward slopes.

Aggregations of larvae can be found also on the windward side of objects such as trees, sheds and other conspicuous objects and on the windward slopes of hills. Infestations found in these situations suggest that beetles flying at night collide with objects by chance, drop to the ground and lay eggs (Maelzer 1961a). In most years, it is the north facing side of objects which is infested.

Eclosion of eggs

Eggs of A. tasmaniae are found in batches in the soil to a depth of about 15 cm. They hatch in about three to four weeks after being laid. Incubation period depends on temperature but not moisture because eggs tend to be laid in places where moisture is not a limiting factor during development.

Activity and survival of newly-hatched larvae

Newly-hatched larvae do not move from where the eggs were laid until the soil around them is moistened with rain. Occurrence of suitable rain varies from year to year and in some years larvae may not move to the soil surface until four to six weeks after hatching. If effective rains do not occur until 30 days after hatching a 50 per cent mortality can be expected due to starvation of larvae and this mortality increases with an increase in the time

without effective rain (Maelzer 1961). It can approach 100 per cent in some years. Once larvae have fed on organic matter, they are more resistant to starvation and can survive long, dry periods without food (Birks et al, 1969).

Larvae live in vertical tunnels in the soil and are stimulated to come to the surface at night to forage for food when a very high atmospheric humidity exists near the pasture surface following rain and, in some instances, a heavy dew. Enough food is taken into the tunnels to provide food for seven to ten days. Larvae do not come to the surface again until their food supply has been depleted. Young larvae rely on surface organic matter while larvae older than the mid-second instar feed on green plant material. It is at least two to three weeks after first coming to the surface before larvae begin feeding on green plant material. As larvae become older they may move out from the centre of the area of infestation in search of food and construct new tunnels. This movement alters the spatial pattern of the infestation.

The biology and ecology of this pest after the mid-second instar is not important for its control because treatment is best carried out before larvae feed on green plant material.

2.3 Control of *A. tasmaniae*

2.3.1 Cultural control

The ecological studies of *A. tasmaniae* that have been made suggested that a number of cultural techniques could be used to reduce damage to pastures. These include -

Interference of preferred oviposition sites

Because adults prefer to lay eggs in bare ground in most years, pastures can be protected by maintaining a grass cover during adult activity. This can be achieved by introducing perennial grasses into a pasture, though well-balanced subterranean clover-perennial grass pasture will be infested if continually overgrazed.

Removal of food source required by young larvae

Young larvae can be controlled by starvation if the surface organic matter is buried by ploughing before they begin feeding on green plant material. Cultivation usually has to be carried out before May for this method to be effective. This control method and the previous method can be combined to give control of both *A. tasmaniae* and weeds. Pastures should be renovated after about four years to prevent the necessary build-up in surface organic matter for young larvae. Only those paddocks which are to be ploughed before May should be cut for hay or heavily grazed through the summer.

Sowing perennial pasture species

In addition to providing a plant cover during summer, perennial plants can withstand damage better than annuals. Perennial plants are usually established plants rather than seedlings at the time of attack and are relatively resistant to attack because larvae can chew only thin or prostrate stems and can not effectively penetrate the crowns of perennial plants.

2.3.2 Insecticidal control

The above control techniques are known to be effective but are not extensively used in most areas affected by A. tasmaniae because of difficulties in establishing and maintaining perennial pastures, ploughing in steep country, and little incentive to change existing rotations and other farm practices.

In the future, application of these techniques may increase in some areas but the heavy reliance on the use of insecticides to control A. tasmaniae larvae will remain for many years to come.

