INFESTATION DENSITIES OF THE PINE WOOLLY APHID (*PINEUS PINI*) ON *PINUS PATULA* AS RELATED TO SITE PRODUCTIVITY AT SAO HILL FOREST PLANTATION

BY

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DECLARATION

I, Seif S. Madoffe , do declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work and that it has not been submitted for a similar degree in any other University.

Signature :

Seif S. Madoffe

Date: 15th August, 1989

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DEDICATION

For your forbearance, Gladys, my wife, Sofia and Neema, my children, this is an inspiration.

ABSTRACT

Between September 1988 and March, 1989 a study was carried out at Sao Hill forest plantation with the following major objectives:-

- to examine the relationship between Pinus patula stand productivity and abundance of the Pineus pini.
- to elucidate the impact of P. pini on tree growth.

Based on a preliminary sampling, the main sampling intensity was determined for a fixed degree of precision.

In the main sampling, the two site classes I and III and the young age class (<10 years) were sampled. Three compartments were sampled in each of the two site classes. In each compartment, sampling continued until 100 infested trees had been recorded. For each infested tree, a 10 cm long twig was pruned from the middle crown whorl. Eggs, crawlers and adult aphids were observed and counts made under a dissecting microscope.

An infestation experiment was established to elucidate growth impact of P. pini infestation on young P. patula seedlings after 24 weeks of growth.

The main findings of the study were that:-

- Population densities were higher in trees of poor sites compared to trees of good sites. The percentages of infested trees were equally high at both good and

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CHAPTER 1

INTRODUCTION

Large scale planting of exotics in Tanzania started around 1950. At present the area under exotic forest trees in Tanzania is about 82,000 ha (Forest Division 1986, Anon 1988). About 88 per cent of the total area is covered by softwoods, the most common species being *Pinus patula*, *P. elliottii*, *P. caribaea*, *P. oocarpa*, *P. kesiya* and *Cupressus lusitanica*. Hardwoods are grown on the remaining area, the dominant species being *Tectona grandis* and *Eucalyptus*.

Sao Hill, with about 42,000 ha planted (93 per cent softwoods) is the largest forest project in Tanzania. Here, the main species planted are *Pinus patula*, *P. elliottii*, *P. caribaea*, *Cupressus lusitanica* and some *Eucalyptus* species. The performance of the tree species at Sao Hill is quite variable. Both biotic and abiotic variables account for some of the variation (Procter 1967, Waring 1982, Diwani et al. 1984a, Canon 1985).

Past reports of forest tree diseases in Tanzania (Griffin 1968) have shown that several diseases previously unknown have developed after the introduction of exotic trees. This has also been the case with forest insect pests, both native (local) and introduced. However, very little has been systematically documented on the subject, compared to what has been done in the neighbouring countries of Kenya and Uganda (Gardner 1957, Austarå and Jones 1971). The first interim report on forest insects of Tanzania was compiled by Mshiu (1984). In 1984, continuous forest insect surveys were initiated. Investigations on potential pests in form of assesment of the damage were also undertaken. These were followed by superficial observations of the causative biotic factors (Diwani et al. 1984a & b).

Several epidemics of forest insect outbreak have been recorded in Tanzania, however in small scale. The most common defoliators are: Gonometa podocarpi, Lechriolepsis basirufa, Orgyia mixta, O. basalis, Icerya purchasi, Dasychira georgiana, Chromothericles sp., Plagiotriptus pinivorus and Heteronygmia dissimilies. These insects are all native living on indigenous host plants but have adapted to the exotics. Pineus pini and Eulachnus rileyi are introduced sap sucking insects. (Forest Division 1982, Mshiu 1984, Diwani et al. 1984b, Schabel et al. 1988). Some of these insects are posing a great threat to our forests, particularly the exotic conifers. Furthermore, there is no reason to believe that other pests may not adapt to the exotics.

As just mentioned, the introduction of exotic softwoods has been followed by the introduction of some of their pests. Pines and Cypresses are very susceptible to attacks by various aphids (Carter 1971, Carter and Maslen 1982). At Sao Hill *Pinus* spp. are attacked by both the pine woolly aphid (*Pineus pini*)and the pine needle aphid (*Eulachnus rileyi*) while *Cupressus lusitanica* is attacked by a *Cinara* sp. (Diwani et al. 1984a&b, Kisaka 1988). At present, the infestation at Sao Hill has given concern to the Forest Division, Tanzania. Kisaka (1988) has recommended that continuous pest survey should be undertaken, furthermore to start breeding programmes for resistance, to undertake chemical control and to carry out various silvicultural practices.

The conifer woolly aphids belong to the family Adelgidae and many of the species are recognized as important pests of *Abies*, *Picea*, *Tsuga*, *Pseudotsuga*, *Larix* and *Pinus*. Carter (1971) describes the family to contain two genera, *Adelges* and *Pineus*. The genera that are used by Börner and Heinze (1957) other than *Pineus* and *Adelges* are described as sub-genera. In this study *Pineus* is discussed.

Before man started afforestation with pines in the southern hemisphere, *Pineus* species must have been restricted to North America, Europe, the Mediterranean region and Asia (Browne 1968). Some were introduced in East Africa in the late sixtees during afforestation programmes with temperate softwood species (Odera 1974, Barnes et al. 1976). In Eastern Africa where only Pinus spp. are grown, the pest don't alternate between primary and secondary hosts (Odera 1974, Barnes et al. 1976). In temperature zones, this species alternates between the two hosts when the primary host is present (Chrystal 1937, Balch and Underwood 1950, Carter 1971).

Surveys carried out in Tanzania in late 1960's revealed that some trees were infested in a Pinus radiata seed orchard stand that was planted in 1967 at Sao Hill from Australian materials (Odera 1974). Infestations were also reported during the same time from seed orchards that were planted in 1968 at Muguga in Kenya and West Kilimanjaro, Tanzania, from the same nursery materials. The infestation at Sao Hill and West Kilimanjaro implies that the pest was probably distributed with the planting stock from East African Agricultural and Forestry Research Organization's (EAAFRO'S) nursery, which was the sole distributor of the seed orchard materials (Odera 1974). At the end of March, 1973, the infestation had covered about 1,700 ha in Tanzania (Odera 1974). Today, in 1989 nearly all pine plantations in Tanzania (Figure 1) have been infested, only with varying degree of attack (Diwani et al. 1984a).

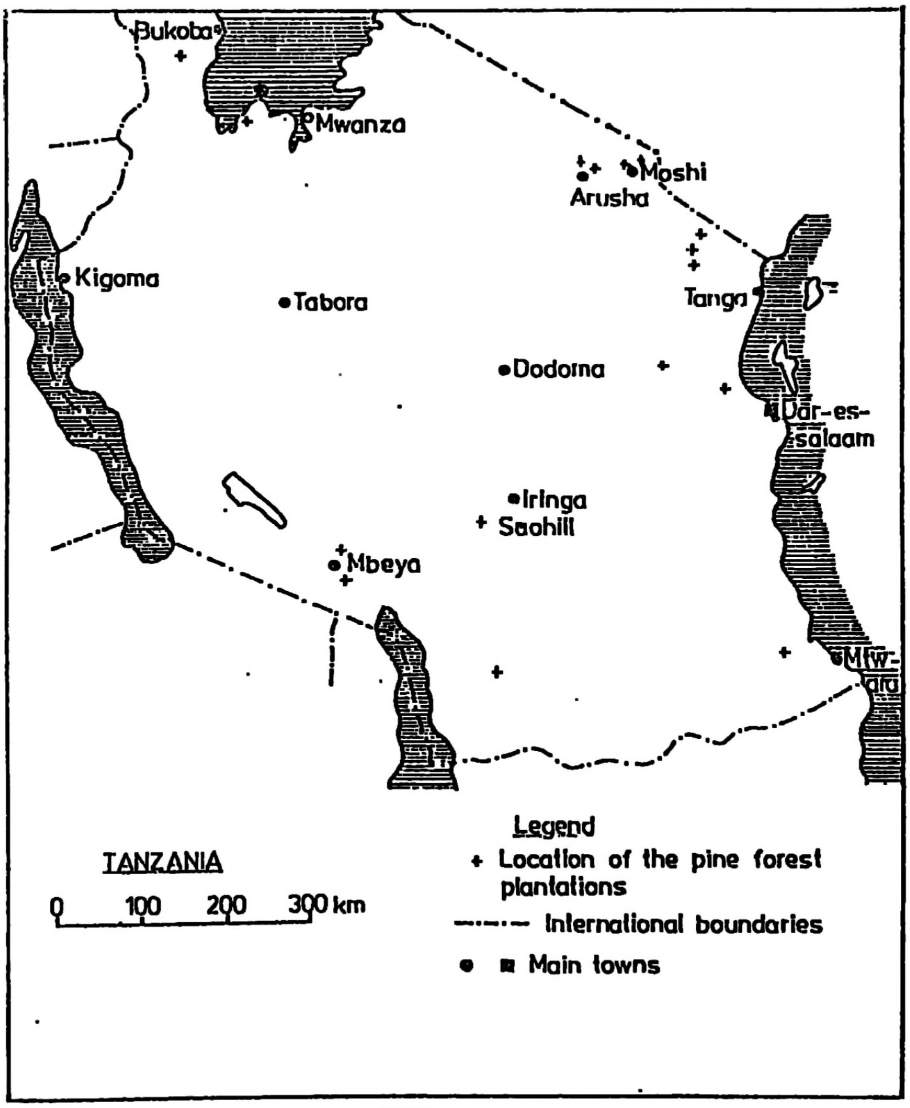


Figure 1. Distribution of the pine plantations in various parts of Tanzania.

Several studies have been initiated in Tanzania on the status of the pine woolly aphid. This include the population dynamics, the impact on tree growth and biological control. These studies are in a very early stage to give any conclusive remarks. Surveys carried out at Sao Hill revealed that tree mortality and growth loss is associated with heavy attack, especially in young stands grown in inferior sites (Mansy 1988, pers. comm.).

No systematic scientific work has been done todate in Tanzania to assess the occurrence of this aphid in relation to stand site productivity. A number of biotic, edaphic and climatic factors are known to influence the relative abundance of insect populations (Berryman 1981). A sound approach to elucidate a complex problem, is to single out one (or a few) factors for closer studies. The information so obtained may assist in future pest management systems, which may include various silvicultural procedures. The present study was therefore carried out at Sao Hill with the following objectives:

- to examine the relationship between pine stand productivity and abundance of the pine woolly aphid.
- to elucidate the impact of *P. pini* on tree growth.

CHAPTER 2

LITERATURE REVIEW

Pineus has been well studied in Europe, Russia and North America. Over the last few decades there has been some work on this pest in the tropical and subtropical regions of Australia, Tasmania, New Zealand, South America and in Africa.

In this chapter the historical review of the pest is given, emphasis is on the most recent work on the pest/host relationship and the related subjects.

2.1 Family Adelgidae

2.1.1 Historical review

Citing from Ghosh (1983) the adelgids were known, according to Annand (1928), as far back as 1583. However, Cholodkovsky (1896) gave the first valuable contribution to the knowledge of the group. The biology and taxonomy of the adelgids was first described by Börner (1908) and the first monograph on the biology was published by Marchal (1913). Nearly all the available information on this group of insects was compiled by Annand (1928).

Inouye (1953) and Börner and Heinze (1957) have given detailed accounts of adelgids of Japan and Europe, while Eastop (1966) and Shaposhnikor (1967) have contributed with keys for identification of the USSR and Australian fauna. Carter (1971) has given a world check-list of the species within the family. In Eastern Africa sub-region this study came in the late sixties and the pioneers include: Brown (1968), Mailu (1972), Odera (1974), Barnes et al. (1976). The present world fauna includes over 46 species, many of which are known only from a single host (Ghosh 1983).

2.1.2 Description of the family

Within the order Homoptera the superfamily Aphidoidea has three families, namely Aphididae, Adelgidae and Phylloxeridae. The later two differ from the first in that both sexuales and parthenogenetic forms are oviparous as opposed to viviparity in the parthenogenetic forms of Aphididae. The fore wing is devoid of radial sector, which is otherwise normally present in Aphididae. Adelgids in general have short 2-5 segmented antennae, with 2 primary rhinaria in apterae and 3 in alatae; the wings are usually held roof-like in response and the cubitus 1 and 2 remain separated in the fore wing (Ghosh 1983).

The adelgids are known to feed only on Coniferae. Normally, the biology involves host alteration, the primary hosts being Picea spp. and the secondary hosts are species of other conifers. On the primary host, characteristic galls are formed as a response by the plant to the feeding of the fundatrix on the developing terminal bud (Ghosh 1983). A total of 5 generations (of which 4 are parthenogenetic) covering a period of two years complete the normal lifecycle (Carter 1971, Ghosh 1983).

They may have also a monoecious anholocyclic life cycle with only two generations of sistens and progredious forms, where primary host is absent. Where secondary hosts are absent, the generations consist of pseudofundatrix and alate non-migrants (Chrystal 1937, Carter 1971).

2.1.3 Genus Pineus

The main morphological feature that separates Pineus from Adelges lies in the reduction of the abdominal spiracles in the former to four distinct pairs, Adelges has five. Other differentiating features are mostly confined on the head and the wax glands (Carter 1971).

All stages of the Pineus species are extremely small, bearely visible to the naked eye, and their presence can usually be detected only from the presence of small tufts of white "wool". These small clumps of "wool" appear initially around the base of the pine needles on the young growing shoots. As the number of aphids increases, a solid mass of "wool" is produced which may spread down the branches of the tree and even on the trunk.

Beneath each of these tufts of "wool", which is in fact a waxy exudation, will be found a feeding insect, reddish or purplish brown in colour and just under 1.0 mm long. When mature, these "feeders" are often surrounded by about a dozen yellowish-orange eggs each about 0.3 mm long. From the eggs hatch small "crawlers", flattened straw-coloured insects each about 0.4 mm long: these are capable of active crawling and may also be carried by the wind. After a short period, the "crawlers" settle down in a suitable feeding site, insert their sucking mouthparts into the host tissues and develop into the "wool" covered feeding and reproductive stages (Brown 1968). Citing from Mailu et al. (1980), Odera (1972) showed that the length of the life cycle for the Pineus species found in East Africa is 75± 7.3 days in the field at any time of the year (19.0°C to 24.5°C), thus it has overlapping generations over the year.

The crawlers have about four instars. Dispersal occurs mainly during the crawler stage, but also eggs are transported by wind (Mailu 1972, Odera 1974). Adults are wingless females, but also winged females are produced. However, these winged adults die out, unlike in the northern temperate regions where these winged adults move to the primary host (Mailu 1972).

In the species recorded in E. Africa, no males have been noticed. Wingless females reproduce parthenogenetically, and eggs are laid in groups. About sixty eggs are found clustering around the females and these eggs hatch in about 10 days (Mailu 1972).

Pine woolly aphid crawlers are positively phototactic, but do not settle onto surface exposed to strong light (Mailu et al. 1982b). This characteristic makes them settle in the hidden and tight crevices, hence an important factor for aphid survival.

2.2 Introduction, spread and host trees of the pine woolly aphid in East Africa.

The pine woolly aphid was introduced in Rhodesia (now Zimbabwe) and Kenya on *Pinus taeda* and *P. caribaea* scions imported from Australia in 1962 and 1968 respectively. These are the first known occurrences of the genus *Pineus* in Africa south of Sahara (Odera 1969 and 1974, Barnes et al. 1976). In his world check list of the family Adelgidae, Carter (1971) listed *Pineus* species occurring as pests on pines in South America and Australia but did not mention any *Pineus* species in Africa south of Sahara. The pest has not been reported from Uganda, Zambia and Malawi (Odera 1974, Löyttyniemi 1980, Katerere 1983, Salender and Bubala 1983). This was partly because these countries did not participate in joint seed orchard planting programmes as did Tanzania, Kenya and Zimbabwe (Odera 1974).

In Kenya, where the first observation was made in 1968, the spread had obviously occurred very fast. In the same year, heavy infestation was found in pines around Muguga (centre of infestation). In Zimbabwe, the initial spread was slow. However, it picked up in 1968 (when first noticed) partly because the condition was very favourable for population build up (Barnes et al. 1976).

