ECOLOGY OF *PRATYLENCHUS PENETRANS* ASSOCIATED WITH NAVY BEANS (*PHASEOLUS VULGARIS* L.)

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ABSTRACT

ECOLOGY OF PRATYLENCHUS PENETRANS ASSOCIATED WITH NAVY BEANS (PHASEOLUS VULGARIS L.)

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A "holistic" approach was used to study the ecology of Pratylenchus penetrans associated with navy beans. Studies on the pest system included determination of the field distribution and incidence of Pratylenchus penetrans in Michigan bean fields. The pathogenicity of P. penetrans to navy bean cv Sanilac was evaluated and the susceptibility of dry bean varieties to P. penetrans was examined. The influence of environmental factors of temperature and moisture on the development of the pathogenic relationship between P. penetrans and navy beans was studied. Effects of interacting components of mycorrhizae and kidney beans which are grown in rotation with navy beans were examined.

The research findings indicated an aggregate-type field distribution of P. penetrans, and this expresses the need for careful design of experimental sampling

procedures and analyses of nematode data. Pratylenchus spp. was found in 68% of Michigan bean fields. A pathogenic relationship between P. penetrans and navy bean cv Sanilac was observed. However, the degree of susceptibility of varieties to P. penetrans varied, and three tolerant varieties (Gratiot, Saginaw and Kentwood) were identified. The population dynamics of P. penetrans varied over two navy bean growing seasons.

The pathogenic relationship between P. penetrans and navy beans was emphasized by adverse conditions of temperature, soil type and soil moisture. Reproduction of P. penetrans was reduced at 15 and 30 C, respectively and at high and low soil moisture levels corresponding to -5 and -1000 centibars, respectively. Optimum conditions for growth and development of P. penetrans were 25 C and a soil moisture level corresponding to a matrix potential of -50 centibars. These conditions were also optimum for plant growth in the absence of P. penetrans.

Mycorrhizal associations with G. fasciculatus increased growth and yield of navy bean cv Sanilac. The detrimental effects of P. penetrans on navy beans were minimized in the presence of G. fasciculatus. The research data provided information which could be used

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for development of management strategies for control of *P. penetrans* in dry bean production.

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1.0 INTRODUCTION

1.1 Agricultural Production Systems

Agricultural production systems represent vital linkages in the complex structual components of the world. The output of these systems is a function of natural and synthetic inputs such as climate, soil factors, fertilizers, plant varieties, pest and pest control inputs. Optimum production and economic returns from agricultural production systems are obtained through effective management of these variables.

The output and economic returns of agricultural production systems can be significantly reduced by the detrimental effects of pests, and therefore pest management is a significant component. In many crop production systems pest control involves a single management factor effected through the use of pesticides. The continual use of pesticides, however, may lead to further development of the deleterious side effects of a "pesticide syndrome" (van den Bosh et al. 1971). The beneficial effects of pesticides cannot be discounted. However emphasis must be placed on the development of integrated methods (cultural, biological and chemical) for management of

pests in crop production systems. The concept of pest management defined as the coordination and implementation of pest control strategies that will result in favorable economic, ecologic and sociologic consequences (Bird, 1979) must be adopted to achieve optimum economic returns from crop production systems. The concept of integrated pest management is recognized and practiced by a significant number of farmers in the context of "farming practices". The application of this concept in modern-day agricultural systems has however been less than desired. This is related to the immediate economic gains which have resulted from the use of pesticides. Lack of understanding of the pest-crop ecosystem has also impeded the developement and implementation of integrated methods of pest control.

The use of large monocultures in agricultural systems, the resulting decrease in species diversity, and the development of pest resistance to pesticides has resulted in increasing pest problems in crop production. These factors together with the awareness of the problem of depleting energy reserves has lead to an interdisciplinary movement to make integrated pest management a reality. New approaches to implementation of pest management are essential for greater success. Implementation techniques, and applications of the concept have been addressed by several

researchers (Stern et al. 1959; Haynes et al. 1973; Orishchenko 1974; Waters and Ewing, 1974; Tummala, 1974; Shoemaker, 1974; Polyakov, 1974; Haynes and Tummala, 1974; Croft et al. 1976; Harsh, 1977; Haynes and Tummala, 1978; Ferris, 1976).

1.2 Approach to the Study of Pest-crop Ecosystems

In the past the "reductionist" approach was adopted in conducting studies on pest-crop interactions, in attempts to achieve pest control. This involved a concentration of effort on one pest and one crop. Pest-crop interactions, however are influenced by other components of the ecosystem. To truly determine and understand the nature of pest-crop interactions it is necessary to adopt a "holistic" approach to the study of pest-crop ecosystems. This is achieved through studies on the separate components of the pest-crop system and also through studies on the interdependence of each component of the system. The principles of a "holistic" approach are based on the separation of the pest-crop system in to components of (1) the object of control (the pest) (2) the associated crop (3) other interacting components of the system. Because of the complex nature of ecosystems it is almost impossible to examine all possible interactions of the components. Studies are generally limited

to first, second and third order interactions (Tummala and Haynes, 1979). Moreover, the components of the system can be divided into controllable factors such as plant variety, soil type and uncontrollable factors such as temperature, moisture and humidity. The number of controlled and uncontrolled factors involved in any study can be varied.

1.3 Nematode Problems in Agricultural Production

Plant parasitic nematodes are pests which function by detrimentally affecting the physiological mechanisms of plants. Growth is usually retarded with consequent reduction in yield and economic returns. The development of effective feasible nematode control practices could aid in increasing output and economic returns from agricultural production systems. The development of these control practices will be influenced by the nature of the pest-crop system, natural resources and socio-economic conditions. Moreover, projections of future conditions should be considered in developing control methods, as practices developed to suit prevailing conditions could become obselete in the future due to changes in various aspects of the pest-crop system, and socioeconomic conditions. In the light of the diminishing natural energy

resource, the development of low energy control inputs must be considered. This requires a decrease in the use of high energy nematicide inputs, and the development of an integrated nematode control approach which embraces well-balanced use of multifactor control strategies such as nematode resistant varieties, crop rotation, optimum planting dates, biological and chemical control. The development and implementation of this integrated control concept, however, requires a sound understanding of the functioning of the nematode-crop systems. This understanding can only be achieved through appropriate research on pest-crop ecosystems.

1.4 Statement of the Problem

Root-lesion nematodes *Pratylenchus* spp. are common in many crop production systems in Michigan. *Pratylenchus penetrans* is the most predominant species. It is a pathogen of many field crops such as potatoes, corn, soybeans, oats and wheat. Dry beans are commonly grown in rotation with many of these crops, and the presence of *P. penetrans* in dry bean roots has been reported (Bird, 1977). The nature of the relationship between this nematode pest and dry beans has not previously been established. In order to develop effective control strategies for management of this nematode pest it is necessary to study the ecology

of P. penetrans associated with dry beans.