The provision of a sequential plan for A. tasmaniae will not only ensure an economic basis for treatment with insecticide but should also reduce the incidence of prophylactic treatment of whole properties, especially with lindane applied with a superphosphate topdressing. This latter practice prevents adherence to a stock-withholding period after insecticidal treatment of a pasture and increases the risk of undesirable residues of insecticide in produce. Lindane, applied as a surface spray or with a superphosphate topdressing, has been the most widely used insecticide for the control of A. tasmaniae in South Australia. However, in the future, there will probably be a trend towards organic phosphorus compounds because of a world-wide shortage of lindane and "pressures" against the use of persistent organic chlorine compounds in agriculture. Treatment with organic phosphorus compounds is more expensive than with lindane at present and the compounds are insecticidally active for shorter periods than lindane, so there will be an even greater need for more information on economic densities of A. tasmaniae and the optimum time of insecticidal application.

The most benefit obtained from controlling A. tasmaniae larvae with insecticide occurs when the insecticide is applied before larvae begin feeding on green plant material. If treatment is delayed until bare patches appear in the pasture, then irretrievable pasture losses have already occurred. The correct timing of treatment in a district can be estimated from the district's rainfall pattern during summer and autumn. The pattern indicates times of adult activity and oviposition, hatching of eggs and the first migration of larvae to the surface (Section 2.2.). When it is apparent that newly-hatched larvae have been stimulated to come to the surface to feed, the most susceptible areas on a property can be inspected and, if larvae are found, the remainder of the property can be surveyed.

Appendix I shows the daily rainfall frequencies for Macclesfield, 1971, and Woodside, 1972, which were used successfully to detect early activity of first instar larvae in the field.

When young larvae are found, it is still difficult to decide whether or not to treat other than very heavy infestations because there is little information on how to assess the extent of future damage to a pasture by an infestation of young larvae. For a sequential plan to be effective in determining whether or not an infestation of young larvae is worth treating, the plan should be based on the expected damage which could be caused by different densities of young larvae.

If treatment is considered necessary, the insecticide is best applied just before or during rain and after a period of at least five or six days during which rain has not fallen. This is because rain falling after the dry period described above stimulates most of the larvae to come to the surface to replenish their food supply and ensures that the majority of larvae in the treated pasture come in contact with the insecticide before the insecticide loses its activity.

3. A TECHNIQUE TO RATIONALISE THE CONTROL OF *A. tasmaniae*

Damage to pastures by *A. tasmaniae* and prophylactic treatment with insecticides to control *A. tasmaniae* in pastures will occur as long as there is a paucity of reliable information on both the mean densities of young larvae above which it is economic to treat and a method to estimate, with reasonable accuracy, the mean density of a population of young larvae. The development of a sequential plan to determine the economics of treating young *A. tasmaniae* larvae in pastures will alleviate both these current shortcomings. A knowledge of the biology and ecology of the insect being sampled and decisions on what is required from the plan are prerequisites for the development of sequential plans (Stevens *et al* 1962). With *A. tasmaniae* the biology and ecology are well understood (Section 2.2.) and the decision required from the plan is whether an infestation of young larvae in pasture is economic or not to treat.

3.1 Sequential Sampling

Details of sequential sampling, construction of sequential plans and their application are fully discussed by the Statistical Research Group, Columbia University (1945), Wald (1947) and Wetherill (1966).

Sequential sampling offers a technique to rapidly classify populations into broad infestation classes with predetermined accuracy and a minimum of sampling. It does not provide estimates of population parameters (Waters 1955).

In studies concerned with the economic injury levels of pest species, populations are usually classified as being either economic or not economic to treat.

A typical form of a sequential plan to assist in determining the economics of treating a pest infestation is shown in Figure 2 (Harcourt 1967). The plan is defined by a pair of parallel decision lines that are the criteria for distinguishing whether or not an infestation of a pest is economic to treat. Where an infestation needs to be divided into a number of density classes, more than one pair of parallel lines can be computed.

Waters (1955) described the fundamental information necessary to calculate the equations of the decision lines for plans making economic decisions on pest populations.