In Tanzania, the pine woolly aphid was first found at Sao Hill and West Kilimanjaro forest plantations in 1968 (Odera 1974). Tanzania which was a member of East African Agricultural and Forestry Research Organisation (EAAFRO) and participated in seed orchard planting programme probably got the pest through _P. radiata_ nursery planting stock imported from Australia through Kenya in 1964 (Odera 1974).

The initial introduction of _Pineus_ was probably in the form of a few eggs lodged in the needle bases or bud scales of the scions (Barnes et al. 1976). Barnes et al. (1976) reported that spread of eggs and crawlers was probably carried on the clothing of men working in the nurseries, or by distribution of nursery stock. Spread within plantations was fast through wind dispersal of flightless crawlers and eggs, or by insects, birds and other animals. Spread was faster in large and uniform stands/monocultures than small and isolated stands (Odera 1974).

In East Africa, about 41 species of pines have been introduced and about 30 species are recorded as furnishing food for the pine woolly aphid (Odera 1974, Barnes et al. 1976). Certain species and varieties of conifers are more prone to attack, and support higher aphid development rates than others (Barnes et al. 1976, Mailu et al. 1982b, Carter and Nichols 1985). For example, in Eastern Africa Pinus massoniana, P. virginiana, P. elliottii, P. contorta and P. radiata were the most favoured species. P. patula was readily attacked while P. ayacahuite and P. strobus var. Chiapensis were found resistant (Odera 1974, Barnes et al. 1976). In E. Africa, development is restricted to pines since the primary host of the aphid (Picea sp.) is not grown on the African continent (Odera 1974). Pines of all sizes are attacked (Odera 1974, Barnes et al. 1976).

2.3 Taxonomic status of the species in East Africa

The woolly aphid was tentatively identified as P. laevis or P. pini according to Dr. W.R. Richards of Canadian Entomology Research Institute (Odera 1974). Development of P. laevis is restricted to P. radiata and is characterized by a cephalic shield bearing gland-facets in three groups, about the same size and arranged in small clusters of two to five glands each. In contrast, the cephalic shield in P. pini, bears distinctly smaller gland facets adjacent to or mixed with large ones.

One problem was to decide whether these morphological differences indicate that different species are involved or whether they are the result of different plant microenvironments affecting the same species (Odera, 1974). Differences in size perhaps indicate a degree of suitability of particular pines as a source of nourishment. The occurrence of slightly different specimens from different plants is probably natural, since every parthenogenetic egg gives rise to a parthenogenetic clone of different genetical constitution. A certain degree of morphological variation within a single collection is therefore expected (Odera 1974).

Unlike P. laevis, P. pini attacks a large number of pine species and Dr. Richards suggested that the species could be called P. pini (L). However, Eastop (1988) is of the opinion that the P. pini/ laevis complex is an unresolved mystery, requiring further investigations.

2.4 The pine woolly aphid situation at Sao Hill

At Sao Hill the pine woolly aphid was found in all the four divisions of the project, only with varying degrees of attack. General surveys showed a decrease in this pest in some compartments particularly in the older stands, contrary to what was expected when first spotted in the late sixties (Kisaka 1988). This was due in part to the predators. It seems there is time lag between the aphid infestation and predator establishment in the young stands. This means that young stands may be more affected by sap suckers than old ones (Kisaka 1988). The most abundant local predators were:

Exochomus spp., Coccinellidae, Coleoptera

Chrysopa spp., Chrysopidae, Neuroptera and

Allograpta spp., Syrphidae, Diptera.

These predators are not well established at Sao Hill for effective population reduction (Mshiu 1984).

Tetraphleps raoi, an Anthocoridae, Hemiptera, imported from Pakistan and released at Sao Hill in 1979 was found in almost all the pine woolly aphid infested areas. It has however, not reduced the population sufficiently to prevent tree growth reduction and occasional tree mortality (Kisaka 1988).

2.5 Population dynamics

Insects do not normally cause serious damage to forests unless their numbers increase for some reason or another, to very high densities (Berryman 1987). Berryman (1981) discusses some factors responsible for population dynamics of forest insects. Theoretical and empirical studies demonstrate that site characteristics have important effects on the dynamics of herbivore insects. Given an economically acceptable level of activity (an economic threshold) then sites can be classified into acceptable and unacceptable for planting particular tree species.

Population dynamics as they relate to forest insects is essential for both forest managers and insect pest managers for without it they will often find themselves grouping in the dark for solutions to their pest problems and may even make decisions that compound rather than solve the problems (Berryman 1987).

Several studies on host plant/aphid interaction have been conducted. However, it has proved difficult to estimate how far such aphid/host interactions contribute to aphid population regulation in the field (Dixon 1979). This is partly due to the fact that most aphid species tend to exploit a succession of host plants and disperse over large areas, leading to insurmountable difficulties in population sampling. Also the well established methods for examining the population dynamics of insects with discrete generations are not generally applicable to aphid populations which have overlapping generations. Alternative techniques have either proved unsatisfactory (Carter et al. 1978) or have been of limited use in providing biological insights (Perrin 1976).

Computer simulation methods have been applied successfully in a number of aphid population studies. Using system simulation approach for example, Kidd (1985) found that seasonal changes within trees have an important influence on growth development and reproduction and mortality of Cinara pinea. In another approach, Gilbert et al. (1976) developed models potentially capable of assessing the relative importance of all the factors influencing population fluctuations.

In East Africa wide fluctuations in numbers of the pine woolly aphid have occurred, and these variations in the population densities were related to rainfall and activities of the predators (Barnes et al. 1976, Mailu et al. 1980). Crawler dispersion and heat have also been implicated as causing mortality to the aphids (Mailu et al. 1980).

2.6 Infestation pattern and population estimation.

2.6.1 Infestation pattern.

Aphids and other light-bodied insects may be carried long distances by wind. Successful establishment of air-borne insects or those transported by other agencies depends on their longevity and ability to find susceptible hosts (Johnson 1969).

Infestation pattern of Adelgidae may be sporadic or focal. Sometimes medium sized trees are infested; in other instances only young plants are attacked (Ghosh 1983). Odera (1974) observed the infestation of pine woolly aphid to occur in patches within individual stands, and thus trees under heavy, moderate or light infestation coexisted with individual trees which were not infested.

The mode of insect distribution on the tree is mainly affected by light, temperature and wind, and so the insects could attain the favourable microclimatic sites (Salama and Saleh 1974). The effect of variation in plant tissue quality on the success of insect herbivores has thoroughly been studied (Larsson 1985). Some of the best known examples of adaptations to within-plant differences in tissue quality are found among sap-feeding insects (Wratten 1974, Parry 1974, Carter and Cole 1977). Aphids of the genus _Cinara_ feed mainly on stem and branch internodes of various conifer species and are known to change their feeding sites within the crown as the growing season proceeds (Carter and Maslen 1982). Three species of _Pineus_ feeding on red pine, _Pinus resinosa_ had different patterns of colonization (McClure 1982).

On P. patula the highest number of pine woolly aphid is found in the middle crown (Mailu et al. 1982a). This agrees with the findings of Ford and Diamond (1973), on P. strobus and also Lasota and Shetlar (1986) on Douglas fir but disagrees with the findings by Diamond and Allen (1974), on Picea abies. Further, McClure (1982), found high concentrations of Pineus boerneri and P. coloradensis on the lower branches of 3-year old growth Pinus resinosa. The lower and middle crowns of P. patula and P. resinosa receive less direct rays of the sun owing to shade of branches above it. This would tend to encourage aggregation of aphids in the middle crown where there is less strong direct light. On the other hand, spruce crown tend to be thick, with less sunlight penetrating through middle parts of the tree crown, leaving some without enough light. Aphids would, therefore, tend to aggregate in the areas with light, hence their heavy concentration in the upper branch whorls on spruce (Ford and Diamond 1973). Working with Eulachnus rileyi, Odendaal (1980), found large numbers of insects where light conditions are good.

2.6.2 Population estimation

The estimation of insect abundance is an essential part of almost every phase of modern forest pest management. In such operation labour and costs must be considered (Morris 1954). Instead of counting total populations abundance is usually measured by an index that is relatively easy to estimate and related to insect numbers over the whole tree. Several methods have been suggested for some defoliators, the commonest one uses insect density in the middle part of the tree (Srivastava et al. 1984, Mason 1987). Other cheap and relatively efficient methods include simple ocular estimation of defoliation accompanied by examination of tree crown foliage and estimating the percent of foliage removed (Connola et al. 1966). Aerial photography has also been used (Anderson 1964, Telerica 1981). Dealing with Pineus, needle length on the host tree and percentage of twig covered with "wool" have been used (Diamond and Allen 1974, Mailu et al. 1978a, Mailu et al. 1982a).

2.7 Economic importance of the pine woolly aphid

2.7.1 Aphid infestation and its impact on growth

Aphids are economically important insects since they attack most plants, infesting roots, leaves, stems and fruits. Although several well-known aphid species are polyphagous during parts of their life cycles, the majority of aphids are monophagous or oligophagous (Hille Ris Lambers 1950, Eastop 1973). By sucking the phloem sap they can cause deformities and loss of growth, their excretions can favour the growth of mould and they can transmit virus diseases from plant to plant (Carter and Nichols 1985, Kidd 1985).

The genus Pineus may contain several species which cause concern, when they attack and spread in pine plantations. These pests have long been of economic importance in the northern temperate zones (Browne 1968). In North America and Canada the pests have caused considerable losses in forestry, when both nursery stock and plantations are infested. During the onset of infestation, trees are often felled to control the spread of infestation, (sanitation felling) which itself contributes to the loss brought about by the pest (Yaseem and Ghani 1966, Browne 1968).

Attack by the Pineus leads to discoloration and defoliation, mostly of the old needles. The first sign of damage is stunted needles followed by abortion of buds (Dixon 1971a & b, Carter 1977, Mailu et al. 1978b).

In addition to stunted needles and needle shedding, the reduced increment observed in pines attacked by Pineus is also probably due to inhibition of bud growth, or reduced shoot elongation. The youngest branches are the most suitable for penetration by the stylets, hence the topmost branches would show the most stricking effects. With the young shoots dying, the whole plant may succumb depending on the degree of infestation (Mailu 1972, Tanton and Alder 1977, Mailu et al. 1978b).

The effect of Pineus infestation may vary with the species of the host, some species are capable of tolerating heavy attacks (Barnes et al. 1976). There is close relationship between the infestation density and loss of yield (DeBoo et al. 1964, Mailu et al. 1978a & b). Cummulative aphid attack could lead to tree mortality especially in plantations grown at inferior sites (Mailu et al. 1978a &b). As to the Balsam Woolly Aphid, Arthur and Hain (1986) showed that 2 - 7 years of continuous attack resulted in tree mortality. In the stem infesting aphid species, the salivary injections of these insects have some chemical effect on the cambium causing abnormally increased stimulation of growth which results in the production of hard brittle wood. (Balch et al. 1964, Mitchell 1967).

2.7.2 Evaluation of economic consequences

In any evaluation of the economic consequences of insect infestations all the following factors should be taken into consideration.

- the value of plantation at different stages,
- optimum rotation and interest-paying capacity,
- the loss of increment resulting from various degrees of infestation,
- the risk of successive infestations,
- tree mortality,
- secondary pests and
- the cost of control measures.

In a somewhat simplified way economic losses resulting from infestation can be calculated from the following relationships (Austarå 1968):

$$B = \frac{Yr}{1.0p^{r-d}} + \sum \frac{Ta}{1.0p^{a-d}}$$

$$L = B - B1.0p^{-t}$$

Where: L = Current value of the loss caused by infestation.

B = Value of the standing crop at rotation age and intermediate thinnings discounted back to the year of infestation.

Yr= The value of standing crop at rotation age.

P = The rate of interest.

r = The rotation age.

d = The age of the stand at the time of infestation.

Ta= Value of thinnings at the time of extraction.

a = The age of the stand at the time of thinning

t = Extension of rotation and delay in output of thinnings due to infestation.

From the above relationship, a clear indication can be obtained of the profitability or otherwise of applying control measures to prevent infestations (Austarå 1968).

2.8 Control measures

In any insect control programme, the main concern is with the species whose injurious potential is established and whose control is either a social or economical necessity (Clark et al. 1982). Several control measures have been discussed and they broadly include: chemical, biological, silvicultural and genetical. Amongst the aphids and other tree feeding insects there is considerable variation in life cycle pattern, so much, so that for effective control purposes the species must be studied in the environment (Carter 1975). As aphids can be very efficient immigrants and as they have a high reproductive potential, some long lasting approach to pest control programme have been suggested (Carter 1975).

Chemical spraying is detrimental to non-target organisms, contaminates environment and is very expensive. Timing of application and optimal coverage of the shoots with the insecticide are critical to control, however, difficult to achieve (deGroot 1985). It should therefore be used as a short-term measure when all other fail. Exclusive reliance on insecticides in pest control have created problems in insect control and environment (Metcalf 1986). These problems strengthened the need for methods based on understanding and management of the ecosystems. A growing body of information on the reproduction (Lowery and Sears 1986) and behavior (Gibson et al. 1982, Boitean et al. 1985) of insects should also be considered.

Several chemical insecticides have been tried against P. pini in E. Africa (Brown 1970). Odera (1971) suggested that propoxur and endosulfan are the most effective insecticides against all developmental stages of P. pini in E. Africa. Gamma BHC spray was partly effective in

Kenya but was not successful in Zimbabwe (Odera 1971, Barnes et al. 1976). Chemical spraying to eradicate P. pini showed complete failure in Hawaii (Culliney et al. 1988).

A variety of parasites, predators and pathogens control forest insect pests and can play a significant role in regulating insect population (Price et al. 1980). The natural enemy complex of the Adelgidae comprises parasites mostly belonging to the Chalcididae, Proctotrapidae and predators of Coleoptera (Coccinellidae), Diptera (Chamaemyiidae), Hemiptera (Anthocoridae), Neuroptera and Acarina (Anystidae). Most of the natural enemies are known of host genera Adelges, and Pineus (Ghosh 1983). Species of Leucopis (Diptera: Chamaemyiidae) have been considered the most important predators of adelgids in Europe (Ponomarera and Gabrid 1984) and Africa (Eichhorn 1968). Chacko (1973) describes Tetraphleps raoi as the most important predator of Pineus sp. at Shillong, India. Its importance is associated with the feeding habit which devour all stages of Pineus. Leucopis was also found to be important (biocontrol). Culliney et al. (1988) reported L. obscura to have regulated P. pini at its higher densities, to below economically significant levels in Hawaii.

Both local and introduced predators have shown some positive effects in controlling Pineus in Eastern Africa

(Mailu 1972, Barnes et al. 1976, Mailu et al. 1980, Diwani et al. 1984b). Accordingly there is clear evidence that Exochomus species is the most abundant and effective local predator attacking P. pini in Eastern Africa. On the other hand, Tetraphleps raoi is one of the most effective exotic predators of the Pineus.

Working on predator release program for balsam woolly aphid, Harris and Dawson (1979) found similar results as those obtained in E. Africa with Pineus. On the other hand Clark et al. (1971) found predaceous Diptera and Coleoptera well established, but not significantly reducing the damage in Abies species. Parasites and highly-virulent polyhedrosis virus have been found an outstanding example of the biological control of an introduced insect (Clark et al. 1982).

There is considerable evidence to suggest that the correct siting and proper management practices of pine species are important silvicultural factors in the control of Pineus (Barnes et al. 1976). Several beetle pests have been reduced to a tolerable level by simple silvicultural operations (Waring and Pitman 1980, Larsson et al. 1983). Studies to evaluate the effects of silvicultural treatments on a number of suggested indices of susceptibility have been undertaken (Matson et al. 1987).