1.4.1 Approach to the study of the problem

A primary prerequisite for development of optimum control practices is an understanding of the behavior of the pest-crop ecosystem. To determine the relationships which govern the behavior of the P. penetrans-navy bean system, a holistic approach was adopted whereby the pest-crop system was separated into the following components:

(1) the object of control - the pest, P. penetrans

(2) the associated crop - Phaseolus vulgaris

(3) other interacting components (mycorrhizae, rotation crops, bacteria and fungi).

Scientific experimental procedures were used in this investigation to study the relationships which govern the behavior and interdependence of each component of the total pest-crop system. The established relationships are expressed in the form of mathematical equations, which could be used for computer simulation of a model of the pest-crop system. This model could also be used for development of control strategies for management of P. penetrans. The development of the model was not undertaken as part of this disseration. The research was limited to studies on the pest, the associated crop, and two other interacting components (mycorrhizae and crops grown in rotation with

with navy beans.

1.4.2 Overall research objective

To establish the ecological relationships which govern the behavior of the *P. penetrans* - *Phaseolus vulgaris* system.

1.4.3 Research outline

1.4.3.1 The pest system

(1) Determine the field distribution of *P. penetrans*.

(2) Determine the incidence of *P. penetrans* in dry bean fields in Michigan.

(3) Develop and maintain a population of *P. penetrans* for use in this research study.

(4) Identify and develop a key to the stages in the life cycle of *P. penetrans*.

1.4.3.2 Pest-crop interactions

(1) Evaluate the pathogenicity of *P. penetrans* associated with dry beans.

(2) Study population dynamics of *P. penetrans* associated with navy beans.

1.4.3.2.1 Influence of environmental parameters of temperature and moisture

(1) Determine the effect of temperature on the population dynamics of P. penetrans under field and greenhouse conditions.

(2) Examine the influence of temperature on germination, growth and development of dry beans.

(3) Study the influence of temperature on P. penetrans and dry bean interactions.

(4) Determine the effect of soil moisture on the population dynamics of P. penetrans.

(5) Observe the effect of soil moisture on growth and development of dry beans.

(6) Determine the effect of P. penetrans on dry beans at different soil moisture potentials.

1.4.4 Influence of interacting components

1.4.4.1 Mycorrhizae

(1) Determine the effect of mycorrhizal associations on growth and development of dry beans.

(2) Examine the interactions of mycorrhizae and P. penetrans on dry beans.

1.4.4.2 Rotation crops - Kidney Beans

(1) Examine the effect of P. penetrans on different cultivars of dry beans and identify tolerant or resistant cultivars for use in the management of P. penetrans.

2.0 LITERATURE REVIEW

2.1 *Pratylenchus penetrans*

2.1.1 Taxonomy

The root-lesion nematode (*Pratylenchus penetrans*) is a member of the phylum: Ashelmintha, class: Nematoda, subclass: Secernentea, order: Tylenchida, suborder: Tylenchina, superfamily: Tylenchoidea, family: Pratylenchidae, subfamily: Pratylenchinae, and genus: *Pratylenchus*. It was described by Bastain in 1865, as *Tylenchus obtusus*. This description and illustrations, however, were inadequate for specific identification of the species. De Man described the same species in 1880, and is generally credited with identifying the first *Pratylenchus penetrans*. The species was first found on potatoes by Cobb in 1917. In 1922 Micoletzy placed this nematode in a new subgenus called *Chitinotylenchus* and the genus *Tylenchus* was synonymized with *Anguillulina* Gervais and Van Beneden by Baylis and Daubeney in 1926. In 1934 Filipjev's classification of the Tylenchida (which is the present-day classification of the group) defined *Chitinotylenchus* as a distinct genus excluding *Pratylenchus*. With the aid of the monographs of Sher and Allen (1953) and

Loof (1960), the species was placed in a new genus called Pratylenchus. The correct citation for this nematode is Pratylenchus penetrans (Cobb, 1917) Filipjev and Shuurmans-Stekhoven 1941.

2.1.2 Morphology

Pratylenchus penetrans (Cobb, 1917) Filipjev and Shuurmans-Stekhoven 1941 is vermiform in all stages, with females ranging in length from 343-811 µm and males varying from 300-514 µm (Corbett, 1973). The species is characterized by its broad head with conspicous sclerotization, and a lip region which is flat in the front with well rounded margins. It has a typical tylenchoid oesophagus with a stoma containing a stomatostyle which is 13-16 µm in length. The median bulb is moderate in size and the oesophagal glands overlap the intestines ventrally in a lobe about 1.5 times the body width. The excretory pore is opposite the oesophageal-intestinal junction, with the hemizonid occupying about two-thirds of a body annule immediately in front of it. The location of the vulva is sub-equatorial, and the reproductive system is monodelphic. This nematode has a short post-uterine sac which is undifferentiated and varies in length from 1.0 to 1.5 of the vulval body width. The species is characterized by its distinctly spherical spermatheca. The tail is generally rounded with a smooth

tip and 15-27 annules on the ventral surface. The cuticular annulations are fine and the lateral field contains four incisures, the outer bands of which may be partly areolate, while the central field may contain oblique striae near the vulva, becoming areolate behind the vulva but not extending to the top of the tail.

The male nematode is similar in morphology, with a lateral field containing four incisures extending to the bursa, occasionally with oblique lines in the central field near the mid-body. The spicules are slender with well-marked manubria and ventrally arcuate shafts 14-17 µm in length. The gubernaculum is simple and about 3.9-4.2 µm in length. The tail is twice as long as the anal body diameter (Corbett, 1973).

There are, however, significant intraspecific morphological variations in this species (Roman and Hirshman, 1969; Tarte and Mai, 1976). Tarte and Mai (1976), observed pronounced heteromorphism among specimens of Pratylenchus penetrans. Variations in tail shapes were distinct. Several shapes of stylet knobs were characterized, and 50% of the specimens observed had knobs which were anteriorly flattened and indented. The shape of the spermatheca also varied from round to oval. Variations in the lateral field were present, and in some cases a fifth lateral line was observed. They concluded that environmental

factors and particularly host plants influenced such morphometric characters as body length and width, oesophagus and stylet length, tail terminus, growth of the ovary and shape of the median bulb.

2.1.3 Distribution and host range

Pratylenchus penetrans is the most important species of this genus, causing injury to a wide range of economic plants. Members of this genus are commonly called root-lesion nematodes because of the characteristic lesions which they produce on infected roots (Godfrey, 1929). *P. penetrans* has a wide host range, occuring on over 350 plant species (Corbett, 1973). Host species of economic importance include field crops such as tobacco, alfalfa, cotton, soybean, dry beans; cereals e.g. wheat, corn, oats; vegetable crops such as: tomato, potato, carrots; fruit trees such as: apple, peach, strawberry, cherry and many ornamentals and turfgrasses.