The information required is -

- the mathematical distribution of the pest in the crop
- an estimate of the economic injury levels of the pest in the crop to set classification limits which have a practical meaning

To use the plan, sample units are chosen at random from an infestation and evaluated in sequence until the sample from the population falls into one classification - category.

Ives (1954) compared the main differences between conventional and sequential sampling. There are three variables involved with both - the sample size, Type I error (the probability of rejecting the null hypothesis when it is true) and Type II error (the probability of accepting the null hypothesis when the alternative is true). With conventional sampling, the sample size and the value of the Type I error are chosen in advance and the test which gives the best protection against a Type II error is used. Decisions are made on the basis of the sample data as a whole and, because insect populations are usually contagiously distributed, a large and time consuming sample is required to give reasonably accurate estimates. In sequential sampling, Type I and Type II errors are fixed in advance and the sample size varies because sampling is only continued until the sample from the population is classified. This procedure can lead to a reduction in excess of 50 per cent of the number of sample units normally required to make the decision at a given level of accuracy (Statistical Research Group, Columbia University, 1945). Because the ordinate of a sequential plan is the cumulative number of the population index per sample unit (eggs, larvae, measurement of damage), the least number of sample units are required to make a decision when the density of the population index is either very high or very low. A larger number of sample units is required with intermediate densities, especially with densities around the economic injury level. While it is highly probable that a decision will be reached, it may be desirable to set upper limits for the number of sample units which should be taken. If a decision is not reached after this number, the decision to treat then relies more on other managerial criteria rather than economics per se. A table based on the sequential plan can be used in the field (Harcourt 1967, Morris 1954).