There are a few trees that have good reputation for resistance to aphid attack (Odera 1974, Barnes et al. 1976, Hoff and MacDonald 1977, Mailu et al. 1982b). The reasons for resistance to aphids are practically unknown and deserve investigation (Carter 1975, Hoff and MacDonald 1977). From these studies breeding for resistance poses good prospects for the control of *Pineus* (Barnes et al. 1976, Tanton and Alder 1977). These prospects agree with the work of Odendaal (1980) and Hoff and MacDonald (1977) on *Eulachnus rileyi* and *Pineus coloradensis* respectively. It seems that when we understand and manipulate the nutrition of our trees we may be able to impose a more subtle yet effective regulation on our aphid pests (Carter 1975). Another and yet promising control measure is the Integrated Pest Management (IPM) as for example discussed by Coulson and Stark (1986) and Bostanian and Coulombe (1986).

2.9 Mechanisms of stand susceptibility and outbreaks

Site factors are a set of physical parameters on which a particular forest stand grows. The physical structure of a vegetation, and its associated microclimate, the influence of parasites and predators and the host finding and reproductive behaviour of the insect play an important role in determining the level of insect attack (Lario 1978, Hodkinson and Hughes 1982). The suitability of a particular site for plant growth depends on soil, physical and chemical characteristics and climate. On the other hand the susceptibility of a plant to attack and injury by phytophagous insects is often related to the degree of climatic stress on that plant (White 1969 and 1974, Barnes et al. 1976).

Host-plant suitability and acceptability have traditionally been measured as separate components of host-plant preference (Hanson 1983, Lance 1983). Martinat and Barbosa (1987) provided evidence that the usual methods of assessing a host's suitability may actually confound effects of its acceptability. In general insects are likely to cause more damage as site conditions become more xeric (Bejer-Petersen et al. 1974, Barnes et al. 1976, Löyttyniemi 1979, Odendaal 1980, Berryman 1981, Heikkenen 1981, Larsson and Tenow 1983). Air contaminants may influence outbreak patterns of forest insects. However, causal relationships have usually remained uncertain due to lack of experimental studies (Neuvonen and Lindgren 1987).

Stand density and age are important variables associated with the probability of insect damage to forests (Furniss et al. 1978, Edwards and Wratten 1980, Stoszek et al. 1981, Berryman 1987). For example, bark beetle outbreaks have been associated with high stand densities presumably because high densities lead to poor host condition or low vigour (Matson et al. 1987). Both preformed static defence and induced dynamic defences offer barriers to insects against plants (Edwards and Wratten 1985, Berryman 1987). Considerable amount of energy is needed to synthesize defensive chemicals (Waring and Pitman 1980) and the amount of energy reserves of plants depend on many factors, including light, soil nutrients and water, season of the year and plant ageing (White 1974, Mattson 1980, Larsson and Tenow 1984, White 1984, Carter and Nichols 1985).

The species composition of a stand may also directly affect the production and survival of insect pests. The insect species must be able to select its particular food plant(s) from amongst the complex array of available species and it must ensure that the period of feeding activity coincide with periods of plant availability (Stoszek et al. 1981, Hodkinson and Hughes 1982).

The relationships between site characteristics and the suitability of the insect habitant are important arrays to anticipate the intensity of insect activities on a particular site. Direct relationships are easily assessed as compared to indirect factors. Indirect factors should however be in our mind when carrying out insect population studies. Because of the association between environmental conditions and stand susceptibility, silvicultural practices can be used to improve stand resistance (Belanger and Malac 1980).

2.10 Forest site productivity

The capacity of a tree species to thrive and successfully compete on a particular site is influenced by both internal (physiological makeup of the tree) and external (environmental) factors (Pritchett 1979, Berryman 1981). The external factors of which soil forms the major component are very important in determining site quality, i.e. the capacity of the land to produce trees. Site productivity can therefore be considered as the sum total of site quality and management input (Pritchett 1979). Productivity is however, subject to varying degrees of alteration by manipulation of growing stock or modification of the site.

Pragmatically, the goal of any evaluator of forest site productivity is to select a relatively few easily measured soil and site factors that integrate all other factors that are important to the growth of a particular species. The most important factors include stand density, genetic differences of the species, competition control, disease and insect problems, climatic, physiographic and soil factors (Pritchett 1979).

Direct measurements of forest productivity on a site that is thought to be best suited for timber production is not always possible, because suitable stand for measurement may not exist. Methods have therefore been found to make possible sufficiently accurate estimates of productive capacity by reference to certain permanent factors of the environment for example indicator plants that are easily measurable and mappable (MacLeod and Running 1988).

2.10.1 Site quality

Forest site quality estimation generally intends to quantify potential productivity (Carmean 1975). Commonly the forester measures productivity (tree or stand) and assumes that it closely approximates the potential of the site (Hagglund 1981). It can be assessed directly or indirectly (Schönau and Whihelmij 1980). Site index is presumably the most widely used indicator of site quality in forests (Tesh 1981). It is defined as the height of dominant trees in an even-aged stand at a specified base age. For a given species at a given age, dominant height is closely related to the capacity of a given site to produce wood of that species (Spurr and Barnes 1980). Observed productivity is however, a complicated manifestation of the interactions between biotic and abiotic factors (MacLeod and Running 1988).

The determination of site index is usually accomplished by measuring the height and age of a number of trees in a forest stand, assessing a set of guide curves with these data pairs, and inferring site index by interpolating height to the base age. Real site index can only be derived by using stem analysis techniques or by measuring stands at the appropriate base age (MacLeod and Running 1988). Several other methods for determining site quality have been suggested (Lee and Sypolt 1974, Schönau and Purnell 1987).

The usual systems of site quality determination involving the measurement of standing timber provides the required data if the area under consideration is stocked with stands of the desired species which are sufficiently mature to permit application of the method. From qualitative viewpoint, low level of productivity is usually associated with extremely arid soil conditions and the occurrence of high yield on deep moist well drained sites (Kozlowski 1982). The method in use should well be defined in advance for sound conclusion on the site quality.

2.10.2 Site/insect interactions

Site characteristics can affect the suitability of insect habitats on two basic ways; they can have a direct effect on insect survival and reproduction and they can indirectly effect these parameters through their influence on the host plant (Figure 2).

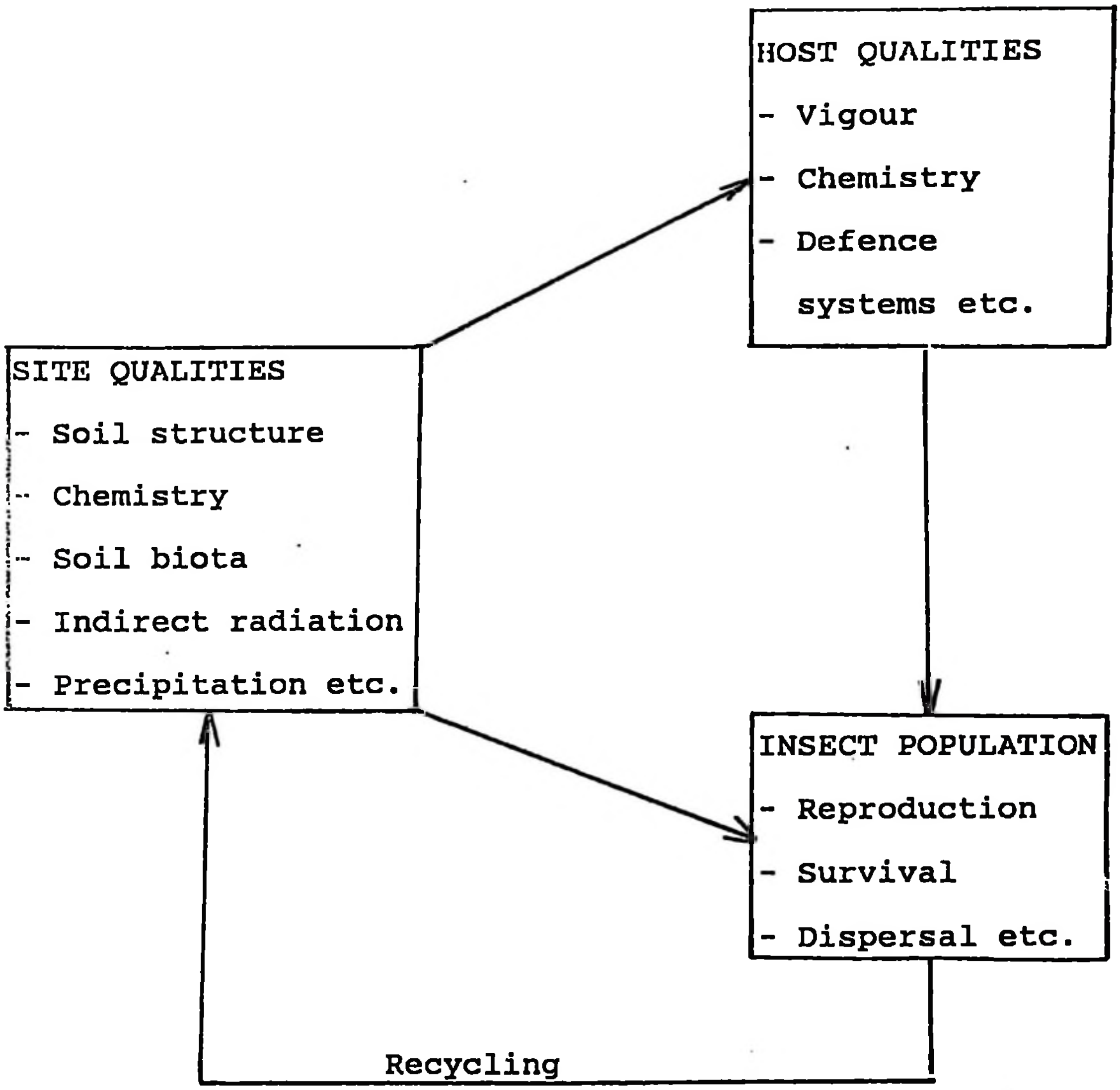


Figure 2. Direct and indirect interactions between characteristics of the site and herbivore insect populations (Berryman 1981).

Berryman (1981) gives a theoretical relationship between site characteristics and damage by insect herbivores. Reduction in tree survival, growth and yield as a result of attacks of insects and diseases have long been recognized (Berryman 1987). In most instances where substantial numbers of trees are killed or severely damaged, the effects of the pest on site productivity are easy to recognize and estimate. Susceptibility of some species to insects and diseases varies depending on the growing site, those in inferior sites having higher colonization/incidences of attack (Carter and Nichols 1980).

Some insects such as the southern pine beetle can cause major tree damage and significant reductions in site productivity. Insects such as tip moth (Rhyacionia spp.) and pine sawfly (Neodiprion sp.) may result in the loss of one or two years growth, but they have little lasting effect on productivity. In most instances the pest damages can be identified and assessed. Many of these insects are found in stands of poor vigour, where outbreaks are often triggered by soil moisture stresses and natural or human disturbances (Berryman 1981, Pritchett 1979, Arthur and Hain 1986). Exotic trees could have higher production in absence of their natural pests and diseases (Jackson 1965).

2.11 Sampling techniques

Many pest management programmes do not require exact estimates of population density but rather require that pest populations are categorized into density classes which are related to predictable levels of crop loss.

As it is normally impossible to count all the individuals in a population, it is necessary to estimate the population by sampling. Naturally the estimates should have the highest accuracy commensurate with the amount of work expended, and if this is to be so a sampling programme which lays down the distribution, size and number of samples will need to be drawn up. There is no universal sampling method, however, optimal sampling designs are those that provide a good estimate of the population mean density with the least number of samples (Southwood 1987).

Sampling of a particular insect population must be resolved about the distribution and life cycle of the insect involved (Graham and Stark 1954). If life-cycle is known, preliminary work is necessary to gain some knowledge of the distribution of the insect and the cost (work involved) of the sampling. The researcher also needs to be clear as to the exact problem he is proposing to investigate (Morris 1960).

Sequential sampling is also an important tool for an extensive forest insect survey program, which seeks to monitor changes in the distribution and density of insect populations over large areas (Iwao 1975). Sequential sampling often reduces the number of samples required to make a decision about control requirements by assessing the data as they are collected. Waters (1955) gives the mathematical plan for any insect and he concludes that the cost of scouting can be reduced by as much as 50 percent. Sequential sampling plans are available for many important biological problems and for several forest pests (Morris 1954, Connola et al. 1959, Mailu et al. 1978a, Turgeon and Régniére 1987, Régniére et al. 1988).

In forestry, sampling pattern is either random or systematic. Selection of a particular pattern depends on the object of the programme. Stratified random sampling is preferred to random or systematic sampling for most ecological work because dispersion is seldom, if ever normal (Abrahamsen 1968). Stratification should be based on information on the density distribution of the population.

Most insect sampling has however, suggested that small units, carefully stratified yield the most efficient design (Morris 1960). Appropriate sampling procedures for different developmental stages of conifer woolly aphid is discussed by Ford and Diamond (1973), Diamond and Allen (1974), Bryant (1976) and Mailu et al.(1982a).

Sampling intensity can be determined in two ways:

(i) By calculating the number of field plots required for a given probability level and allowable sampling error (Snedecor and Cochran 1980).

(ii) By selecting a fixed sampling intensity or number of sampling units before starting field work. This number can be decided upon based on the limitation of time and money available (Southwood 1987).

This chapter shows the complexity of problems with which one has to deal when studies of insect ecology are undertaken. It is also clear that in a short time study like a Masters dissertation, only a very limited part of such a problem complex can be studied.

CHAPTER 3

MATERIALS AND METHODS

3.1 Location

The experimental site is at Sao Hill forest project, Mufindi District, Iringa Region (Figure 3). The project is managed by the Forest Division of the Ministry of Lands, Natural Resources and Tourism. It is located at 8°18'S to 8°33'S and 35°6'E to 35°20'E.

3.1.1 Area and tree species composition

The plantation comprises of four main blocks, namely Division I, II, III and IV. The total area of the reserve is about 152,650 ha of which 60,000 ha is plantable, and up to 1988, 42,000 ha was already planted (Anon 1988). Divisions I and II have a total of 21,000 ha planted, division III and IV have 16,000 ha and 5,000 ha respectively. The main species are (acreage in brackets): *Pinus patula* (31,439 ha), *P. caribaea* (1,312 ha), *P. radiata* (209 ha), mixed pines (1,689 ha), *Cupressus lusitanica* (135 ha) and *Eucalyptus saligna*/ *grandis* (4,000 ha). In spite of its superior growth, the planting of *P. radiata* was abandoned towards the end of 1960's due to its susceptibility to the needle blight, *Dothistroma pini* (*Scirrhia pini*).