P. penetrans is commonly found in the northeastern states of the U.S.A., southern Canada and Europe infecting corn and potatoes (Dickerson *et al.* 1964), onions (Bergeson, 1962), celery and other field crops (Townshend, 1963). In the U.S.S.R., *P. penetrans* has been found in the roots of cotton, potato, beans, rye, wheat, tomato and strawberry, causing significant damage (Krall and Riispere,

1965). This nematode has been described as the most widespread and economically important plant-parasitic nematode in Michigan (Knierim, 1963; Knobloch and Bird, 1980)

2.1.4 Life cycle

Pratylenchus penetrans is an obligate parasite with overlaping primary and secondary life cycles, varying from 37-86 days, depending on temperature. The cycle is shortest at a soil temperature of 30 C, although fewer eggs are deposited at this temperature than at temperatures of 20-24 C (Mamiya, 1971). Reproduction takes place by amphimixis (Hung and Jenkins, 1969; Thistlewaite, 1970), involving cross fertilization and formation of two polar nuclei in the maturing oocytes. Chromosome division figures indicate that meiosis occurs. Eggs are laid singly in the soil or in roots of infected plants (Corbett, 1973). Mamiya (1971) estimated an oviposition rate of 0.8-1.1 eggs per day for 35 days. First-stage juveniles are formed within the egg four to five days after oviposition, and under the influence of hatching stimuli,eggs containing the first-stage juvenile hatch to release second-stage juveniles in six to seven days after egg laying (Thistlewaite, 1970). Free-living in the soil the second-stage juveniles orient themselves towards

susceptible roots by a heat gradient and enter the zone of maturation in the plant roots. Adult males and females are formed following three additional molts (Figure 2.1).

Soil temperatures influence the length of each stage (Mamiya, 1971) and optimum temperatures for reproduction have been given as 21-23 C (Christie, 1959; Mamiya, 1971). Various other environmental factors such as moisture, oxygen supply and soil pH also influence reproduction, growth and survival of P. penetrans (Morgan and McLean, 1968; Willis, 1972; Corbett, 1973). Barker et al. (1975) also observed that the rate of reproduction was influenced by light intensity. Soil type influences survival (Townshend and Webber, 1971), which is generally higher in sandy soils as compared to heavier clay soils. P. penetrans overwinters in all stages in the soil or in the roots of infected plants, becoming quiescent by the mechanism of anhydrobiosis. Fourth-stages and adults, however, are the most important overwintering stages (Kable and Mai, 1968; Miller, 1968; Dunn, 1972). Optimum temperatures for overwintering are given as 1.0-4.5 C.

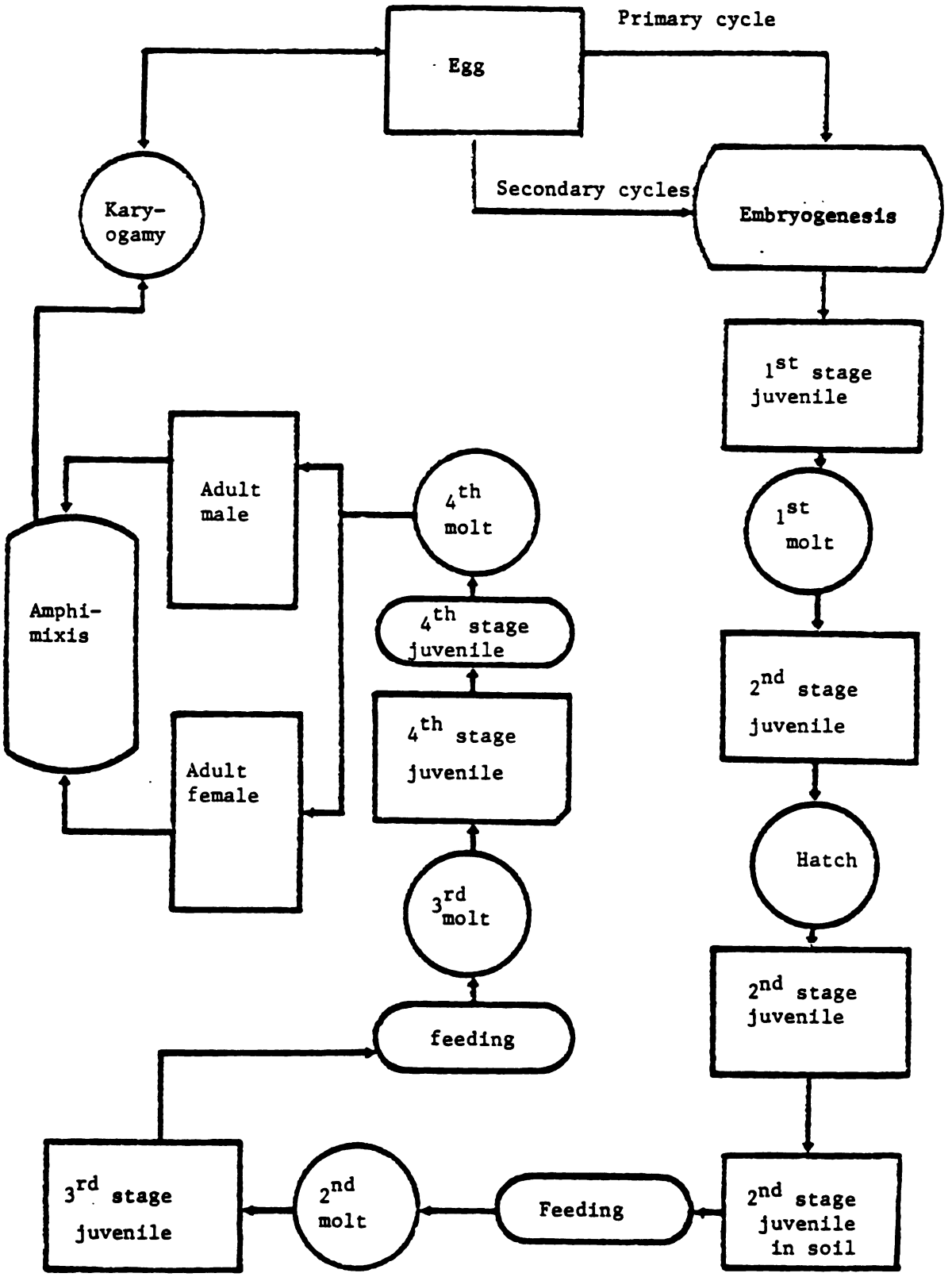


Figure 2.1 Life cycle of Pratylenchus penetrans

2.1.4.1 The primary cycle

The primary cycle is the first life cycle initiated by the pathogenic stages after a period of overwintering (Figure 2.1). The cycle involves periods of inoculation, incubation and infection. The exact mechanism of attraction to susceptible roots is not known. Thermotropic responses by P. penetrans have been reported by El-Sherif and Mai (1968). Klinger (1965) suggested however that the attraction of nematodes to the roots is related to chemical stimuli, especially carbon dioxide and amino-acids. Generally attraction occurs in the immediate vicinity of the roots at distances of about 1-2 cm away. Lavallee and Rohde (1962), also observed the attraction of P. penetrans to plant roots. This theory is supported by Shepard (1970) who pointed out that nematodes are equipped with neuro-sensory systems and their behavioral patterns are influenced by environmental factors. Root exudates in the soil could possibly act as chemical stimuli and behavioral patterns of nematodes could be set into action. This could involve secretory processes of the oesophagal glands of nematodes. The behaviorial-activated nematodes could then respond to gradients of

stimuli such as heat or chemical substances from root exudates.