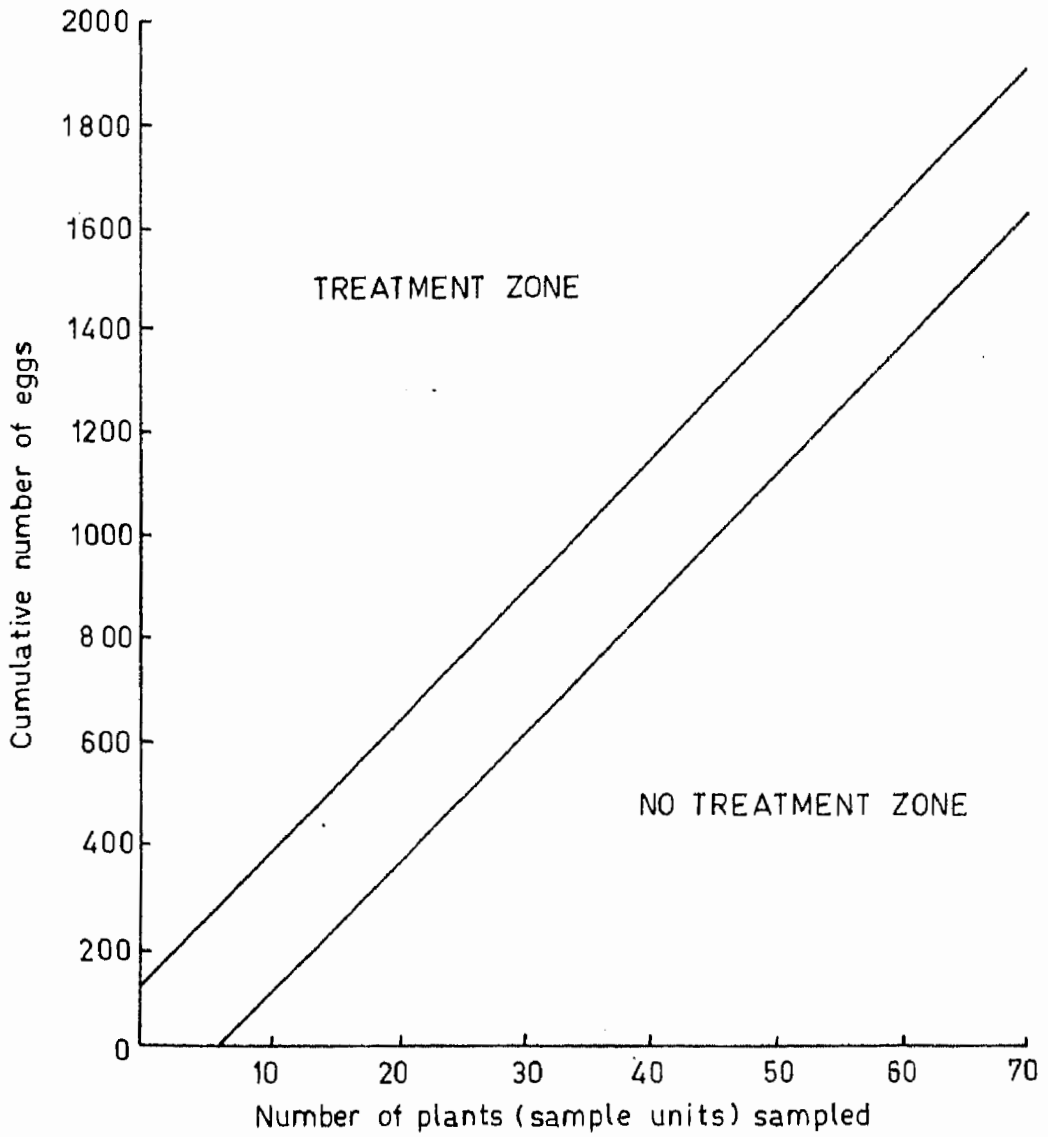


Figure 2 : A sequential plan for sampling eggs of the cabbage maggot, *Hyalemya brassicae* (Harcourt, 1967)

Waters (1955) described the average sample number curve and an operating characteristic curve which can be computed to give an indication of the performance of a plan. The former indicates the expected average number of sample units required to make a decision at different population levels. The latter indicates the chance of making a correct decision on whether or not to treat at the various population levels that are expected. These curves are shown for a simulated sequential plan for A. tasmaniae in pasture in Section 6.

3.1.1 Use of sequential sampling in agriculture

Sequential sampling was developed for quality control in industry during the 1939-45 war and its value in enabling reliable conclusions to be drawn from a minimum of data caused it to be classified restricted within the meaning of the U.S.A. Espionage Act (Moroney 1965). This classification was removed in 1945 because of widespread demand, mainly from industry, for access to information on this technique. Initially, its most extensive use was in the inspection for defects in mass-produced products in secondary industry.

Now it has been applied to pest situations in agriculture, mainly where the cost/benefit ratio is high and especially where the density of a species over an extensive area has to be classified e.g. a number of destructive insects in forests in northern America. Plans have been developed where eggs (Morris 1954), larvae (Reeks 1956, Stark 1952, Stevens et al 1962, Waters 1955), oviposition slits of sawflies (Ives et al 1958) and damage (Safranyik et al 1970) were used as forest pest population indices. Ives et al (1965) constructed a plan to evaluate the economic treatment of "white grubs" damaging coniferous seedlings in Canada. The white grubs involved a number of different scarab species. Insufficient knowledge of the hazard represented by the different population levels of white grubs reduced the usefulness of this plan.

Harcourt (1967) developed a sequential plan using egg-counts to determine the need to control Hylemya brassicae (Bouche) in vegetables and Sylvester et al (1961) developed a plan using the number of Myzus persicae (Sulzer) on sugar beet plants. While not strictly agriculture, Oaklands (1950) used the technique to sample for the occurrence of cysts in the edible parts of fish. Reference is made to Oakland's work to demonstrate the value of this plan where destructive sampling of a useful commodity is necessary to make a decision.

Sequential sampling has not been used to classify densities or assist in determining the economics of controlling any insect pest infestation in Australia.

3.2 Distribution of Insects

In this thesis, frequency distribution or distribution refers to the mathematical description of the dispersion or spatial pattern of a population of insects.