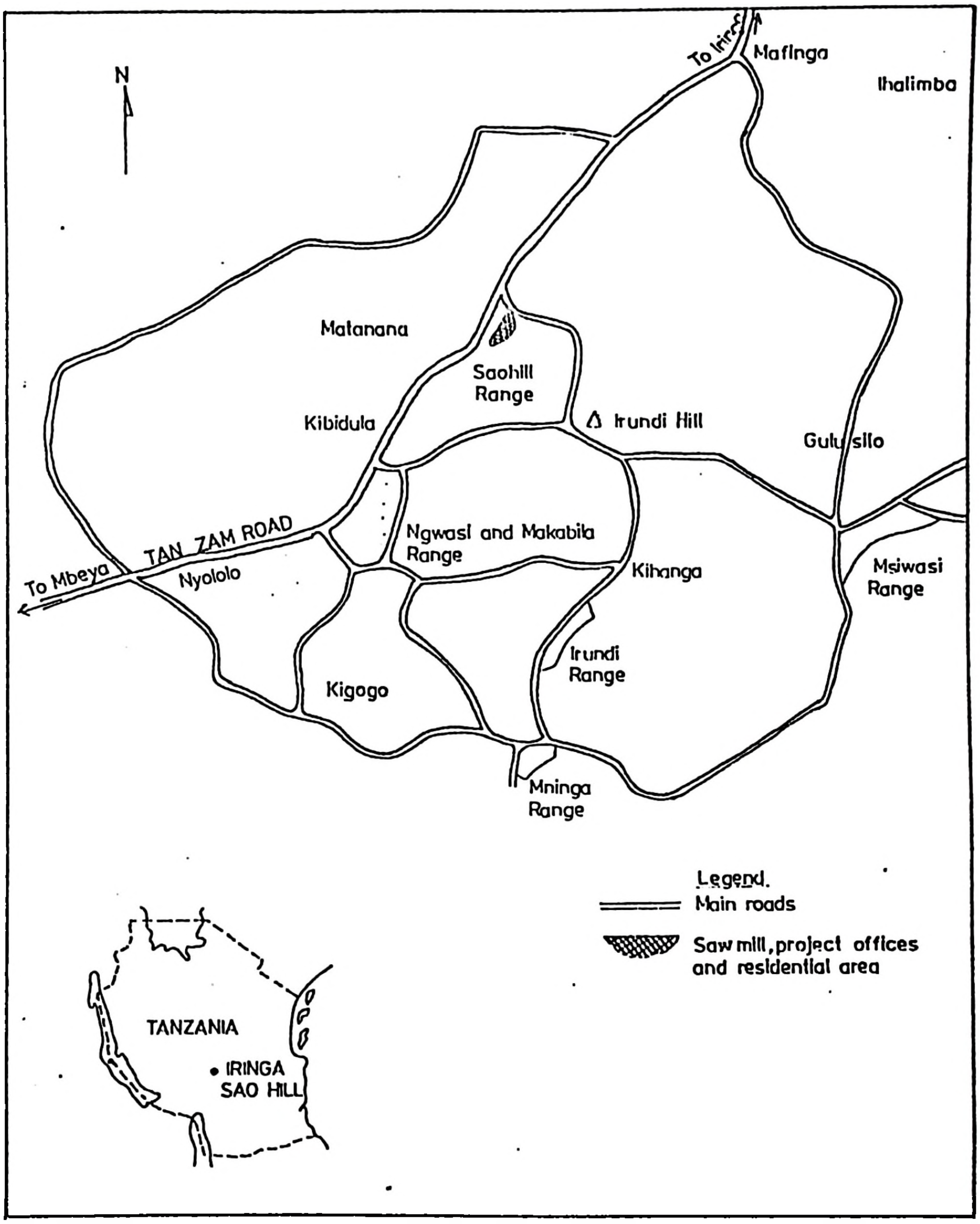


Figure 3. Sao Hill forest plantation map.

Lately, planting of *P. elliottii* is also stopped due to its slow growth, inferior wood for both timber and pulp production and susceptibility to pine woolly aphid (Mtuy 1988 pers.comm.). Present emphasis is therefore placed on planting *P. patula*, *Eucalyptus* spp. and finding alternative species to replace *P. radiata* and *P. elliottii*.

3.1.2 Climate

The climate at Sao Hill is characterized by rainy season from November to April and long dry season from May to late October. Detailed meteorological data for the Sao Hill is given by Nykvist (1976a). Rainfall ranges from 600 mm to 1500 mm per annum, with an average of 1300 mm. The escarpment in the east receives more rain than the rest of the project.

The temperatures are fairly cool, the mean monthly minima vary between 10°C to 18°C and maxima 23°C to 28°C. Temperatures are lowest in June and July during which frost may occur.

Prevailing winds are monsoons, which blow from south east in the dry season and north east in the wet season.

3.1.3 Topography, soils and natural vegetation

The land form is generally rolling, interacted with some low hills and wide flat-bottomed valleys. The altitude ranges between 1,700 m to 2,000 m above sea level.

The whole plantation is intersected by rivers and streams with wide swampy valleys.

A detailed description of the soils at the Sao Hill-Mufindi area has been given by Nykvist (1975). The soils are sandy loams with low base exchange capacity; pH ranging from 4.5 to 6.5. The soils are derived from the basement complex rocks and are generally considered as less fertile than those of volcanic origin. Nykvist (1976b) observed the following on the contents of macronutrients:

- There is no clear differences in chemical composition between catenas; and
- There is a high content of nitrogen and exchangeable potassium in the valleys and the lower parts of the slopes. No clear trend was observed for phosphorous, magnesium and calcium.

The dominant vegetation is savanna grassland. Some areas are bushy with species of Brachystegia, Albizia, Cussonia, and Julbernardia.

3.2 P. patula plantations at Sao Hill

P. patula was first introduced by the colonialists into the area in the 1930's. The first plots with seed crop origin from South Africa and Australia were planted at Kigogo arboretum. The plots along with other older plantations developed to being the main seed source for the afforestation at Sao Hill.

Large scale planting was not started until 1951. Prior to 1977, seedlings were being raised in Swaziland beds, at present tubed stock is used. Spacing has varied from one locality/division to the other, however 2.44 x 2.44 m is used in most blocks. Spot weeding is usually done about a year after planting. In the sawlog working circle, silvicultural treatments include pruning and thinning whereas the pulp wood circle needs only access pruning.

The current annual planting target is about 2,000 ha. The project is managed on two working circles, sawlogs and pulp wood (Anon 1988). The rotation is 15 to 16 years and 25 to 30 years for pulpwood and sawlogs circles respectively.

The performance of *P. patula* at Sao Hill is quite variable. On high quality sites, *P. patula* produce about 600 m^3 per hectare at rotation age (25 years) with mean annual increment of about 25 m^3 per ha. In certain locations, the performance of P. patula, P. elliottii and P. caribaea has been observed to be unsatisfactory (Tangwa et al. 1988). At Sao Hill, there are two main developmental projects which consume most of the wood produced from the plantation.

- A saw mill with an input capacity of 60,000 m^3 per annum and
- Pulp and paper mill with input capacity of 300,000 m^3 per annum

3.3 Pine woolly aphid at Sao Hill

As already mentioned, Pineus pini (Macquart) (Homoptera: Adelgidae) was first recorded at Sao Hill forest plantation towards the late 1960's as an isolated attack of Pinus radiata seed orchard planted in 1967 (Odera 1974).

From the seed orchard at Kihanga arboretum, infestation spread quickly to other pine species in the arboretum and later to the other parts of the plantation. Sporadic infestation is common at Sao Hill and the general trend shows east west spread of the aphid, probably following the direction of the monsoon winds. Division III laying north east and division IV in the further south of the plantation and well isolated from the centre of spread have the least infestation. The highest population of P. pini is found in the arboretum area possibly due to the various pine species grown there and to its situation near the centre of the epidemics.

Today, about 12,000 ha of P. patula distributed throughout the plantation are infested with P. pini with varying degree of attack. Dead trees, associated with attack are not uncommon, particularly in the inferior young stands (Mansy 1988 pers.comm.). Various predacious insects are present in nearly all sites with P. pini. The most common predators are found within the Chryosinnelidae, Syrphidae, Chrysopidae, Coccinellidae and Anthocoridae (Diwani et al. 1984b).

3.4 Field work

The following studies were conducted between September, 1988 and March, 1989.

(i) Sampling the pine woolly aphid populations

(ii) Infestation experiment

3.5 Sampling the aphid population

3.5.1 Preliminary sampling

Ideally this was done to determine the number of sample units (trees and twigs) required for a fixed degree of precision on the main sampling. Sampling was though preceeded by a general plantation survey aimed for the general impression of the aphid attack, age distribution and site productivity.

Three site classes I, II and III assumed from the general impression of the tree growth were used in this study (Hagglund 1981). Three age classes, young (< 10 years), middle (10 - 15 years) and old (> 15 years) were obtained from the plantation maps and used for the study. A total of nine compartments were sampled.

Since there were no site class maps for Sao Hill forest plantation, I used the work of Adegbehin and Philip (1979) to determine the site classes. This was later supplemented with the work of Chamshama (1979). On the basis of their work it was difficult to distinguish with a sufficient degree of precision between site classes I and II and II and III in the young age class. Ideally the experimental sites were supposed to represent widely differing conditions (site classes) so that comparisons of population levels could be based on broad ranges of differences. Based on these arguments, site class II was excluded from the main sampling.

In the selected compartments, sampling continued until 20 infested trees were recorded in each of the three sites and three age groups. Sampling was done from the middle edge east to west of each compartment. The first tree along the transect was randomly picked, using random numbers 1 - 10. Compass and pacing were used to determine direction and distance between sample trees. Every third tree was considered a candidate. However, the nearest tree along the line was taken for cases where pacing didn't hit a tree.

Once chosen, the trees were thoroughly checked for the aphid attack. This was done repeatedly until the 20 infested trees had been tallied. One twig was cut from the infested trees on the eastern orientation of the middle crown branch whorl. From each infested twig, a 10 cm long sample, measured from the latest point of attack towards the base, was cut (Mailu et al. 1982a). The samples were separately kept in polythene bags and stored in a refrigerator until aphid counts were undertaken in the laboratory.

Trees with age above 10 years were very difficult to sample. Therefore, for practical reasons (time and money were most limiting) sampling was to be restricted to only young age class between 5 and 10 years in the main sampling. Morover, experience at Sao Hill shows that pines in all age groups are prone to Pineus attack (Figure 4).

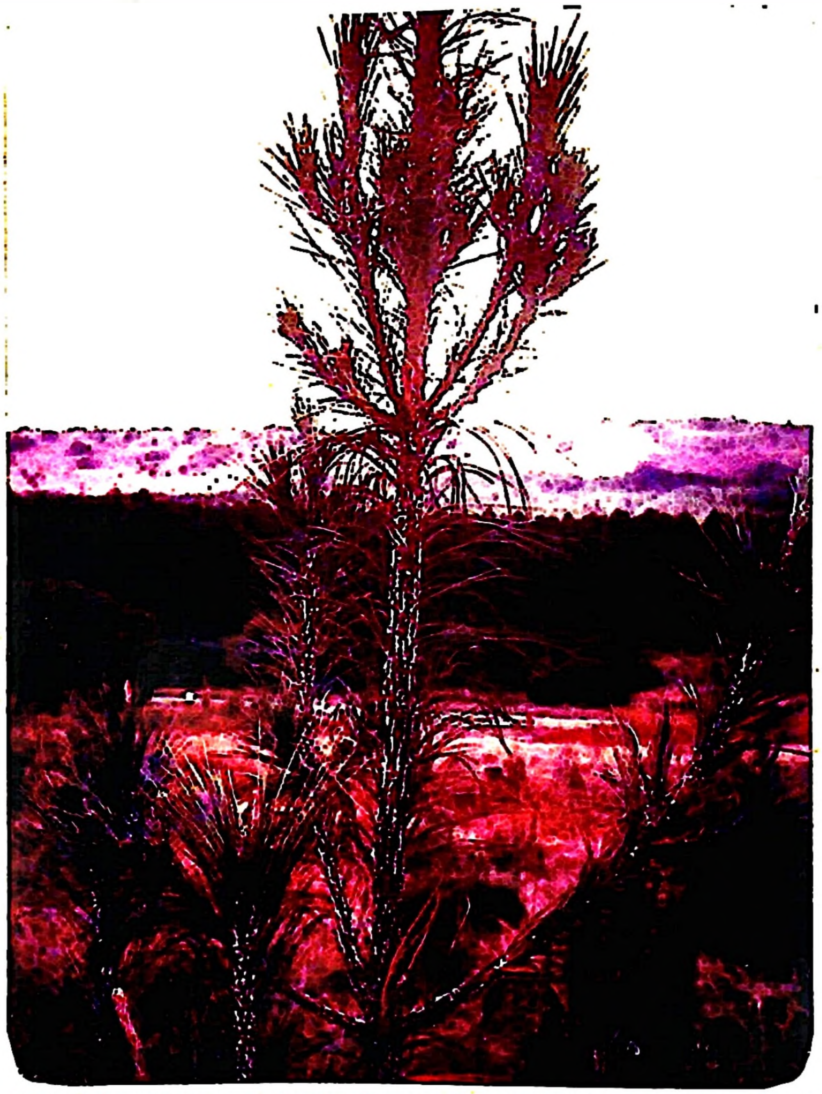


Figure 4. Pineus infestation (whitish shoots) on Pinus patula trees of different ages at Sao Hill forest plantation.

3.5.2 Site class

Plantation maps were used in choosing the compartments. In the procedure of determining the site classes, maps of the compartments were covered with a grid divided into cells of 0·5 x 0·5 cm (map scale being 1:25,000). The cells were numbered 1,2,3,4 etc. from the south west corner of the compartment, to the right, then right to left in that order.

Random numbers were used to pick four sample plots in each compartment. A circular plot with radius 25m (giving 0.04ha) was placed at about the centre of each selected plot. Four dominant heights (dominant height refers to the mean height of the 100 fattest trees/ha) were measured in each plot. For each plot, mean dominant height (MDH) was determined as the arithmetic mean of the heights of the measured dominant trees. The age of individual compartments was obtained from the plantation maps. Reference was made to the site classification curves for Sao Hill (Figure 5) constructed completely by the deviation method to predict the site quality for each plot (Adegbehin and Philip 1979). The site classes of the compartments are presented in Table 1.

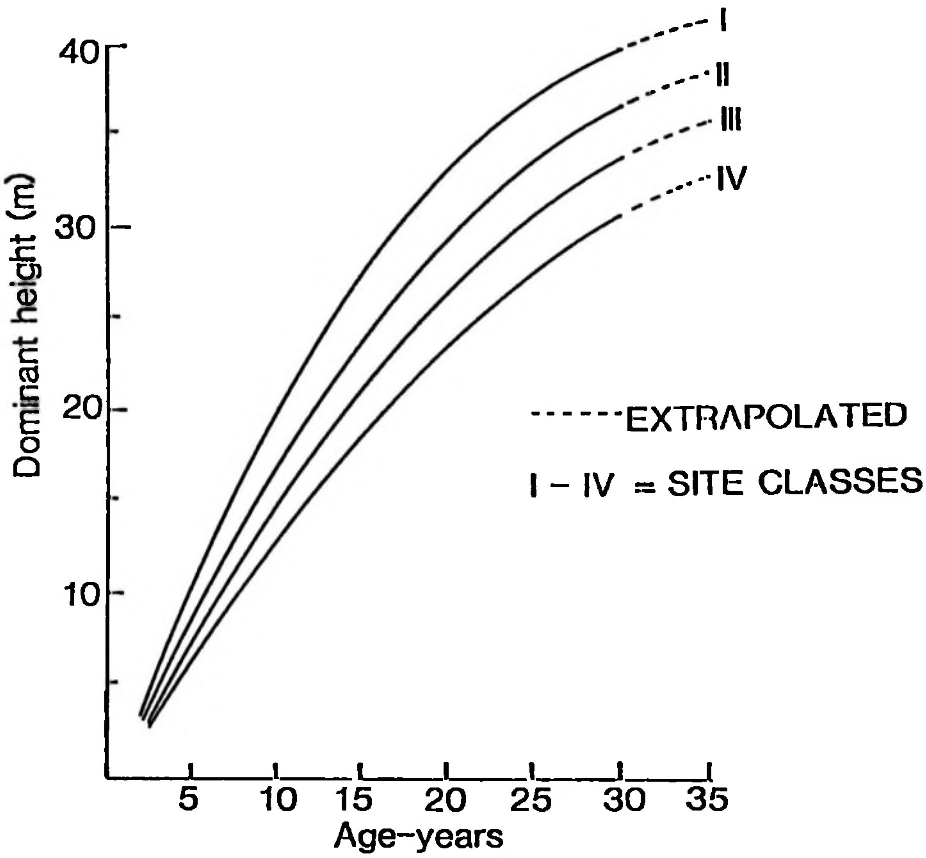


Figure 5.Site index curves-24,27,30 and 33 m at 20 years (Adegbehin and Philip 1979).

Table 1. Age and mean dominant heights(m) used in determining site class for the individual compartment.