2.1.4.1.1 Inoculation

Inoculation represents the period of the life cycle during which nematodes are stimulated to move towards and penetrate susceptible plant roots. The second, third and fourth stages, and adult males and females can be used to inoculate plants in research experiments, but generally fourth stage juveniles and adult males and females are the most pathogenic stages. These migrate towards the roots and with the aid of their stylets they rupture the cell wall and penetrate the plasmalemma and enter the root cortex, migrating through and between the parenchyma cells. Inoculation is temperature dependent (Rohde, 1963; Dickerson et al. 1964; Sonitrat and Chapman, 1970).

2.1.4.1.2 Incubation

The incubation period follows the inoculation period and ends with the appearance of plant disease symptoms. Reports indicate that incubation periods vary depending on the host plant. In some plant species the incubation period is short and root-lesion symptoms develop within a few hours producing a brown coloration in the cytoplasm of the infected cells. In other species this

may take several hours to occur (Mountain and Patrick, 1959; Pitcher et al. 1960).

2.1.4.1.3 Infection

Infection represents the stage in the life cycle following the appearance of symptoms and ending with the final response of the host plant to the pathogenic nematode. During the infectious period nematodes migrate into the cortex, where they feed and reproduce or move to other cortical areas of the root system. They usually align themselves with the longitudinal axis of the root, just outside the epidermis (Rohde, 1963).

As the nematodes feed on the cellular material the cells become disorganized and much of the cytoplasm disappears or retreats together with the nucleus, against the cell wall. Necrosis of cells follow the path of the nematodes. That part of the epidermal layer adjacent to the nematodes becomes discolored and appears deep brown in color extending into large groups of cells. The nematodes continue to feed on the cortical cells and later the cell walls disintegrate and cavities appear in the cortex. The walls of these cavities are sometimes lined with brown tissue. P. penetrans is an obligate parasite and does not exist in saprophase for any length of time. As soon as the nematodes become associated with dead tissue they migrate

away and penetrate new living tissue (Pitcher et al. 1960; Rohde, 1963; Dickerson et al. 1964; Odihirim and Jenkins, 1965; Troll and Rohde, 1966).

2.1.4.2 Secondary cycles

Secondary cycles are generally initiated by progeny of the first generation (Figure 2.1). The length of the cycles and the number of generations are largely dependent on the host plant and temperature. Secondary cycles can be initiated by migration of pathogenic nematodes from infected roots to healthy roots, or from inoculation through movement of pathogenic stages in the soil, towards susceptible roots. The stages of the secondary cycle are similar to those of the primary cycle, and result in formation of necrotic root tissue, which may slough off. Bacteria and fungi can enter the necrotic wounds, and cause a complex disease syndrome to develop (Corbett, 1973).

2.1.5 Symptomatology

The intensity of symptoms of the root-lesion disease caused by P. penetrans varies depending on the host plant and environmental conditions. Within susceptible plant species marked differences occur in the relative amount of visual symptoms observed. In general, however, the primary symptoms appear as necrotic lesions

on the roots. Root-lesions first appear as tiny water-soaked spots, but these soon turn brown or almost black. The lesions appear mainly on the young feeder roots, but they may be found anywhere along the root system. Lesions generally coalesce with each other by expanding longitudinally along the root axis, but they may also expand laterally girdling and killing the entire root. As the lesions enlarge, the infected cells in the cortex collapse and the discolored area appears constricted. The secondary symptoms include yellowing of leaves, which reduces the photosynthetic capabilities of the plant, resulting in stunting and general poor growth of the plants.

These symptoms result from the inefficient functioning of the diseased root system which is unable to allow adequate uptake of water and nutrients from the soil (Mai, 1960; Pitcher *et al*. 1960; Mountain, 1961; Dickerson *et al*. 1964).

2.1.6 Ecology

Environmental conditions greatly influence population dynamics of *P. penetrans* and the development of plant diseases caused by root-lesion nematodes.

2.1.6.1 Temperature

Disease development is to a large extent influenced by temperature, as the activity and survival of the nematodes are governed by this factor. Acosta and Malek (1979) reported on the influence of temperature on population development of different species of Pratylenchus on soybean. P. penetrans and P. scribneri showed greatest reproduction potential at a temperature of 25 C. It has been reported that P. penetrans increases in the soil in late summer and early autumn, and decreases in late spring and early summer (Di Edwardo, 1961; Miller et al. 1963; Ferris, 1967; Olthof, 1971; Olthof and Potter, 1973). The fluctuations are a result of migration of the nematodes in the roots early in spring and summer and out of the roots in late summer. Although the population dynamics is greatly influenced by temperature the host crop with which the nematodes are associated has a significant influence on population development.

The inital population density is also of great importance and Oostenbrink (1966) observed that the initial population density at the time of planting was a consistant parameter for estimating decreases in yield of the host crop. He found a significant linear relationship between initial population densities and tuber weight of potatoes

infected with P. penetrans. Olthof et al. (1973) also observed a positive correlation between yield loss and initial population densities of P. penetrans associated with potato roots. Seinhorst (1966) observed that a minimum density of 1.0 P. penetrans per gram of soil was necessary to cause damage to some crops. Oostenbrink (1966) reported that densities from 0.4 to 1.0 per gram of soil in sandy soils and densities of 0.7 to 2.0 per gram in organic or loam soil were required to cause significant reduction in yields of crops infected with P. penetrans. El-Sherif and Mai (1966) observed a linear relationship between numbers of P. penetrans that invaded roots and numbers transferred to plants when the initial inoculum density was above 200.

2.1.6.2 Soil nutrients

Population densities are also affected by soil nutrients, either directly or indirectly through the influence of soil microorganisms. Walker (1969) demonstrated that additions of nitrogen to soil decreased populations of P. penetrans. Kirkpatrick et al. (1964) observed similar responses, and noted that populations were significantly reduced in plants which received high rates of potassium. Interactions of nematicides and fertilizers can also influence population densities

(Vitosh et al. 1978).