The mathematics necessary to calculate decision lines for a sequential plan are available for insect populations where the frequency distribution of a particular growth stage of the insect or an index of the population can be described by either a normal, Poisson, binomial or negative binomial distribution (Waters 1955).

The distribution of most insect populations is contagious or overdispersed and the variance exceeds the mean (Cassie 1962, Evans 1953, Nef 1962, Prebble 1943, Wadley 1950). There are limited examples where the distribution is random and the variance equals the mean (Chiang et al. 1959, Morris 1951). Departure from randomness towards a contagious distribution can be explained simply as deviations from the three conditions necessary for a Poisson (random) distribution (Waters et al. 1959). The three conditions are that each individual in the population has the same chance of occurring in any area, that any area has the same chance of an individual occurring in it and that the presence of one individual in an area does not, in any way, affect the chances of another falling into it. The first condition rarely holds under natural conditions, the second is not usually met and the third is seldom true. Occasionally, it may be found that the variance is less than the mean (Southwood 1968), though the only example found of a binomial distribution is with the population index used for larch sawfly and is the ratio of larch sawfly oviposition sites to total number of new shoots (Ives 1954). Frequency distributions of some insects have been fitted to the normal distribution (Stark 1952, Stevens et al. 1962). The normal distribution is a continuous distribution, but discrete distributions (insect counts) can approach normality as the sample size increases (Ives 1954).

With contagious distributions, Bliss (1958) considered that the negative binomial distribution was the most versatile and generally useful. Early-instar A. tasmaniae larvae appear to be strongly overdispersed in pasture which suggests that their spatial pattern could be described by a negative binomial distribution. The negative binomial distribution is described by two parameters, the mean and the exponent, k , which is a measure of overdispersion or aggregation and often referred to as the dispersion parameter. Small values of k indicate a strongly aggregated distribution whereas a large value indicates that the distribution is more random and approaching a Poisson distribution (Southwood 1968). The actual value of k is used in the calculation for the equations of the decision lines of a sequential plan.

Generally, interpretation of frequency data, including parameters such as k , has certain limitations because the biological and statistical components can be easily confused (Waters et al. 1959). The observed data might satisfactorily fit more than one distribution, the same distribution can be derived from several distinct mathematical and biological sets of premises, and the parameters of most discrete frequency distributions are strongly influenced by the form and size of the sample unit and by the population density. The quantitative expression of aggregation through a frequency distribution may reflect a real aggregation tendency (true contagion) or it may be a statistical artefact (apparent contagion). Waters et al. (1959) considered that while the negative binomial distribution can include true and apparent contagion it permits a more valid interpretation of the biological factors involved with the true contagion compared to other contagious distributions.

An important factor affecting the apparent distribution of a population is the size of the sample unit (Burrage et al. 1954, Cole 1946, Jones 1937, Macfadyen 1962, Waters 1959). With negative binomial distributions, the size of the sample unit influences the value of k (Waters et al. 1959), hence the sample unit used to develop a sequential plan must be used in the application of the plan.

The true contagion recognised by the negative binomial distribution may be due either to active aggregation of the insect or to some heterogeneity of the environment (microclimate, soils, plant) (Southwood 1968).

Waters (1959) made a general comment that spatial distribution often changed markedly with different stages of development of an insect. This has been demonstrated with soil-dwelling insects, including scarab larvae in pasture (Burrage et al. 1954, Guppy et al. 1970). Guppy et al. (1970) fitted the distribution of all soil-dwelling stages of Phyllophaga spp. to negative binomial distributions and the value of k increased with each stage. They considered that there was an increased randomness with dispersal of older larvae. A similar observation was made by Salt et al. (1946) with larvae of an elaterid, Agriotes sp., in pasture. This change in distribution with age emphasizes the importance of determining the distribution of A. tasmaniae larvae at the stage when a sequential plan would be used to assist in determining whether control measures were needed. The distribution of A. tasmaniae larvae would probably tend to be more random in the older stages after they disperse while foraging for food.