Locality/compt.	Age (yrs)	MDH (m)	MDBH (cm)	Site class
Kibidula 28	7	14.8	17.5	I
Nyololo I.18	8	16.2	21.8	I
Gulusilo III.27	9	18.5	22.3	I
Gulusilo III.B44	10	19.2	22.9	I
Sao Hill S13.a(ii)	15	27.0	28.0	I
Nyololo 17	8	14.2	19.0	II
Sao Hill C.37	12	20.0	26.8	II
Msiwasi MS13	17	26.5	28.0	II
Matanana I.38	7	10.0	15.5	III
Matanana IV.3	8	11.5	18.1	III
Gulusilo IIIa.14	9	14.5	21.0	III
Matanana I.18	11	17.0	23.8	III
Sao Hill S 13.a(i)	16	22.0	26.5	III

3.5.3 Main sampling

Based on the work of Mailu et al. (1982a) a single twig (10 cm long) from one tree was chosen as the sample unit in estimating the mean aphid population density for the stand. Number of sample units, i.e. trees (or twigs), were determined by using the results of the preliminary sampling and deciding on the sampling precision (SE = 10% of the mean ($\bar{X}$) for this study). The following equation was therefore used to determine sample size (no. of trees):

$$n = \frac{4S^2}{L^2} \qquad \text{(Snedecor and Cochran 1980)}$$

where:

n = sample size

S^2 = variance between trees (aphid populations)

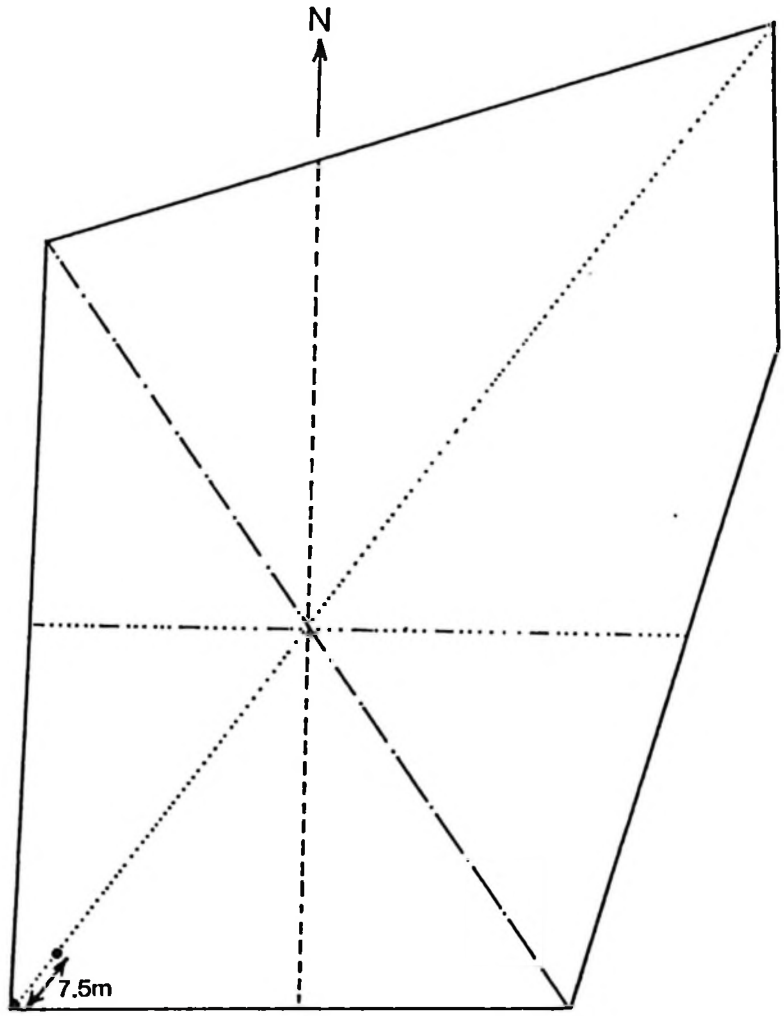
L = allowable error

From the above relationship, an average of 100 infested trees was considered adequate (Table 4, page 70). Selection priority was given to the most uniform (in terms of terrain and stocking) compartments.

Sampling procedure was as discussed under preliminary sampling, however, sample units/trees were taken in the following order (Figure 6):

- longest diagonal
- shortest diagonal
- mid-eastern to western edge
- mid-southern to northern edge

This order was consistently followed until the 100 infested trees were tallied. Distance between the edge/corners of the compartments were determined in advance from the given maps. Ten to twenty trees to the centre were not sampled in order to avoid double counting for the second and subsequent movements.



• Sampling point

Figure 6.The general location of sample points in each compartment measured after every third tree (2.5×3m = 7.5m).

Sampling between the selected compartments was done in quarters (25 trees) in order to reduce variations associated with the developmental stages of the insect, i.e. time laps before taking first and last sample. The movement was in the following order:

1st	quarter,	site	class	I
2nd	"	"	"	III
3rd	"	"	"	I
4th	"	"	"	III

This was done repeatedly until all the sample plots were covered. A ribbon was tied at any stopping point/tree to facilitate continuation to the following quarter. Distribution of sample plots, age, and acreage is given in table 2.

Table 2. Compartment data for the main sampling.

Location/compt.	Compt. code	Site class	Age (yrs)	Acreage (ha)
Kibidula 28	10		7	35.0
Nyololo I. 18	11	I	8	14.0
Gulusilo III.27	1		9	15.5
Matanana I. 38	12		7	30.5
Matanana IV. 3	7	III	8	30.4
Gulusilo IIIa.14	13		9	44.2

The following measurements/records were made during the sampling of the pine woolly aphid populations:

(a) Infestation

Every sample tree was recorded either infested (I) or non-infested (N). This was done visually from the ground and or climbing and cutting a few branches/twigs (Figure 7).

(b) Diameter at breast height (DBH cm)

DBH was measured in the main sampling for all the sampled trees using a plastic diameter tape. On slopes, records were made on the uphill side of the tree to one cm diameter class.

(c) Total height (HT m)

Suunto hypsometer was used to measure all sampled trees in the main sampling. Records were made in 0.5m height classes. Because of crown density some heights had to be estimated. Adjacent trees with clear top were used to make these estimations.

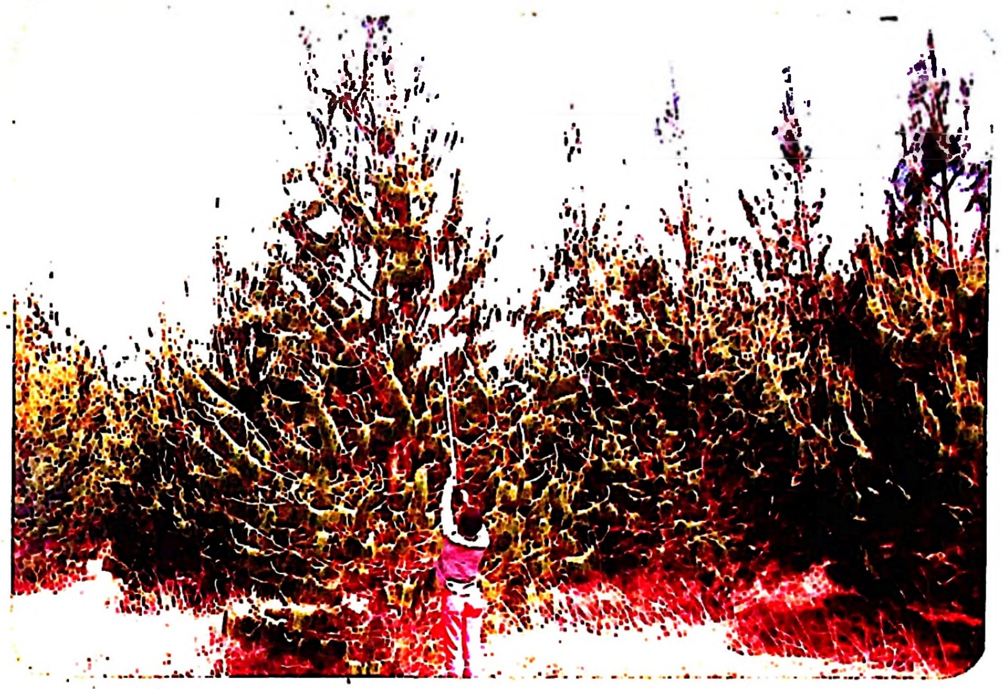
(d) Aphid counts

In the laboratory the number of eggs, crawlers and adults on each sample twig were counted under a dissecting microscope.

(e) Volume, m^3/tree

The volumes of sample trees i.e. V = f (HT, DBH, F) were determined according to Malimbwi (1987).

(a)



(b)

Figure 7. Recording aphid infestation at Sao Hill forest plantation (a)Pruning twigs for observation (b)Observing on the tree.

3.5.4 Statistical analysis of data

Data were analysed by using SAS software (SAS Institute, 1985). Analysis of variance (ANOVA) was performed on aphid population (eggs, crawlers, adults and total) to test differences between these variables among treatments (sites and age classes). Correlation between volume production, and total aphid population among treatments was determined by simple linear regression (SLR). Duncan's New Multiple Range Test was used to separate differing means (Alder and Roesler 1972).

3.6 Infestation experiment

3.6.1 Experimental design and layout

Since the exact history and development of the aphid infestations is not known for the various compartments and sites, it is not possible to evaluate the impact of aphid attacks on the trees. Is, for instance, reduced tree growth caused by infestation, or are possibly small trees infested because of their poor growth. Some information may however, be obtained by for example, infesting pine seedlings artificially with aphids, and recording the impact on growth and dry matter production (Carter 1977).

The experiment was performed at Irundi, in the forest research nursery. Two treatments were used, aphid

infested and non-infested Pinus patula seedlings. In each treatment 30 randomly picked potgrown seedlings, 10 months old from a nursery stock were used. The treatments were separated by six rows of Eucalyptus saplings and the whole experiment was enclosed in three rows of Cypress saplings. The trial was under mild shade from trees to prevent the aphids from direct sun rays. (Mailu et al. 1982b). Seedlings were about 10 cm apart. Watering was done once a day during the dry periods.
Weeds were removed once spotted, and the aphid infestation was monitored frequently and recorded accordingly. Ten seedlings randomly picked from the same nursery stock were uprooted and roots carefully washed to remove the soil. Green weight of roots and shoots were separately determined and later oven dried (105°C) to constant weight to determine the dry weight which was considered to be representative for the whole plant material of the experiment.

Two aphid infested twigs, of about same density of attack, were loosely tied by thread around the stem of each of the 30 seedlings. The other half were uninfested. At the end of the trial, the 30 infested seedlings were thoroughly observed for aphid attack. For the attacked seedlings, aphid counts was done under a dissecting microscope.

The following measurements/records were made:

(a) Diameter and total height

Diameter and total height were measured at the start of the experiment for the test plants. Vernier caliper and a ruler were used for diameter and height measurements respectively. All measurements were taken on a six cm mark measured from the pot soil level of the seedlings. Routine diameter and height measurements were made once fortnightly.

(b) Aphid counts and biomass production

At the end of the experiment, six months after infestation, aphid counts were made on the attacked seedlings. Eggs, crawlers and adults were counted separately to give the total population of the whole plant. Dry weight for each of the 60 seedlings was determined separately. For the infested seedlings, the aphids were removed before oven drying the seedlings.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General distribution of the pine woolly aphid at Sao Hill

The general distribution of the pine wooly aphid at Sao Hill is given in Figure 8. Several plantations of _Pinus patula_ are infested, only with varying intensity of attack. _P. elliottii_ plantations which cover about 10 per cent of the whole plantation show more incidences of attack than _P. patula_. There is a general east-west distribution of infestation. At Kihanga arboretum (centre of infestation) with 29 pine species (Table 3) _P. massoniana_ and _P. viginiana_ were the most severely attacked. _P. elliottii_ was severely attacked. _P. strobus_ and _P. caribaea_ were free of attack while _P. patula_ was moderately attacked. Pines growing on the edges of roads, rivers and large forest openings often sustained the heaviest infestation.

Fast spread of _Pineus_ at Sao Hill is probably associated with uniformity in the pine crop. Lack of serious and systematic control measures particularly when the outbreak was first reported, 20 years ago, could be another and yet an important possibility. Odera (1974) and Barnes et al. (1976) showed that lack of uniformity

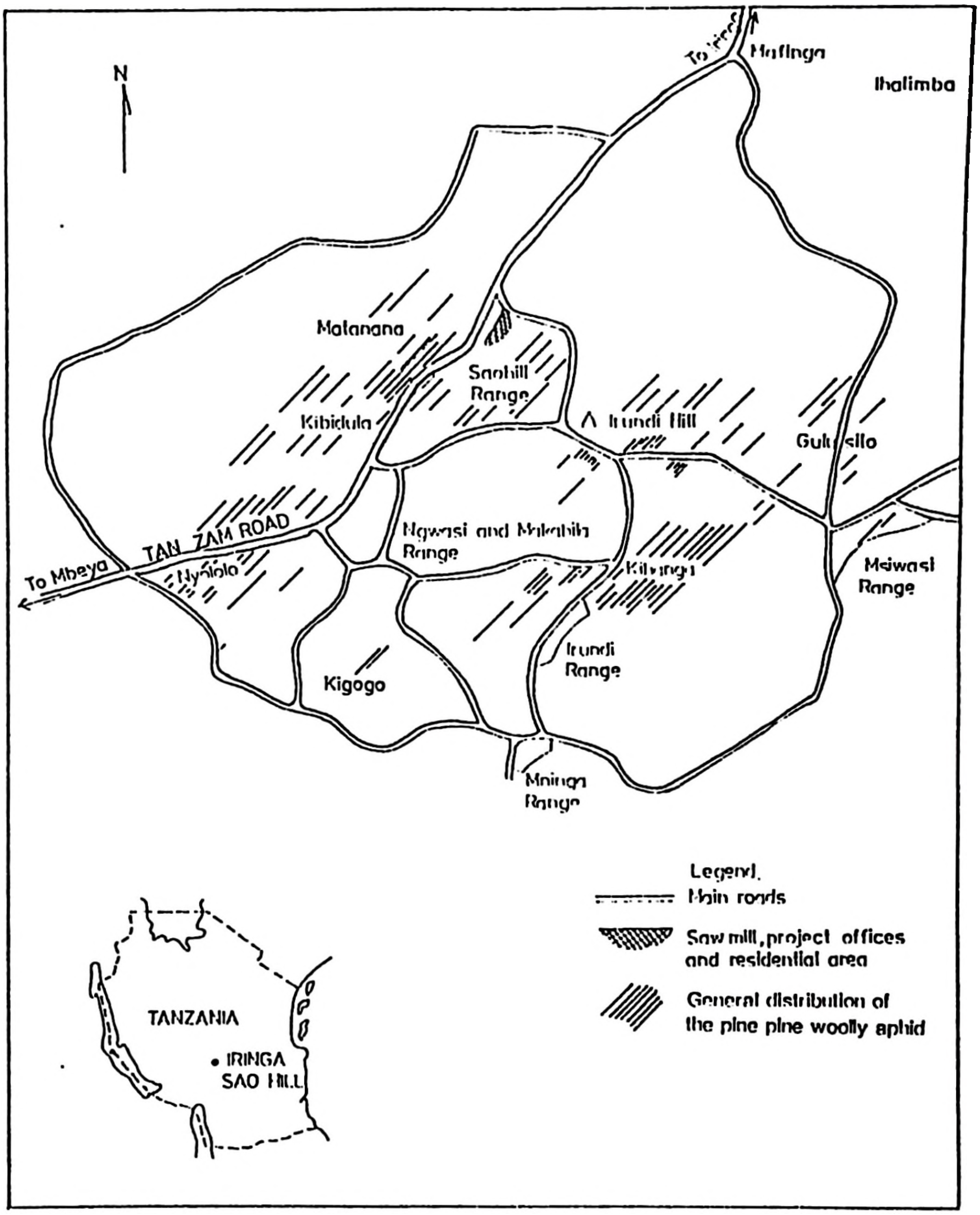


Figure 8. The general distribution of the pine woolly aphid at Sao Hill forest plantation.

Table 3. *Pinus* species at Kihanga arboretum grouped accor to relative severity of attack by *Pineus pini*.