2.1.6.3 Soil moisture

Soil moisture is essential for movement and survival of nematodes. Excess soil moisture results in detrimental effects on populations by limiting their movement and reducing their oxygen supply. In general, population densities are higher in sandy soils which are well aerated and permit retention of adequate amounts of soil moisture. Thompson and Willis (1970) reported that significantly lower root and foliage growth of Empire birdsfoot trefoil (Lotus corniculatus L.) was observed at a soil moisture level of 50% field capacity when compared to growth at a moisture level of 70-100% field capacity. Population development was higher at the higher soil moisture level. Kable and Mai (1968) reported that the rate of population increase in P. penetrans was greatest at moderate soil water potentials and least at high water potentials. They concluded that the widespread occurrence of high population densities of P. penetrans in sandy soils was related to an interaction of soil temperature soil moisture and soil type.

2.1.6.4 Interactions with fungi

The root-lesion nematode disease can predispose plants to infection by fungi, e.g. Aphanomyces euteiches on peas, Fusarium oxysporum on lucerne and peas, Verticillium alboatrum and Verticillium dahliae on eggplant, peppermint, peppers, potatoes, strawberries and tomato (Miller and Edginton, 1962; Bergeson, 1963; Rich and Miller, 1964; Mountain and McKeen, 1965; Miller et al. 1967; Olthof and Reyes, 1969). Studies on the role of P. penetrans and Meloidogyne spp. in dry rot of kidney beans caused by Fusarium solani f. spp. phaseoli indicated that low inoculum densities of the fungus caused greater infection of dry root rot than high inoculum densities. However nematode infection had no significant effect on the severity of the disease (Hutton et al. 1972). Oyekan and Mitchel (1972) reported on the development of a synergistic interaction between Pratylenchus penetrans and Fusarium oxysporum in a wilt-resistant pea cultivar (Wisconsin perfection).

2.1.6.5 Nematode-Nematode interactions

Reports on the interaction of nematodes and their effects on yields are limited. Freckman and Chapman (1972) reported that Heterodera trifolii (Goffart) and Pratylenchus penetrans (Cobb) did not affect the penetration

of either nematode on red clover roots. Studies on the dynamics of field populations of Hoplolaimus columbus and Meloidogyne incognitia indicated that in some fields H. columbus replaced M. incognita while in other fileds the distribution of the species remained constant (Bird et al. 1974). Gay and Bird (1973) also reported on the influence of concomitant Pratylenchus brachyurus and Meloidogyne spp. on root penetration and population dynamics. McIntyre and Miller (1976) reported on the interactions of Tylenchorhynchus claytoni and P. penetrans in tobacco roots. They observed that population densities of P. penetrans were reduced in roots which were previously exposed to T. claytoni.

2.2 Navy Beans (Phaseolus vulgaris L.)

2.2.1 Importance

Navy beans are an important part of the diet of many people in numerous parts of the world. They are relatively inexpensive and highly nutritious, containing high amounts of protein, and smaller amounts of phosphorus, iron and vitamin B (Andersen, 1955). Dry beans are produced in many countries, and the major world producing countries include Brazil, U.S.A., Mexico, Yugoslavia and Italy (Martin and Leonard, 1967). In the U.S.A., the leading bean producing states include Michigan, California, Idaho, Colorado and Nebraska. Over 90% of the beans produced in the humid section of the U.S.A. are grown in Michigan and New York. Bean production ranks third in value in Michigan field crops, navy beans forming the major class of beans (Erdman et al. 1965).

Total estimated 1979 U.S. dry bean acreage was 1396.6 thousand acres and total Michigan dry bean acreage was 500 thousand. Bean production has remained constant from 1978 at an estimated level of 86,000 tons. Consumption however, has increased and is estimated at 80,000 tons.

2.2.2 Marketing

The canning industry forms the main market for navy beans. About 85-90% of the beans destined for domestic consumption are canned and the remainder are packaged and sold as dry beans. Other navy bean products include vegetable beans (beans in tomato sauce without meat), beans and ground beef, beans and weiners, beans and vienna sausages, beans with bacon soup, beans with molasses and baked beans (Anonymous, 1971).

2.2.3 Supply and price

The navy bean industry is characterized by considerable fluctuations from season to season. While the grower price fluctuates during a marketing season, retail prices of canned beans have remained relatively stable over the last few years. As bean production is concentrated in the Saginaw valley and the Thumb district, unfavorable weather in these areas can cause fluctuations in the total supply of navy beans.

The domestic demand for navy beans is quite inelastic. Also, there is a low influence of small California white beans (which is the only other bean which can be substituted for navy beans in the canning industry), on navy bean domestic demand. Therefore decreases in supply of navy beans would result in significant increases

in price (Anonymous, 1971).

2.2.4 Production factors affecting yield

The main reasons for the decline in navy bean yields have been attributed to (1) unfavorable environmental conditions of temperature and moisture, (2) choice of bean variety, (3) cultural practices, (4) soil fertility factors, (5) diseases and use of uncertified seed.

2.2.4.1 Environmental factors

The navy bean plant is a warm season annual adapted to a variety of soils. Optimum temperatures for growth range from 19 to 25 C (Martin and Leonard, 1967). High temperatures interfere with seed setting while low temperatures are unfavorable for growth. Austin and MacClean (1972) observed that temperature and moisture can affect bean germination, photosynthesis and respiration. They observed that rates of photosynthesis were lower in plants grown in low temperature regimes than for plants grown in high temperature regimes. Bean seeds germinate poorly in damp soils, and slow growing seedlings are subject to maggot injury, damping off and root rot diseases. In order to meet the moisture requirements for germination, beans are generally planted early in June in Michigan (Andersen et al. 1975). Adverse soil physical conditions result in detrimental

effects in dry bean production (Smucker and Mokma, 1978).

2.2.4.2 Navy bean varieties

A considerable amount of research has been carried out on bean breeding and varietal development, in order to produce high yielding disease resistant varieties (Anonymous, 1971; Adams, 1978). Improved varieties include Robust, which was the first virus resistant variety, Michilite, which is not only virus free but also shows improved quality, Sanilac, which was the first upright disease resistant bush-type bean plant, Seaway, Seafarer and Gratiot which are early maturing varieties. These improved varieties are grown on approximately 80% of the bean acreage in Michigan, Ontario and to a lesser extent in New York, Chile, Australia and Hungary (Anonymous, 1971).

2.2.4.3 Cultural practices

Navy bean plants thrive best in medium textured soils which are high in organic matter, and are provided with adequate drainage. Cultivation usually involves general practices for row crops, with emphasis on seed-bed preparation and subsequent tillage for weed control. A 1977 survey of cultivation practices in bean producing areas in Michigan indicated that 35% of the farms were plowed in the spring and 61% in the fall. Two-thirds of

these farms showed indications of poor soil structure. Andersen et al. (1975) reported that excessive tillage was practiced on many of the farms resulting in compaction problems and inefficient root growth. It is generally recommended that the soil should be tilled only when dry and only to a depth that includes the compacted zone.