The dispersion of an insect population may be related to its mean density. Bliss et al. (1953) assumed that the spatial pattern of low densities of insects is often random and can be described by a Poisson distribution, while the spatial pattern of the same insect at higher densities is contagious and can be described by a negative binomial distribution. They

considered the random distribution with very sparse populations resulted from the low chance of individuals occurring in any sample unit. However, Cassie (1962) refuted this effect of mean density and distribution when he showed that it was difficult to demonstrate non-randomness in sets of samples with a mean less than unity, a situation which may arise either through scarcity of organisms or smallness of the sample unit. He concluded that this did not mean that scarcity induced randomness, only that a departure from randomness was not evident unless an unusually large number of sample units was taken. Anscombe (1949), Morris (1954) and other workers also differed from Bliss *et al.* (1953) and found distributions of some insects were contagious at low densities and tended to become more random at higher densities. With negative binomial distributions, an increase in mean density resulted in an increase in the value of k . The effect of mean density of *A. tasmaniae* larvae on the frequency distributions obtained will have to be understood for a sequential plan to be meaningful.

In addition to density, many other components of the environment may influence the dispersion parameters of a population (Andrewartha 1971, Hutchinson 1953, Southwood 1968). Salt *et al.* (1946) studied the effect of environmental factors, including topography, various soil characteristics, vegetation and other fauna on the distribution of wireworms (Elateridae) in pasture.

In one pasture they found that the distribution was correlated to a "highly significant degree" with nine factors and to a "significant degree" with three factors while in a second area the distribution was correlated to a "highly significant degree" with three factors and to a "significant degree" with one. They considered that these factors caused the non-random distribution found because of their influence on wireworm oviposition and larval movement and survival. For the most part, the environment is heterogeneous with respect to favourable and unfavourable conditions for a particular species and this often leads to the species being contagiously distributed (Elton 1949).

The distribution of early-instar *A. tasmaniae* larvae in pastures is most likely to result indirectly from environmental factors influencing the place where females lay eggs, rather than the effect on larvae *per se*. These factors have been discussed in Section 2.2 and include weather conditions stimulating adult emergence and behaviour, pasture cover during the period of adult activity, summer rainfall, the presence of obstacles such as trees, topography and, when moisture is not limiting, compaction of the soil surface. In very dry years, the amount of rain may influence the distribution of larvae where it ensures the survival of newly-hatched larvae only in depressions in the pasture or alongside stone outcrops where the effective rainfall is increased with "run-off". When pastures are being sampled to define the distribution of *A. tasmaniae* larvae, a number of pastures differing in these environmental factors should be sampled to determine whether any significantly affect the distribution of larvae.

3.3 Pest Damage Assessment

Most objective damage assessment studies of pest/crop interactions are designed to provide information to estimate the economic injury level or the economic threshold of the pest as described by Stern (1966) and these estimates can be used to compute a sequential plan. The economic injury level is that density of the pest above which it is considered economic to treat and the economic threshold is that density at which control measures should be carried out to prevent an increasing pest population from reaching the economic injury level. The economic injury level is more applicable to A. tasmaniae because A. tasmaniae is a univoltine species and migration of larvae is limited, hence, larval densities in a pasture do not increase during the damaging stages of the larvae in any one year. The economic threshold applies more to multivoltine pests where a number of generations of the pest occur just prior to and during the susceptible stage of the crop.

Stern (1973) reviewed the general, world-wide development and use of economic thresholds. This provides a useful introduction to damage assessment studies and applies to economic injury levels.

An essential prerequisite for estimates of economic injury levels is an understanding of the mechanism of damage (Smith 1967) to provide relationships between pest densities and yields.