Species	Planting year	Relative severity of attack
massoniana	1969	very severe
virginiana	1972	
elliottii	1966	
lambertiana	1966	
pinaster	1966	
kesiya	1966	
muricata	1966	severe
rensifolia	1970	
merkussii	1971	
roxburghii [1]	1974	
radiata [2]	1974	
patula	1974	
taeda	1966	
clausa	1969	
oocarpa	1970	moderate
leiophylla	1970	
durangensis	1966	
montezumae	1966	
teocote	1968	
michoacana	1970	light
montezumae	1972	
tenuifolia	1973	
patula [3]	1975	
strobus	1966	no attack
caribaea	1970	

[1] Provenance trial, average attack = severe, however, variations between provenances

[2] Seed orchard, average attack = severe, however, variations between clones

[3] Provenance trial, average attack = light, however, variations between provenances

in the pine plantations could hinder a fast spread of the pine woolly aphid. At Sao Hill for example, once the pest had become established, subsequent spread was much faster than in Muguga, Kenya, because pines occur in larger uniform stands (Odera 1974). Diwani et al. (1984a) reported that lack of proper monitoring and control systems in some of the pine plantations of Tanzania has contributed substantially to the unprecedented spread of <u>Pineus</u> in nearly all the pine plantations in Tanzania. The outward spread from the epicenter is likely to continue steadly in all directions where pines are grown. At present there are no obvious permanent barriers to block further expansion throughout the entire range of pines in East Africa and elsewhere. Thus every favourable habitat supporting susceptible species of pines will become infested.

The broad distribution of infested plantations/trees at Sao Hill suggests that the entire plantation area was subjected to aphid attack. Survey results have indicated that the distribution of the infestations appeared to be patchy throughout the occurrence of the pine woolly aphid. Many stands and/or trees had remained clean within the infested areas. Frequently, branches of highly infested trees grew side by side (with foliage intermingle) with completely uninfested trees. These observations suggest that some varieties or clones may be resistant to the pine woolly aphid. Variation of <u>Pineus</u>

attack within and between pine stands was also detected in Zimbabwe (Katerere 1983). Hoff and MacDonald (1977) found similar relations with woolly aphid on white pine species. In conclusion he pointed out that the patterns of variability in woolly aphid infestations is not immediately clear. Nonetheless, he emphasized that knowledge about variability patterns in response to pests is important to hybridization programs. The nature of resistance to attack by P. pini was not studied here, however, experience elsewhere considers it to be unclear (Odera 1974, Barnes et al. 1976).

The east-west distribution of Pineus is most probably associated with the movements of the prevailing winds. Odera (1974) and Barnes et al. (1976) has shown that spread of the pine woolly aphid within plantations has been remarkably rapid and almost certainly by wind dispersal of flightless crawlers and eggs. In Kenya and Zimbabwe for example, Pineus was noticed to have spread off the research stations westwards in the direction of the prevailing east wind on to the pine afforestation reserves (Odera 1974, Barnes et al. 1976). Further Odera (1974) demonstrated the importance of wind in the dispersal of the aphid by using plastic sheets 30 x 30 cm coated with "Tanglefoot". Crawlers were recovered on the sticky traps at different intervals, extending up to 60 m away from the nearest infested tree. The biggest catch was recorded on traps that were facing east and lying west of the infested stand. The importance of wind in the spread of aphids has also been demonstrated by Medler and Ghosh (1969).

High incidences of infestation on the edges of roads, streams and forest openings further confirms the role and importance of wind on the dispersal of Pineus. Any feature of the landscape that serves as a wind corridor has been shown to direct the migrating aphids, which have feeble capacity for directed flight, to the most exposed trees (Diamond and Bishop 1968, Odera 1974, Mailu et al. 1978a). The possibilities of aphids and other light bodied insects to be carried long distances by wind is well known. Robkin and Lejeune (1954) and Brown (1958) demonstrated that the larvae of adelgids and scale insects, are aerodynamically unstable and are thus capable of a dispersal range of approximately 5 km. Hu et al. (1986) observed that distribution and spread of poplar scale insects also are related to wind speed and direction. Johnson (1969) and Pedgley (1982) observed that many insects are delivered by air currents directly into habitats or into places near by as if they were inert particles. Salom and McLean (1989) has also shown the importance of wind on insect dispersal.

The successful establishment of air borne larvae or those that are transported on animals and other agencies/ vectors depends on their longevity and ability to find a susceptible host. Crawlers of Adelges for example are very active, and it has been observed that some of these crawlers are capable of crawling up to 30 m or more under natural conditions (Balch 1952). Their movement and activeness are some adaptive mechanism to find and settle on a suitable feeding spot. The most unequivocal evidence of population movement of the pine woolly aphid is provided by the appearance of fresh infestations in areas that were previously clean of the insect (Odera 1974).

Another possibility of spread is by birds, animals and humans, especially field workers, vehicles and equipment on which the aphids may attach to. The movement of the infested nursery stock is probably the greatest factor contributing to the spread of the insects to distant points (Odera 1974, Barnes et al. 1976). At Sao Hill wind spread is most probable the greatest factor because nursery stock is usually screened for Pineus infestation before being taken to the field. Morever, the original infested stock was confined to Kihanga arboretum.

Pines are growing as exotics at Sao Hill, an environment different to that of their origin. Trees in a new environment may experience an extended period of suscept-ibility to pests before the tree and pests have had the evolutionary time to adapt to each other (Berryman 1987). Working on host plant susceptibility and choice by conifer aphids, Carter and Nichols (1980) found that Elatobium abietinum infestation in Britain have shown that certain species and varieties of Picea are more prone to attack and support a higher aphid development rate than others. Among the aphids that dwell on conifers it can be seen that both physical and biochemical qualities of the plant determine susceptibility and choice. (Carter and Nichols 1980, Rohfritsch et al. 1986).

4.2 Preliminary sampling

4.2.1 Relationships between site and *Pineus* population

Table 4 gives the records and the results of the aphid sampling of the 9 selected compartments. A total of 518 trees were sampled. The percentage of infested trees varied from 27.4 per cent (Compt. code No. 6, site class II) to 47.6 per cent (Compt. code No. 7, site class III), however, there were no significant differences between the three sites.

The distribution of *Pineus* population between compartments and sites and ANOVA results are presented in appendices (i) and (ii) respectively. In all cases, eggs were found in highest numbers, followed by adults in most compartments while crawlers were found in lowest numbers. A total of 3082 aphids were counted. Densites within sites with mean numbers per 10 cm shoot in bracket were: Site class III: 1421 aphids (23.67), site class II: 831 aphids (14.72) and site class I: 778 aphids (13.00). *Pineus* population density was significantly influenced by the sites (Table 5).

However, separating the mean differences by Duncan`s New Multiple Range Test, no significant population differences were detected between site classes I and II for the total population density. Differences were more likely to be found between the two extreme sites, I and III. As mentioned in Chapter 3, Materials and Methods, it was difficult in the young age class to clearly separate site class II from site classes I and III.

Table 5. Pineus pini population for various site classes in the preliminary sampling.

Site	Mean population per 10 cm twig length and (SE)			
class	Eggs	Crawlers	Adults	Total
I	5.12(0.41)c*	3.68(0.39)b	4.20(0.40)c	13.00(0.93)b
II	6.32(0.58)b	3.30(0.37)b	5.02(0.47)b	14.72(1.05)b
III	10.15)0.79)a	6.82(0.62)a	6.70(0.46)a	23.67(1.44)a

*Values followed by different letters in a given column are significantly different ($p<0.05$; Duncan`s New Multiple Range Test, Alder and Roesler 1972)

4.2.2 Relationships between age and *Pineus* population

Table 6 shows the effect of age on *Pineus* population. With exception of the crawlers there were no significant differences between the three age classes. In the young age class however, 1160 aphids were counted compared to 971 and 952 for the middle and old age classes respectively. Mean total (and standard error) aphid population was 19.15 ± 1.35, 16.18 ± 1.17, and 15.86 ± 1.35 for the young, middle and old age classes respectively.

Trends in the data showed (Appendix i) that total *Pineus* population was more abundant, although not statistically different, in the young age class compared to the other two classes. This trend may indicate that young trees can be more vulnerable to aphid infestation than old trees. All sample compartments in the young age class of this study were not thinned. This might have reduced the vigour considerably due to competition for water, nutrients and light compared to trees in old thinned stands. This could be even more pronounced at inferior sites, thus favouring the possibilities of *Pineus* development.

Table 6. *Pineus pini* population for three age classes in the preliminary sampling.

Age classes	Mean population per 10 cm twig length and (SE)			
(years)	Eggs	Crawlers	Adults	Total
Young(<10)	7.85(0.71)a*	5.93(0.61)a	5.37(0.43)a	19.15(1.35)a
Middle(10-15)	7.15(0.61)a	3.95(0.40)b	5.08(0.45)a	16.18(1.17)a
Old(>15)	6.58(0.69)a	3.80(0.41)b	4.48(0.51)a	15.86(1.35)a

*Values followed by different letters in a given column are significantly different ($p<0.05$; Duncan's New Multiple Range Test, Alder and Roesler 1972)

These considerations may well agree with other results: Tanton and Alder (1977) found severity of infestation by Pineus on Pinus radiata trees to decrease with age (Figure 9). Barnes et al. (1976) and McClure (1982) found the same with Pineus on P.patula and P. resinosa respectively. Similarly Larsson and Tenow (1984) reported that young Scots pine suffered more defoliation by Neodiprion sertifer than old trees. The old trees had passed the thinning stage of development, supposedly had a well balanced nutrient economy and high water storage capacity due to their large size, a situation which might render the trees less susceptible to saw fly attack. Young trees were severely suppressed by root and light competition and were consequently heavily defoliated by the sawfly. Intermediate aged stands suffered defoliation of medium severity. During a mass outbreak of N. sertifer, Austarå et al. (1987) found 78 per cent defoliation in young stands of P. sylvestris and 72 per cent in old stands

In another study, Coulson et al. (1974) and Lario (1980) demonstrated that pine beetles outbreaks have been associated with high stand densities, presumably because high densities lead to poor host condition or low vigour. Because of the assosiation between environmental conditions and stand susceptibility, silvicultural practices can be used to improve stand resistance. For example thinning

Figure 9. Changing proportion of severely infested trees with age of the stand (Tanton and Alder 1977).

is recommended as a means for reducing stand susceptibility to attack by southern pine beetle (Dendroctonus frontalis) (Belanger and Malac 1980).

In contrast, Page (1975) found that older trees of Balsam fir (Abies spp.) were the most attacked by Balsam woolly aphid (Adelges piceae). It appears that the taller stands (age is usually correlated with increasing height and diameter), which are normally under greater stress because of their greater transpiration requirements and the greater heights to which water must be lifted, are the ones most seriously affected when the aphid attack further increases the difficulties of water transport.

4.3. Main sampling

4.3.1 Frequencies of infested trees

Six compartments (two also in the preliminary study) all covering about 169.5 ha, 64.5 ha in site class I and 105 ha in site class III were used here. From the young age class, compartments of 7, 8 and 9 years were chosen, and equally represented in both sites. A total of 1644 trees were sampled, 878 trees site class I and 766 trees in site class III. The percentage of infested trees varied from 29.6 per cent (Compt. code No. 11) to 49.5 per cent (Compt. code No. 7). (Table 7). No significant differences were found between sites (ANOVA).

Table 7. Percentage of trees infested by Pineus pini within compartments at each of two site classes in the main sampling.

Compt. code 1)	Site class	No. of trees sampled 2)	Percentage of infested trees
10		279	35.8
11	I	338	29.6
1		261	38.3
12		316	31.6
7	III	202	49.5
13		248	40.3

1) See pages 55 and 70 for derivation of compartment code

2) Stand density about 1680 stems ha^{-1}

No significance differences between sites (ANOVA)

4.3.2 Relationships between site and *Pineus* population

Population numbers in compartments and sites, and ANOVA results are presented in appendices (iii) and (iv) respectively. Within each site class it was observed that population densities of eggs were higher than of crawlers and adults, while the densities of crawlers and adults were about equal. Table 8 shows the mean aphid population and standard error for two sites. A total of 20,011 aphids were counted, 8,837 and 11,174 for site classes I and III respectively. Mean total population per 10 cm shoot length was 29.46 and 37.24 for sites classes I and III respectively. Analysis of variance showed highly significant differences between the two sites, and Figure 10 presents the frequency distribution of the total number of *Pineus* individuals per 10 cm long twigs, showing that there are more trees with higher *Pineus* densities in site class III than site class I. This indicates that site class III is more suitable than site class I for the development of *Pineus*, while the equal percentage of infested trees in the two site classes (Table 7) indicates that the site classes are equally susceptible to infestation.

Table 8. *Pineus pini* population at two site classes in the main sampling.

Site class	Mean population per 10 cm twig length and (SE) Eggs	Crawlers	Adults	Total
I	13.30(0.39)	7.76(0.25)	8.40(0.26)	29.46(0.79)
III	16.76(0.50)	10.08(0.27)	10.40(0.29)	37.24(0.89)

All *Pineus* development stages are significantly different between sites (P<0.05)

4.4. Interactions between site and *Pineus pini* at Sao Hill

Results from my studies agree well with the results of other studies, as discussed in Chapter 2, Literature Review. It is likely that sites with potential for moisture or nutrient deficiencies, or other subtle physical or chemical factors are prime candidates for heavy aphid attack. The trees of site class III, which is inferior to site class I, had the highest population densities, suggesting that the aphid outbreaks may develop in response to host foliage (needles) changes resulting from moisture, nutritional stress or other subtle factors. It is very likely that site class III has poor soil physical and chemical characteristics . Schönau and Grey (1987) have demostrated the importance

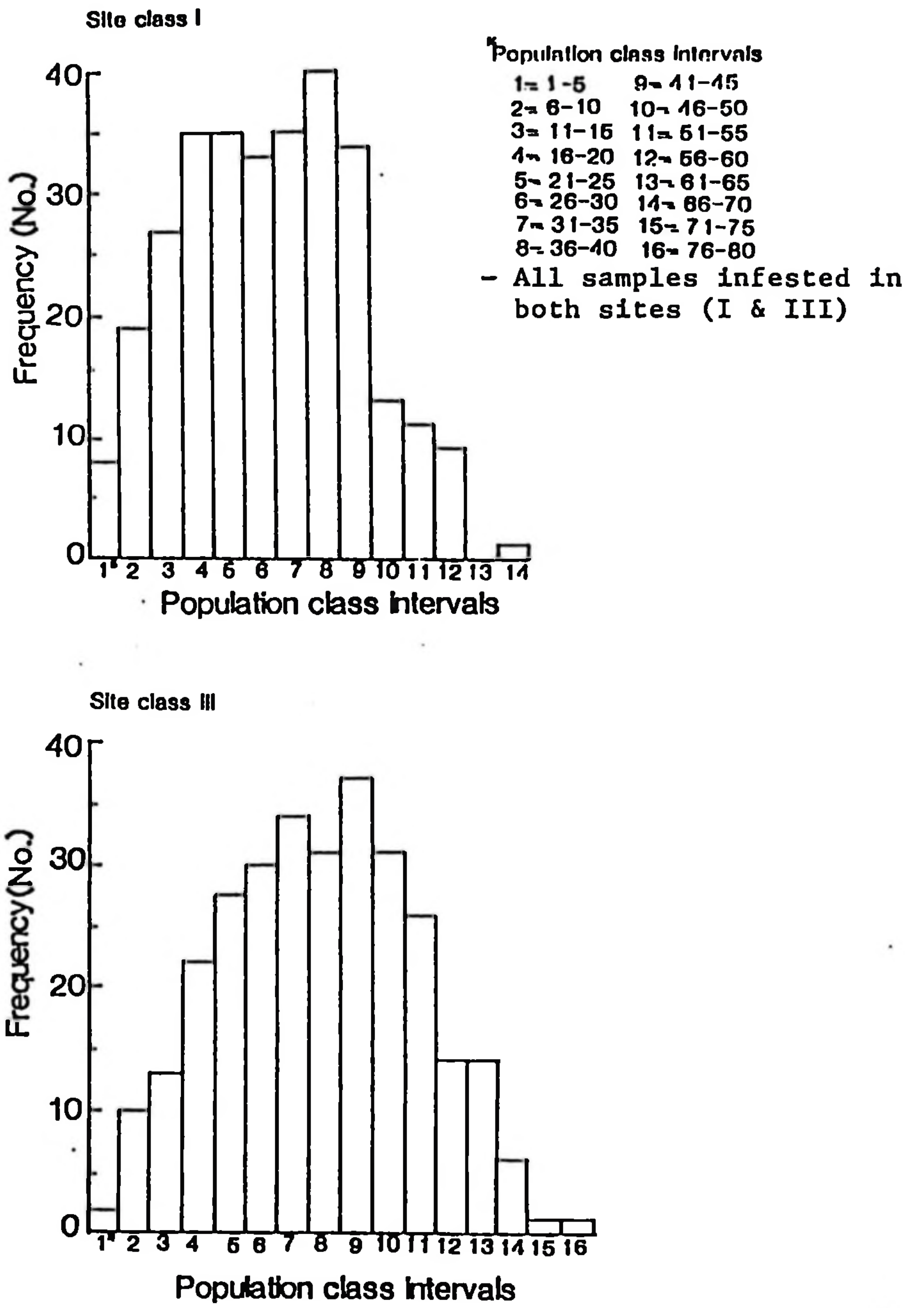


Figure 10. Frequency distribution of <u>Pineus pini</u> population of 300 samples in each of the site classes I&III.

of water and soil as the main factors wich affect the forestry potential in a given site. Earlier, Kozlowski (1982) had shown that water availability is the factor most referred to as having a predominant effect on forest productivity. Observed productivity, a complicated manifestation of the interactions between biotic and abiotic factors, have been used to indicate site quality (MacLeod and Running 1988).