It is recommended that beans should be grown in rotation with suitable crops which will return substantial amounts of organic matter to the soil. In Michigan crops which are used in rotation with beans include, corn, soybean, sugarbeets, alfalfa and small grain. About 30% of the farmers, however, grow continuous beans for about 3 years and this increases conditions of poor soil structure and also encourages development of some bean diseases. A number of herbicides are used effectively for weed control and Eptam is the most effective and widely used herbicide in bean production. Generally bean seeds are planted in rows 20 to 40 in. apart at shallow depths of 2.5-5.0 cm under adequate soil moisture conditions. Under favorable irrigated humid conditions a desirable stand of beans develops from use of planting rates of 40-100 lbs/acre (Martin and Leonard, 1967; Andersen et al. 1975). Cultivation practices, however, depend on the location, soil type and climatic conditions. The importance of choosing

a suitable planting density depending on location and method of production has been noted (Leakey, 1972; Williams et al. 1973; Pinchinat, 1974; Edge et al. 1974; Mafra et al. 1974; Scarisbrick et al. a976).

2.2.4.4 Soil fertility factors

A considerable amount of research has been carried out on the fertility requirements for bean production (Lange et al. 1958; Barker et al. 1966; Bans, 1967; Shea et al. 1968; Melton et al. 1970; Mugwira and Knezek, 1971; Edge et al. 1975). Beans respond more favorable to a long-term soil improvement program involving growing of green manure, fertilized leguminous forages and similar fertility enhancing practices, than they do to direct application of fertilizers (Rather, 1942). Moreover, germinating seedlings can be injured by the direct application of commercial fertilizers. This can be avoided by correct placement of the fertilizers. Andersen et al. (1975) reported that beneficial results can be achieved from band application of fertilizer at planting time. Studies on fertility requirements for bean production indicate that nitrogen and phosphorus are the two most important soil nutrients which are needed for adequate growth. The leguminous nature of navy bean plants enable them to obtain some of their nitrogen requirement from

symbiotic associations with nitrogen-fixing bacteria - Rhizobium phaseoli. Edge et al. (1975) described bean plants as poor nitrogen fixers.

Application of nitrogen fertilizers is necessary in fields which show nitrogen deficiency. In most soils nitrogen fertilizers appear to be more effective when added in the nitrate rather than in the ammonium form (Barker et al. 1966). Zinc, phosphorus and lime interactions with bean yields have been studied (Melton et al. 1970; Mugwira and Knezek, 1971). Reports indicate that yields on acid soils are generally decreased when zinc is applied. Ruschel et al. (1966) also observed effects of interactions between nitrogen fixation and other nutrients on bean yields.

2.2.4.5 Bean diseases

Navy beans are susceptible to a number of diseases caused by bacteria, fungi, viruses, insects and nematodes. Three types of bacterial blights have been observed in bean fields. These include, common bacteria blight caused by Xanthamonas phaseoli, fuscous blight caused by Xanthamonas phaseoli var fuscans, and halo blight caused by Pseudomonas phaseolicola. Andersen et al. (1975) reported the presence of common and fuscous blights in 75 bean fields in Michigan. Rains,

heavy dew and humid weather favor the development of the disease. The common and fuscous blights are enhanced by warm weather while halo blight is promoted by cool weather.

A number of fungal diseases are known to affect bean production. These include bean anthracnose caused by Colletotrichum lindemuthianum, sclerotina wilt or white mold caused by Sclerotinia sclerotium, fungus root rots caused by Fusarium solani, F. phaseoli, damping off and seed decay caused by Pythium aphanidermatum, Pythium debaryanum and Rhizoctonia solani.

Two virus strains, Phaseoli virus 1 and 2 can also cause bean diseases. Extensive breeding programs have resulted in the production of some disease resistant varieties. The Sanilac variety is resistant to bean anthracnose, and to Phaseoli virus 1 strain which causes common bean mossiac disease, but it is moderately susceptible to X. phaseoli and X. phaseoli var fuscans, which cause common and fuscous bacterial blights. The Monroe bean variety is resistant to both virus strains, while Michilite is partially resistant to virus 1 strain. Most of the other bean varieties grown in Michigan are susceptible to these diseases. Management strategies involving suitable crop rotation, use of certified seed, use of bactericides and fungicides can be effective in

controlling these diseases.

2.2.4.6 Nematode diseases

Reports on nematode diseases of dry beans indicate that the crop is susceptible to a number of nematode species within many genera such as, Meloidogyne, Heterodera and Pratylenchus (Blazey et al. 1964; Rhoades and Beeman, 1967; Sen and Jensen, 1969; Taylor et al. 1970; Hartmann, 1971; Ngundo and Taylor, 1974; Freire, 1976; Thomason et al. 1976).

Blazey et al. (1964) investigated the resistance of 55 common bean varieties to Meloidogyne incognita. Seventeen varieties were found to be partially resistant but not immune to this species, for occassionally small galls and females were found even in resistant varieties. Freire (1976), in a study of nematodes associated with beans, found M. incognita, M. javanica, Helicotylenchus nanus, Criconemoides spp., Pratylenchus brachyurus, Hemicycliophora lutosa and Xiphenema spp. in the rhizosphere of the bean roots. Considerable reduction in yields were observed in bean plants infested with M. incognita and M. javanica.

2.3 Symbionts in Association with Navy Beans

2.3.1 Mycorrhizae

Many plants are known to form symbiotic mycorrhizal associations which enhance their growth. The fungus provides the plant with nutrients while the plant in return supplies the fungus with carbon in the form of carbohydrates which are assimulated through the photosynthetic activity of the plant.

Mycorrhizae can be classified as ectomycorrhizae, endomycorrhizae and ectendomycorrhizae. The ectomycorrhizae produce a hypal mantle around the plant roots and an intercellular cortical net of hyphae known as the Hartig Net. Endomycorrhizae are characterized by hyphae which form a loose fungal network in the soil, and also penetrate the root cortex inter and intracellularly. Ectendomycorrhizae exhibit features of both ecto- and endo-mycorrhizae. They form a hyphal mantle and also penetrate the root cortex intracellularly.

Endomycorrhizae are fungi of the Endogonaceae (Phycomycete) and can be divided into septate and non-septate fungi (Gerdemann, 1969). Vesicular-arbuscular mycorrhizae are found in four genera of the Endogonaceae. These are: Gigaspora, Glomus, Acaulospora and Sclerocystis. Vesicular-arbuscular mycorrhizae have been described as

being dimorphic and composed of thick-walled non-septate hyphae, with thin-walled side branches which may lay down septa (Nicolson, 1959; Mosse, 1977). Hyphae of variable sizes are found within the root cortex, but the stele is not infected. Arbuscles which are specialized haustorical structures of the fungus are formed intracellularly as a result of extensive dichotomous branching of the main infection hyphae (Cox and Sanders, 1974). These arbuscles aid in the symbiotic association with plants. Thin-walled spherical structures known as vesicles may be produced intercellularly or intracellularly in the cortical tissue. Vesicular-arbuscular mycorrhizae produce globose, subglobose or eliptical to avoid spores which contain globules of oil. Gigaspora produces azygospores which are borne singly in the soil. These are subglobose and are borne terminally on a bulbous suspension-like cell.