Reduction in crop yields due to insects can result from damage to the foliage and roots of the crop, or to the crop product itself (Southwood et al. 1973). Where insect pests attack foliage and roots, they can reduce the yield by causing a reduction in the absorption of light and photosynthetic processes and a diversion of energy from the crop product to other parts of the plant. Insects attacking the crop product can reduce yield directly by consuming the crop product, or indirectly by causing injury that leads to further damage, such as rotting. Also, reductions in returns from yield can occur due to the effect of insects on the quality of crop products.

Southwood et al. (1973) considered that the relationship between pest density and the damage it causes to the crop is linear, especially for pest densities below densities where intraspecific competition occurs, and the relationship between pest density and yield is sigmoid. A number of other authors considered that these relationships may not be as simple and can be influenced by the host crop and other environmental conditions (Gough 1947, Johnson 1965, Ordish et al. 1965, Smith 1969). In most damage assessment studies only a portion of these curves are shown.

Pest density threshold for severe loss in yield tends to be high for foliage - and root-attacking pests and low for product-attacking pests (Southwood et al., 1973). This is partly explained by the ability of many crops to be able to compensate for foliage and root damage and still maintain near-normal yields, but not usually being able to compensate for quantity or quality of yield where the product is attacked.

Information from pest density/yield relationships can be used to compute cost/potential benefit ratios (the cost of a control measure compared to the increased value of the crop) and dosage response curves (Hillebrandt 1960) which can be used to determine economic injury levels. Cost/potential benefit ratios and dosage response curves do not always take into account all the variables which may influence the economic injury level. These variables include seasonal fluctuations, managerial practices (type of stock, stocking rate, plant variety, condition of crop), market elasticity and future effects of the insecticide on the system. Methods and problems of determining and expressing economic injury levels are discussed in many papers (Barton et al. 1967, Chant 1964, Headley 1972, Hillebrandt 1960, 1961, Judenko 1965, Ordish 1962, 1967, Smith 1971, Toms 1967).

3.3.1 Pest damage assessment studies

Worldwide, assessment of damage to "broad-acre" crops appears to be almost entirely associated with pests of the higher return crops which have yields that can be quantified and/or qualified easily and transformed into monetary equivalents. These crops mainly include a range of cereals (Buckley et al. 1962, Gough 1947, Merritt et al. 1969, Neiswander et al. 1930, Nishida et al. 1970, Raw et al. 1957) and cotton (Brazzel et al. 1956, 1957, Canerday et al. 1964, Joyce 1959).

In damage assessment studies with pasture pests, the effect of the pest on hay yields has been most commonly estimated (Franklin 1953, Pruess et al. 1958, Rastrick et al. 1968), though the effect of Wiseana spp. on pasture production was studied in New Zealand (Allen 1968, McLaren et al. 1969). In the papers and symposia reviewed on pest damage assessment research, few trials were designed to quantitatively measure the effect of a pasture pest on pasture and/or livestock production under grazed conditions. This is probably due mainly to the expense of conducting grazing trials and the uncertainty of obtaining meaningful results.

The F.A.O. manual on "Crop Loss Assessment Methods" (1971) provides a recent listing with a summary of results of damage assessment studies in agronomic and horticultural fields. Studies on insects damaging agronomic crops were reliant mainly on comparisons of yields between naturally infested areas and adjacent areas where the pest was controlled with insecticide.

The results from most damage assessment studies have been a correlation between pest densities and yield which can be used to estimate economic injury levels. Nebulous terms, such as "light", "medium" or "heavy" populations have been used to describe pest densities in damage assessment studies (Canerday et al. 1964, Everly 1960, Gallum et al. 1967).

These studies do not provide the basic information necessary to estimate reasonably reliable economic injury levels.