It has long been recognized that severe defoliation by pine insects occur mainly in stands on poor soils, especially after periods of drought (Larsson and Tenow 1983). Mailu et al. (1978b) have shown that stunting of pine needles as a result of aphid attack gives similar results as defoliation by other insects. Larsson and Tenow (1984) found that Neodiprion sertifer outbreak on Scots pine were limited to infertile soils. These findings support the hypothesis on the fundamental effect of stand nutritive state on the changes in number of the sawfly. In the same experiment he demostrated that the number of sawfly cocoons were higher in unfertilized stands than fertilized ones. These findings could be compared to and used to explain the susceptibility of pines in the inferior/infertile areas to Pineus attack in the current study.

It is likely that more nutrients are available to other processes, eg. synthesis of defensive chemicals in fertilized stands, an effect which makes such stands less susceptible than non-treated stands in a drought situation (Larsson and Tenow 1984). Thus, the findings of low populations in stands of enhanced nutritional quality (White 1974) could be an effect of trees being able to produce more defensive chemicals (Rhoades 1979 & 1985). At Sao Hill, site class I could have more nutrients available for defences, thus explaining the lower population of aphids. Because P. pini has been innocuous in a wide range of habitats at Sao Hill, its population may possibly attain injurious levels only where trees are stressed by poor growing conditions. This may have started to manifest in site class III.

In another study, Carmean (1975) and Stoszek et al.(1981) showed that defoliation of True fir by Douglas fir tussock moth was heavier on upper slopes and ridge sites than in lower slopes. They speculated upper sites to have shallower, better drained and less fertile soil than lower slope sites. Thus, trees in such conditions are more likely subject to stress caused by water and nutrient deficiencies or imbalance, further confirming results obtained in this study. Kushmaul et al. (1979) also showed that inferior sites in terms of slope, poor drainage and low pH values increase the activities of insects resulting in higher losses. On the other hand Bultman and Faeth (1987) showed that overstressed trees can sustain minor insect attack compared to moderately stressed trees. It is likely that over stressed trees have less appealing conditions for the phytophagous insects contrary to the "stress hypothesis" (White 1984). The most inferior sites (site class IV) at Sao Hill,probably having the most stressed trees were not considered in this study because compartments suitable for sampling were not found.

Barnes et al. (1976) has demonstrated that Pineus attack is most severe where the host species is under physiological stress brought about either by inherent unsuitability to the general Zimbabwean climate or by wrong choice of site. Further he showed that some pine species, which have been growing in Zimbabwe for relatively few generations have become physiologically better adapted to local climate and plantation conditions, and this adaptation has apparently incorporated an incidental resistance to Pineus. Working on different insect species, similar findings were reported by Varty (1956), MacClure (1977) and (1982). These findings give an indication of the type of inherent advantage which may be available in a local population, and supports the principle that, when introducing a species for afforestation purposes, it is wise to obtain seed from stands which have been growing under similiar conditions even for a relatively short period (Barnes et al. 1976). At Sao Hill most of the P. patula seed crop for afforestation purposes are usually obtained from old selected seed stands. This might increase resistance to <u>Pineus</u> attack in the subsequent generations as a result of the inherent advantages which may be available in the seed. It is important to note that several additional observations can be made regarding vulnerability of stands or trees at Sao Hill, based, not only on data collected in this study, but upon observations made over similar and/or related studies.

All stages of the aphid, eggs, crawlers and adults were recorded in this study. The population figures showed much higher population densities of eggs and lower densities of adults and crawlers. In almost all cases, population densities of the crawlers were nearly the same to or lower than those of the adults. Working on the same insect in Kenya, Mailu et al. (1980) reported the same relationships of eggs, crawlers and adults. Further, they found that the population fell during rainy seasons and increased in the dry seasons. Barnes et al. (1976) observed a sudden population build-up in Zimbabwe as a result of hot dry spring followed by very poor rains in the summer in 1971. They further noted that <u>Pineus</u> activity is greatest during the hot and dry August to September period. A marked reduction in activity follows the heavy rains which usually fall towards the end of October or the beginning of November. The two studies in Kenya and Zimbabwe demonstrated an apparent impact of seasonal rainfall on the aphid populations. Free-living crawlers are exposed to washing-off and dislodgement by rain, whereas adult aphids are sessile with their stylets inserted into the plant and are covered with wax filaments.

In my study, sampling was done from September to January, thus the Pineus experienced a good balance between the highest activity during the dry period and the period of fluctuations during the rain season. The apparent impact of seasonal rainfall on the aphid populations could not clearly be explained here because sampling was done in a single run (from dry to rainy season). The population fluctuations of the three stages could have been caused by predators or other factors. Several predators, particularly Tetraphleps raoi and some Coccinellidae were observed in the plantation during sampling. Some aphid predators(eg. T. raoi) are host specific, and usually prefer the adults although they feed on eggs (Chacko 1973). Low number of crawlers could also be associated with migration/dispersal by wind.

4.5. Aphid infestation and impact on tree growth

4.5.1 Volume production of the infested and uninfested trees

Mean percentage volume differences between infested and uninfested trees between compartments is given in table 9. In site class I, growth loss ranged form 3.31 per cent to 12.97 per cent. In site class III, one locality (Compt. code 7) didn't show any volume reduction as a result of aphid attack, however, the other two compartments had loss of 4.62 per cent and 4.92 per cent. There was no significant differences (t test, $p>0.05$) between the two sites. Furthermore, there were no significant differences in volume between infested and uninfested trees (t test, $p>0.05$).

In my study, relatively low population densities were found. The relationship between infestation density and damage categories, has been presented by Mailu et. al. (1978b) and is quoted in Table 10.

Table 9. Mean percentage volume differences between infested and uninfested trees in site class I and III.

Compt. code[1]	Site class	Infested[2] Mean vol. dm^3	(SD)	No. of obs.	Uninfested Mean vol. dm^3	(SD)	$\frac{\text{Infested vol.}}{\text{Uninfested vol.}} \times 100$	% difference vol.
10	I	115.70	(58.99)	179	132.93	(63.82)	87.03	-12.97
11		249.90	(109.58)	238	259.21	(123.04)	96.41	- 3.59
1		194.10	(161.75)	161	304.18	(168.70)	96.69	- 3.31
12		72.30	(29.23)	216	66.74	(31.71)	108.33	+ 8.33
7	III	63.60	(35.06)	102	66.89	(30.42)	95.08	- 4.92
13		144.00	(59.44)	148	150.97	(65.05)	95.38	- 4.62

1) See page 55 and 70 for derivation of compartment code

2) No. of observations, 100 trees for each compartment

Table 10. Classification of degrees of damage produced by the pine wolly aphid on *Pinus patula* (Mailu et al. 1978b).

Damage category	Description of damage	Number of aphid adults per cm of twig length	% of twigs infested by the aphids	Tree surface covered with wool
Tolerable	Needles normal 187 to 235 cm or slightly reduced by 15 mm slight attacks, then recovery.	≤ 10	≤ 8	twigs, leader
Critical	Needles reduced by 1/5 to 1/3 of their normal lengths (45 mm to 75mm) some twigs dead	20 - 75	15 - 50	branches, twigs, leader, trunk
Intolerable	Needles heavily stunted Needles 1/2 or loss their normal lengths. Many shoots and buds dead.	≥ 100	≥ 65	trunk, branches, twigs, leader

From the table is seen that when the number of adult aphids per cm of twig length is less or equal to 10, the damage is tolerable. Since the corresponding number in my study was found to be approximately 1 (Table 8) it was unlikely to expect any significant growth losses. However, a few trees were found which were so heavily infested that they probably would succumb (Figure 11).

Additional information on the distribution of trees on volume classes and percentage infested trees within each volume class is given in Figure 12 A, B and C. Since both site classes contain trees of the same young age classes, it was to be expected that site class III would have a higher frequency of trees in the lower volume classes than has site class I (Figure 12 A and 12 B). However, the percentage of infested trees is fairly equally distributed on the volume classes (Figure 12 C), and an analysis of variance showed no significant infestation differences between the volume classes ($P>0.5$).

Figure 11. Tree mortality resulting from Pineus pini infestation (Compartment IV.3, site class III) at Sao Hill forest plantation.

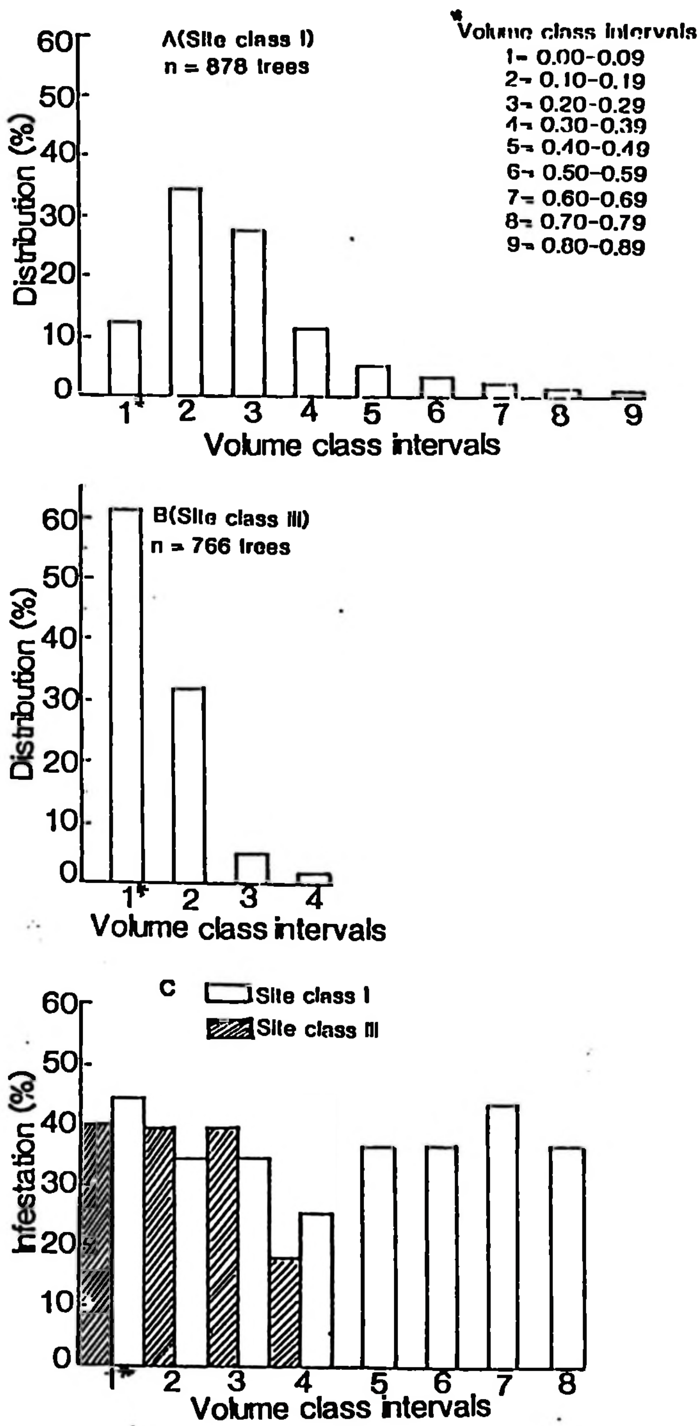


Figure 12 A–C. Distribution of trees on volume classes for site class I and III (A&B), and percentage infested trees within each volume class (C).

Higher volume given by one compartment in site class III (Compt. code No. 12) could possibly be due to the age and intensity of infestation in that particular compartment. Pines apparently can withstand alternation of slight attacks and recovery for up to five years with no noticeable effect on any growth parameter (Mailu et al. 1982b). Barnes et al. (1976) showed that annual fluctuation in Pineus activity allows a tree to recover to a greater or lesser extent during the later part of summer.

On the other hand, higher losses given by one compartment in site class I (Compt. code No. 10), could be due to cummulative (continuos) attack which leads to more impact on growth (Mailu et al. 1978b). Alfaro et al. (1982) and Nichols (1988 a & b) have shown that deteriorated tree conditions in previous years as a result of defoliation affect current years growth.

Mailu (1972) and Mailu et al. (1978b) showed tree growth reduction as a result of Pineus attack. Mailu (1972) reported tree mortality also to occur depending on the degree of infestation as experienced in one compartment (Compt. code No.7)

Working on the same species, Moore (1962) and Barnes et al. (1976) also reported on the relationship of growth loss with Pineus attack. Page (1975) also showed that there was a close relationship between aphid attack on pines and loss of yield. Citing from Mailu et al. (1978b), Odera (1972) noted that mean shoot increments for aphid infested and uninfested pine trees was significantly different. He also noted a marked reduction in the height growth of trees that had been infested for 12 months or more. Annual growth increments of heights and diameters were also larger in uninfested trees.

In many respects the impact of pests that is observed today is a result of lack of pest control in the past. The importance of intensive management, including pest control has been emphasized as vital for growing satisfactory tree crops (Gross 1985). At Sao Hill, no serious systematic control measures have been taken against Pineus since its outbreak, about 20 years ago. Losses might be greater in future without appropriate pest control strategies.

Possibly due to little variation in Pineus densities, a very low negative correlation was found between intensity of attack and growth parameters (diameter, height and volume). Correlation coefficients (r) were very small (<7%) for both sites for the studied parameters.
Earlier studies had clearly shown the existance of such correlation (Mailu et al. 1978b).

Van Emden et al. (1969) have shown that feeding aphids act as "sinks" for photosynthates produced at a distance away in the plant. With increased infestation premature senescence of the tissues may result. This has an indirect influence on tree water potential resulting in the trees developing structural and functional changes in the xylem (Puritch 1971, Arthur and Hain 1986). This could lead to reduction in radial and the general tree growth (DeBoo et al. 1964, Carter 1977, Laurent-Hervouet 1988).

These studies are of value in understanding some relationships between Pineus and P. patula at Sao Hill. In my study this relationship was not studied. However, there was an apparant loss of chlorophyll, needle stunting and needle casting (Figure 11). This could lead to low water/mineral potential, subsequently to tree growth loss. There is likely to be a direct relationship between loss of chlorophyll and population density. This could therefore lead to more growth loss in the inferior sites.

4.6 Infestation experiment

4.6.1 Impact on plant growth by the *Pineus* infestation

The mean diameter and height development pattern, for both infested and non-infested seedlings for a period of 24 weeks is shown in Figure 13 and 14. Effective infestation was manifested at about the 10th week, and at the termination of the experiment, only 15 plants out of the 30 infested had effective infestation. There was a general decline in growth for the infested seedlings, effective from about the 13th week. At the conclusion of the experiment, losses in diameters and heights over the control were 12.2 per cent and 14.1 per cent respectively.

Mean biomass production (expressed as oven dry weight) for the two treatments after 24 weeks growth is given in Figure 15. Mean growth loss was 0.749 g and 2.077 g for roots and crown respectively. The loss of total root growth amounted to 27.8 per cent in dry weight and in shoots 20.9 per cent dry weight. The overall reduction (whole plant) expressed as oven dry matter was 22.4 per cent over the control.