The most widespread V-A endomycorrhizal fungi are found in the genus Glomus (Gerdemann and Trappe, 1974). These fungi produce chlamydospores which are borne on undifferentiated nongametangial hyphae. Spores are usually terminal, however intercalary spores and spores with more than one basal attachment sometimes occur. Two important species of the genus commonly found in Michigan are Glomus fasciculatus and Glomus mossea

(Kotcon, 1978; Bird and Safir, 1979).

Beneficial effects obtained from mycorrhizal associations have been attributed to increase in the absorption surface provided by the extensive branching hyphae of the fungi in contact with soil nutrient reserves. Increases in growth have been related mainly to increase in uptake of phosphorus, but increases in uptake of water, nitrogen, potassium, boron aluminium,manganese and zinc have also been observed (Ross and Harper, 1970; Ross, 1971; Sanders and Tinker, 1971; Ross, 1972; Hattingh et al. 1973; Mosse et al. 1973; Bird, 1974; Tinker, 1975; LaRue et al. 1975; Bowen et al. 1975; Safir, 1977).

Environmental factors such as temperature, light and moisture can affect the development of mycorrhizal associations (Mosse, 1973; Hayman, 1974; Furlan and Fortin, 1977). The degree of mycorrhizal infection may vary greatly depending on the degree of shading which plants receive (Hayman, 1974; Redhead, 1975). The relationship between mycorrhizal infection and soil moisture is not clearly defined, but this is influenced largely by the soil type, the mycorrhizal fungus and the host plant. Generally, optimum soil water required for plant growth enhances mycorrhizal infection. Tinker (1975) reported that soil fertility

factors influence the development of mycorrhizal associations. Generally soils of low fertility favor mycorrhizal infection while soils of high fertility levels may even retard the development of mycorrhizal associations. Mosse (1977) however observed that mycorrhizal associations can be established in soils which contain high levels of phosphorus when relatively high levels of mycorrhizal inoculum are used. The beneficial effects of mycorrhizal associations are therefore of greater significance in soils of low to moderate fertility.

Reports indicate that mycorrhizal associations can influence the development of plant diseases. Vesicular-arbuscular mycorrhizal interactions with pathogenic organisms have been observed (Schenck and Kinlock, 1974). Reduction of infection by Thielaviopsis basicola in mycorrhizal plants was observed (Baltruschat et al. 1973; Schonbeck and Dehne, 1977). Ross (1972) observed interactions of Phytophthora megaspermae var sigae and vesicular-arbuscular mycorrhizae associated with soybeans. Daft and Okusanya (1973) reported that tomato aucuba mossiac virus increased in plants as the mycorrhizal infection increased. Mycorrhizal onion roots however are less susceptible to pink root diseases caused by Pyrenochaeta terrestris (Safir, 1968;

Becker, 1976).

Mycorrhizal-nematode interactions are complex. O'Bannon et al. (1979) observed that T. semipenetrans infected roots grown in infested G. mossea soil did not show evidence of vesicle development but arbuscular development was observed. Interactions of Heterodera solanacearum and vesicular-arbuscular mycorrhizae reduced mycorrhizae and nematode densities and also yield of Tobacco (Fox and Spasoff, 1972). Studies on interactions of Meloidogyne spp. and Heterodera spp. and vesicular-arbuscular mychorrhizal fungi indicated that high population densities of Meloidogyne spp. were associated with low densities of mycorrhizal spores (Schenck and Kinlock, 1974; Schenck et al. 1975). The results of Schenck et al. (1975) support the findings of Baltruschat (1973) indicating an antagonistic relationship between vesicular-arbuscular mycorrhizae and low nematode densities. Schenck et al. (1975) also pointed out that the species of mycorrhizae influenced the nature of the interaction between vesicular-arbuscular mycorrhizae and nematodes. Interactions between mychorrhizal fungi and nematodes are not always detected. Hussey and Roncadori (1978) observed no interaction between Pratylenchus brachyurus and

vesicular-arbuscular mycorrhizae, but plant growth was increased by vesicular-arbuscular mycorrhizae.

3.0 EXPERIMENTAL

3.1 General Procedures

3.1.1 Soil samples

3.1.1.1 Field samples

Soil samples were taken by inserting a conical shaped nematode soil sampler to depth of 5-15 cm in the soil. Six soil cores were taken to fill the soil sampler. The soil was then transferred to plastic bags and stored at 4 C until they were processed for nematode densities.

3.1.1.2 Greenhouse samples

The total quantity of soil in a pot was taken as the soil sample.

3.1.2 Root samples

3.1.2.1 Field samples

Bean plants were uprooted with the aid of a narrow bladded shovel. Roots from six plants were taken to make a composite sample.

3.1.2.2 Greenhouse samples

The entire root system was carefully removed and used to represent a sample from one replicate of

any treatment.

3.1.3 Nematode extraction

3.1.3.1 Soil samples

A modified centrifugation-flotation technique (Jenkins, 1964) was used to extract nematodes from soil samples. Both living and dead nematodes were recovered with this method. In this method 100 cm^3 of soil from the composite sample were added to three gallons of water in a plastic pail. The soil was mixed for three minutes and the sediment was allowed to settle. The soil suspension was poured through a 100 mesh sieve on to a 400 mesh sieve. The soil with nematodes was then washed from the sieve into a 20 ml centrifuge test tube. The soil suspension was centrifuged at 42g for 4.5 min. The tube was removed from the centrifuge and the supernatant liquid was decanted. A sucrose solution with a specific gravity of 1.14 was added to the soil and contents were thoroughly mixed and centrifuged again for 2.5 min. The supernatant liquid containing the nematodes was poured on to a 400 mesh sieve and the nematodes were washed from the sieve into 5 ml test tubes.

3.1.3.2 Root samples

Nematodes were extracted from the roots by a shaker technique. In this method two g of root tissue

were placed in a 125 or 250 ml flask, and 50 ml of an incubation solution (a mixture of 10 ppm Ethoxyethyl mercuric chloride (EMC) and 50 ppm Dihydrostreptomycin sulfate (DSS)), was added to the flask and placed on a gyratory shaker at 100 rpm for three days. Nematodes were recovered by decanting the solution from the flask on to a 400 mesh sieve. Nematodes were washed from the sieve into 5 ml test tubes.