In Australia, the limited number of damage assessment trials recorded have been mainly with pasture pests. In the 1940's, Norris (1944, 1948) studied the influence of Halotydeus destructor (Tucker) on the yields of subterranean clover pastures in Western Australia. The trials were carried out in small field plots (approximately two square metres) which were not grazed. In the first trial, dry matter production in October and seed production were compared between three levels of mite infestation (Norris 1944). The three levels of infestation were none (controlled with insecticide) natural infestation and higher than natural infestation obtained by adding mites. This trial demonstrated the deleterious effect H. destructor can have on subterranean clover pastures, but there was no information of pest density compared to pasture loss. Also, Norris considered that the importance of the plots not being grazed was impossible to assess. In the second trial, Norris (1948) tested the effect of time of treatment on pasture yield. There were no actual estimates of mite densities, but it was demonstrated that the earliest treatments gave the best responses.

Wallace et al. (1952) showed the effect of Hednota (= Talis) pedionoma (Meyrick) larvae on dry matter yields of the main botanical components of pasture in Western Australia. They used small, ungrazed plots and differing rates of application of insecticide to regulate larval densities. In the first year, H. pedionoma attack reduced the production of grasses in October by 85% and total production of pasture in excess of 50%. In the second year following treatment, results were clouded by the residual effect of the higher rates of the insecticide and a lack of oviposition in the no insecticide plot. However, heavily infested plots compared to uninfested plots showed a reduction of 80% in grass yields and 17% in total yield of pasture in October. There was no estimate of larval densities in this trial on which to base economic injury levels. Although the trial was not grazed, and this limitation was recognised, similar results were obtained in large-scale, field treatments where pastures were grazed with livestock throughout the year, though the results of the large-scale, field treatments were considered "unsuitable for statistical analysis".

Wallace et al. (1963) studied in more detail the effect of insecticidal treatment on the yield and botanical composition of sown pastures in Western Australia where the main pests were H. destructor, Hednota spp. and Sminthurus viridis (Linnaeus). They used four different methods to compare differences in pasture production and livestock production (where applicable) between insecticidally treated and untreated areas.

The methods used were small, ungrazed field plots, unfenced grazing trials and fenced trials with intermittent and continuous grazing, respectively. In all trials, they were mainly interested in comparing yields from treated and untreated pasture rather than comparing actual pest densities with loss in production. They considered that the amount of damage being done was much more useful and, in practice, easier to assess than insect population counts. Also, the extent of damage caused by different pest populations varied with the vigour of pasture growth. Using the differences in pasture production from treated and untreated pasture, they calculated an overall average response to treatment from 34 individual observations. They assumed that a spring yield of approximately 750 kg per ha represented one sheep per hectare and then they estimated the number of additional sheep per hectare equivalent to an infestation of the different pests (e.g. average response to H. destructor control was equivalent to 0.6 sheep per hectare, ranging from nil to 1.6 sheep per hectare). There was no allowance made for differing pest densities or seasonal conditions in these sheep equivalents. An economic analysis incorporating the response to treatment for the particular pest and other variables (wool cut per head, wool price, sheep costs, treatment costs) was presented to calculate the net wool revenue per hectare resulting from treatment of a pest on a property.

Reliable application at farm level would rely on pasture growth being similar to the average pasture growth in the trials and the pest densities on farms approximating the mean densities on the trial sites. While the economic analysis gave an indication of the return which may be expected from treatment of any one of the pests, the need for treatment of a particular infestation still relied heavily on the experience of the farmer or adviser.

The damage caused by a number of species of native scarabs which infest pasture in the Northern Tablelands area of New South Wales was studied in pot trials in glasshouses (Davidson 1969, Davidson et al. 1968, 1968a). The larvae of these scarabs are soil-dwelling and can cause a reduction in herbage production of pastures by damaging the roots of grasses and subterranean clovers. The trials were designed mainly to elucidate the mechanism of damage to roots, larval preference for roots of different pasture species and the influence of soil moisture and soil organic matter on larval feeding. Results from these trials were not directly applicable to estimating economic injury levels, but offer important background information on these pests when quantitative damage assessment trials are carried out in the field.