The experimental design did not allow for any analyses of variance to be undertaken. Means for the studied parameters were however used to explain the differences

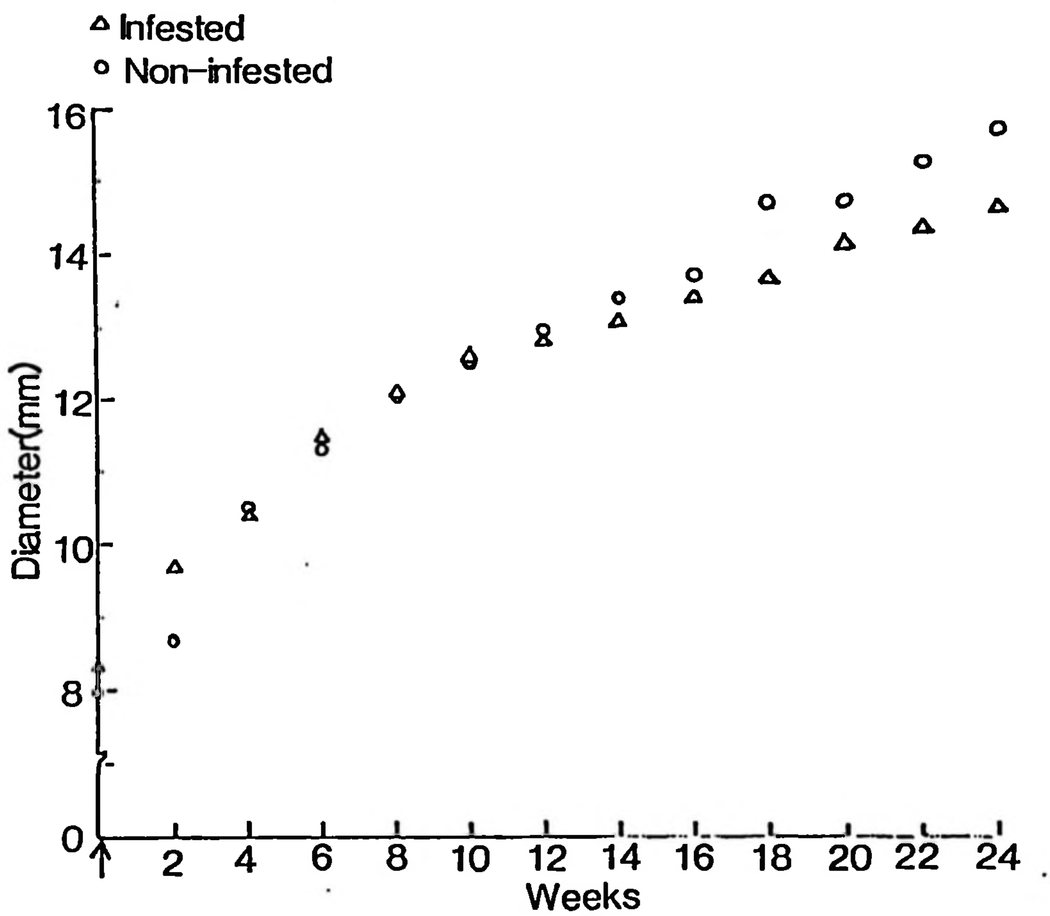


Figure 13. Diameter development of infested and non-infested Pinus patula seedlings during 24 weeks (↑Infestation at the setting of the experiment).

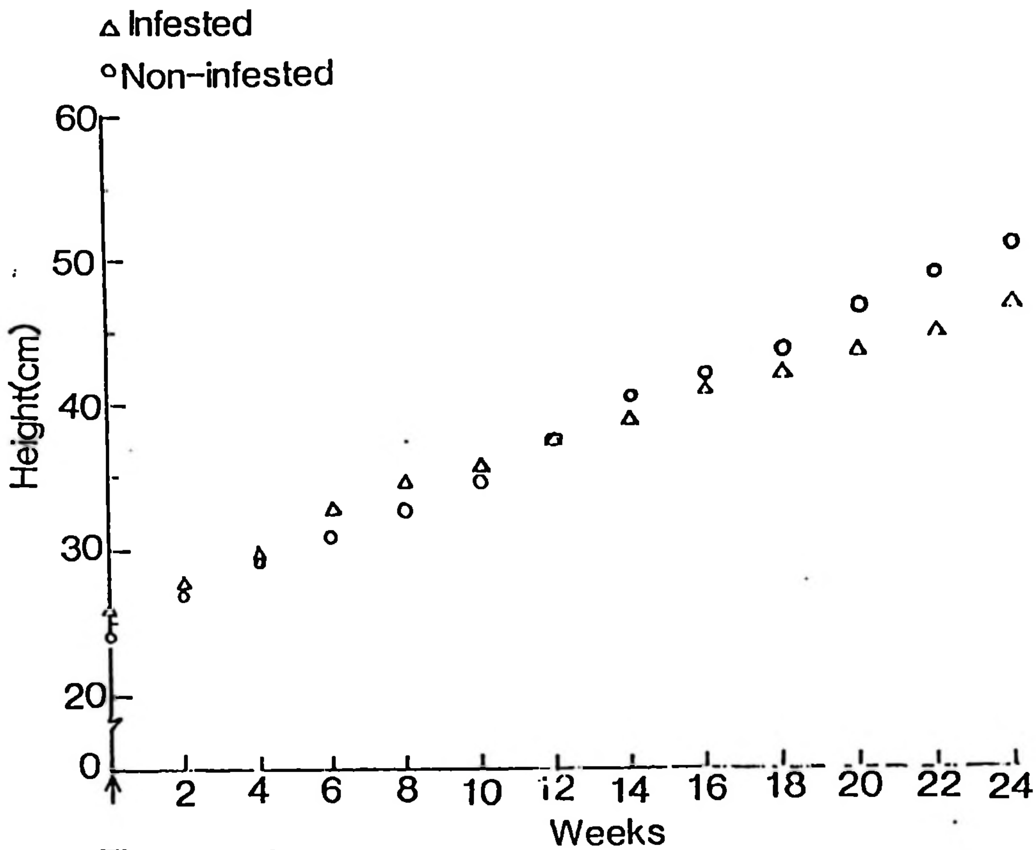


Figure 14. Height development of infested and non-infested <u>Pinus patula</u> seedlings during 24 weeks(↑ Infestation at the setting of the experiment).

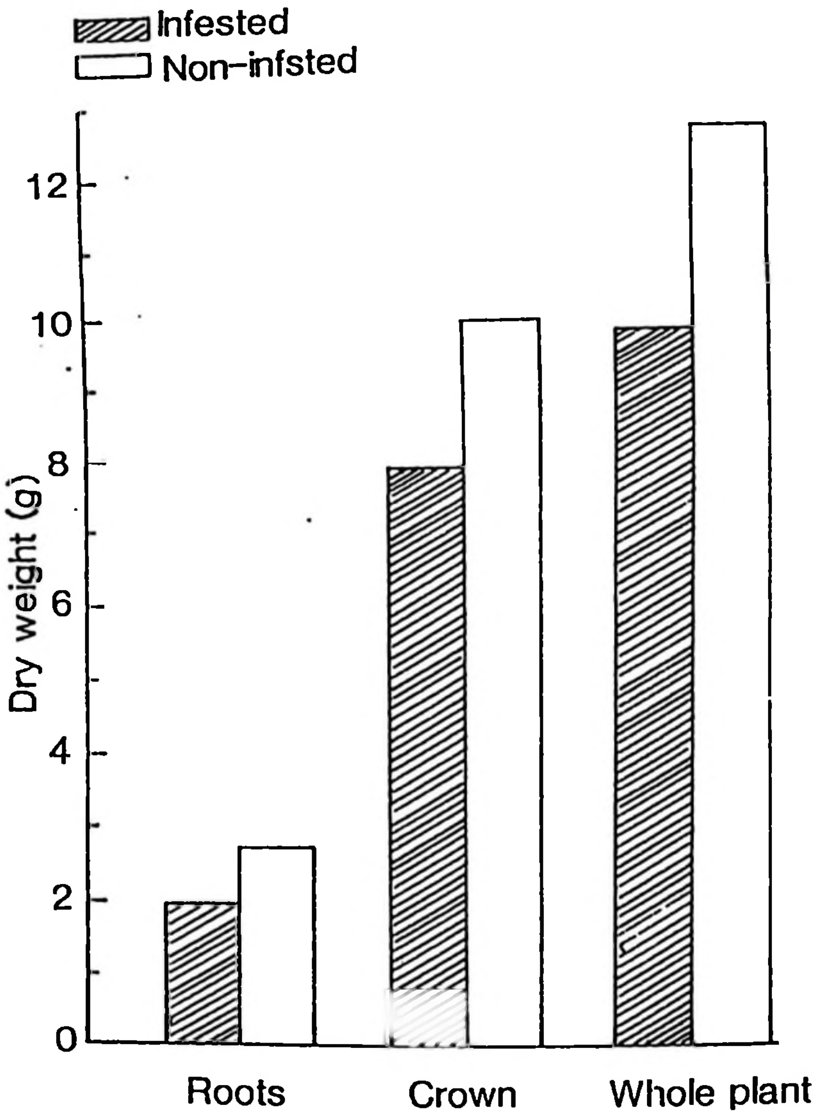


Figure 15. Mean biomass production (g) for the infested and non-infested Pinus patula seedlings during 24 weeks growth.

between the infested and non-infested seedlings, and a few regression analyses were done.

Table 11a shows the mean aphid population per seedling. A mean of 55.4 aphids were counted, highest count given by eggs, and crawlers the lowest. The relationship between Pineus population and individual seedling biomass is given in Table 11b. The relationships are generally weak as depicted by low correlation coefficients. Crown with r = 0.098 has a relatively stronger relationship than roots, r = 0.012.

The reason why I have not found a strong correlation, may be that I lack extreme numbers of population density. The range of population density is between 21 and 112 per seedling which is too narrow to obtain a good correlation (Mailu et al. 1978b).

Table 11a. Mean number of *Pineus pini* per seedling, and standard errors.

Population	Mean	SE
Eggs	27.60	4.17
Crawlers	13.67	1.40
Adults	14.13	2.1
Total	55.40	6.61

Table 11b. Regression equations relating *Pineus pini* population density to individual seedling biomass (g).

Dry weight (g)	Equation	Correlation coefficient(r)
Roots	$Y = 53.63 - 0.224X$	0.012
Crown	$Y = 72.51 - 1.210X$	0.098
Total plant	$Y = 68.95 - 0.817X$	0.083

Y = *Pineus pini* population per seedling

X = Dry weight (g)

Results from this study have demonstrated an apparent tendency of growth loss of the seedlings most likely as a result of Pineus attack. The impact given here after 24 weeks of infestation indicated that younger plants are very sensitive to aphid attacks.

Growth differences between infested and non-infested seedlings started to manifest in about the 13th week and the gap was getting wider towards the end of the experiment. This gap was likely to increase with time. Rogers and Doggett (1984) showed that aphid infested white pine seedlings had 11 per cent loss in growth after one year of infestation. Further they demonstrated that after 2 years the difference in growth increased, and the growth of the uninfested seedlings was significantly better than that of the infested seedlings, both at 95 and 99 per cent levels. This supports an assumption that also in my experiment the difference in growth would have increased with time (Figures 13 and 14).

In another study Fox and Griffith (1977) showed the impact of Cinara aphids on height and diameter developm-ent on 1 to 3 year old loblolly pine seedlings. Carter (1977) also showed that growth loss following aphid infestation of young Sitka spruce plants amounted to 48 per cent in dry weight of shoots, and 7 per cent of roots.

This experiment clearly indicates that *Pineus* infestations of *P. patula* reduce the growth. Therefore it is safe to argue that also infested plantation trees may show reduced growth because of infestation, they are not infested because they initially were slow-growing.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The principal results and conclusions on my study are as follows:

1. Population density of *Pineus pini* was found to be significantly higher on trees of site class III than on trees of site class I.

2. The percentages of infested trees were equally high in compartments of both site classes I and III.

3. The above two relations indicate that susceptibility of *Pinus patula* to *P. pini* is equally high at both good and inferior growing sites. Suitability, however, for the development of the aphid seems to be clearly better on the inferior sites.

4. No significant differences in population density was found between age classes. However, there was a tendency of aphid populations being higher in the younger age class compared to the middle and old age classes. This indicates possibilities of population decrease with age of the host trees.

5. In the plantation trees, there was a tendency of reduced volume growth of the infested trees, but no significant difference between infested and uninfested trees was stated, due to relative low population densities on the trees. However, the results of the infestation experiment showed a clear growth loss in both diameter, height and dry weight of infested seedlings compared to uninfested ones. This strongly indicates that infested plantation trees show reduced growth because of infestation, therefore, they are not infested because they initially are slow-growing.

5.2 Recommendations

The following recommendations are made on the basis of this study.

- More information is needed on the host/pest relationship to be able to evaluate rational measures and methods to control the aphid populations.

- The following studies are relevant:
    - Population monitoring programmes.
    - Elucidate impact on growth (field and laboratory experiments), and economic consequences (field investigations) due to Pineus infestation.

- Laboratory and field experiments on the effect of soil improvement on *Pineus* development (fertilizing experiment).
- The effect of pruning and thinning on the development of *Pineus* populations.
- Biological control experiments (field and laboratory).

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Appendix (i)

Mean *Pincus pini* population per 10 cm twig length within compartments at various site classes for the preliminary sampling.

Compt. code[1]	Site class	Eggs	Crawlers	Adults	Total
1		5.90	3.40	4.55	13.85
2	I	4.95	4.15	3.85	12.95
3		4.50	3.40	4.20	12.10
4		8.65	5.20	4.50	18.35
5	II	6.55	2.85	4.85	13.75
6		4.25	1.60	5.70	11.55
7		9.50	9.20	7.05	25.75
8	III	9.50	4.85	6.55	21.35
9		11.00	6.40	6.55	23.95

1) See page 70 for derivation of compartment code

Appendix (ii)

ANOVA for the mean *Pineus pini* population per 10 cm twig length at three site classes, I, II and III.

(i) Eggs

Source and variations	DF	SS	MS	F
Sites (between)	2	829	414.50	18.39 ***
Within	177	2989	22.54	
Total	179	4818		

(ii) Crawlers

Source of variation	DF	SS	MS	F
Sites (between)	2	446	223.00	17.17 ***
Within	177	2229	12.59	
Total	179	2675		

(iii) Adults

Source of variation	DF	SS	MS	F
Sites (between)	2	195	97.50	8.23 ***
Within	177	2097	11.85	
Total	179	2292		

(iv) Total

Source of variation	DF	SS	MS	F
Sites (between)	2	3936	1968.00	24.38 ***
Within	177	14286	80.71	
Total	179	18222		

***; Significant at p<0.001

Appendix (iii)

Mean *Pineus pini* population per 10 cm twig length within compartments of two site classes obtained in the main sampling.

Compt. code 1)	Site class	Eggs	Crawlers	Adults	Total
10		13.71	8.10	8.57	30.38
11	I	13.43	7.29	8.01	28.73
1		12.75	7.88	8.63	29.26
12		16.01	10.44	10.13	36.58
7	II	17.60	10.35	11.46	39.41
13		16.68	9.46	9.61	35.75

1) See page 55 and 70 for derivation of compartment code

Appendix (iv)

ANOVA for the mean *Pineus pini* population per 10 cm twig length at two site classes, I and III.

(i) Eggs

Source of variation	DF	SS	MS	F
Sites (between)	1	1802.67	1802.67	29.39 ***
Within	598	176.19	44.05	
Total	599	1978.86		

(ii) Crawlers

Source of variation	DF	SS	MS	F
Sites (between)	1	812.01	812.01	39.44 ***
Within	598	93.77	23.44	
Total	599	905.78		

(iii) Adults

Source of variation	DF	SS	MS	F
Sites (between)	1	598.00	598.00	26.81 ***
Within	598	205.45	51.36	
Total	599	803.45		

(iv) Total

Source of variation	DF	SS	MS	F
Sites (between)	1	9102.62	9102.62	43.13 ***
Within	598	878.37	219.59	
Total	599	9980.99		

***; Significant at $p<0.001$