3.1.4 Identification and calculation of nematode population densities

Five ml suspensions from nematode extraction procedures were poured into calibrated petri dishes divided into 10 longitudinal sections. Nematodes were identified and the number of nematodes in 2 sections (1/5 area) of the petri dish were enumerated with the aid of a compound microscope and a stereoscope. Enumerated values, multiplied by 5 were averaged to express density per 100 cm^3 soil and density per 1 g root tissue, respectively. At low densities the number of nematodes in each section of the petri dish were counted.

3.1.5 Extraction of vesicular-arbuscular mycorrhizal spores from soil

Vesicular-arbuscular mycorrhizae spores were extracted from soil using a modified centrifugal-flotation

technique. The method was similar to that outlined in Sec. 3.1.3.1 with a slight modification in the specific gravity of the sucrose solution. In this method for extracting vesicular-arbuscular spores a sucrose solution with a specific gravity of 1.37 was used.

3.1.6 Identification of vesicular-arbuscular mycorrhizae in root samples

Internal hyphae and vesicles were observed by a staining technique. In this method 2.0 g of root tissue were cut thinly and immersed in 10% Potassium hydroxide (KOH) for one hour. The roots were rinsed with distilled water and acidified in 10% Hydrochloric acid (HCL) for one hour. The roots were then removed from the acid and stained with acid fuschin-lactophenol solution for 30 min. Roots were cleared in lactophenol. Arbuscles, vesicles and hyphae were identified with the use of a Spencer compound microscope and percentage root infection was calculated.

3.1.7 Converting time to accumulated degree days

Sampling dates were expressed as the number of accumulated heat units, termed degree days. These heat units or degree days represent the amount of energy

available for growth and development of organisms and plants. The daily minimum and maximum temperatures were used to calculate degree days and the sum of degree days for each sampling period was calculated as the accumumlated degree day value. The base temperature used for calculation of degree days was 10C. Daily temperatures were recorded in degree fahrenheit and a conversion factor of 0.556 was used to convert degree days from degrees fahrenheit to degrees centigrade. The equation for accumulated degree days is:

$$(DD_{10\hat{C}}) = \left(\frac{\text{Min T + Max T}}{2} - 50\right) \times 0.556$$

where $DD_{10\ C}$ is accumulated degree days at base 10 C
Min T = Minimum temperature in degrees fahrenheit
Max T = Maximum temperature in degrees fahrenheit
(Vander Brink *et al*. 1977).

3.1.8 Plant growth analysis

Quantitative growth analysis involving use of growth indeces was conducted. The effect of *P. penetrans* on relative growth rate of plants and leaf area ratios were examined. The relative growth rate provides a valuable overall index of plant growth. The mean value of relative growth rate (R) was calculated using the equation:

$$R = \frac{\ln dW_2 - \ln dW_1}{T_2 - T_1}$$

where R = relative growth rate per week

W_2 = dry weight of navy bean shoot system at time T_2

W_1 = dry weight of navy bean shoot system at time T_1

T = time in weeks

Leaf area ratio represents the ratio of leaf area to total plant shoot dry weight (Evans, 1972). This growth index was calculated using the equation:

$$LAR = \frac{L}{W}$$

where LAR = Leaf area ratio

L = leaf area

W = shoot dry weight

3.1.9 Soil moisture characteristic curves

Soil moisture characteristic curves for three soil types were developed using the method described by Richards (1965), and modifications of this method. The method involved estimation of percent moisture associated with specific matrix potentials, with the use of pressure plates. The percent gravimetric moisture was calculated from the equation:

$$\text{\% Gravimetric moisture} = \frac{\text{Weight of soil water}}{\text{Weight of oven dried soil}} \times 100$$

and the percent volumetric moisture was calculated by multiplying the gravimetric moisture by the bulk density of the soil:

$$\text{\% Volumetric moisture} = \frac{\text{Wt. of soil } H_2O}{\text{Wt. O.D. soil}} \times \frac{\text{Wt. of O.D. soil}}{\text{Volume of soil}} \times 100$$

$$\text{\% Volumetric moisture} = \text{\% gravimetric moisture} \times \text{bulk density}$$

where bulk density = $\frac{\text{Wt. O.D. soil}}{\text{Volume of soil}}$

O.D. soil = oven dried soil

3.2 Pest System

3.2.1 Field distribution of *Pratylenchus penetrans*

3.2.1.1 Method

A field site measuring 238.60 x 15.24 sq. m in size covered with a rye cover crop was used to study the field distribution of *Pratylenchus penetrans* in 1977. The field was divided into 184 plots. Each plot measured 3.81 x 3.81 sq. m in size (Figure 3.1). A soil sample consisting of six soil cores was collected from each plot.

Four of these plots were randomly chosen and each plot was divided into 16 subplots, each subplot measuring 0.96 x 0.96 sq. m in size (Figure 3.2). A soil sample consisting of six soil cores was taken from each subplot.

One of the 16 subplots was selected from each of the four main plots. Six soil samples each consisting of one soil core were taken from the selected subplots within the four main plots (Figure 3.2, A, B, C, D).

Following sampling the field was divided into two equal sections. The upper half of the field was ploughed while the lower half was left with the rye cover crop. The field was allowed to remain as described over the winter. In the spring (April, 1978), the field

1	2	3	4
8	7	6	5
9	10	11	12
16	15	14	13
17	18	19	20
24	23	22	21
25	26	27	28
32	31	30	29
33	34	35	36
40	39	38	37
41	42	43	44
48	47	46	45
49	50	51	52
56	55	54	53
57	58	59	60
64	63	62	61
65	66	67	68
72	71	70	69
73	74	75	76
80	79	78	77
81	82	83	84
88	87	86	85
89	90	91	92
96	95	94	93
97	98	99	100
104	103	102	101
105	106	107	108
112	111	110	109
113	114	115	116
120	119	118	117
121	122	123	124
128	127	126	125
129	130	131	132
136	135	134	133
137	138	139	140
144	143	142	141
145	146	147	148
152	151	150	149
153	154	155	156
160	159	158	157
162	162	163	164
168	167	166	165
169	170	171	172
176	175	174	173
177	178	179	180
184	183	182	181

Figure 3.1. Plot plan for the study of the field distribution of Pratylenchus penetrans.

B_1 - PLOT 24

1	2	3	4
8	7	A 6	5
9	10	11	12
16	15	14	13

B_2 - PLOT 52

1	2	3	4 B
8	7	6	5
9	10	11	12
16	15	14	13

B_3 - PLOT 122

1	2	3	4
8	C 7	6	5
9	10	11	12
16	15	14	13

B_4 - PLOT 173

1	2	3	4
8	7	6	5
9	10 D	11	12
16	15	14	13

Figure 3.2. Sampling scheme for subplots.

was divided into 184 plots. The above sampling scheme was repeated (Figure 3.3) and soil and root samples were taken from the lower half of the field covered with rye. In June, 1978 the upper half of the field was divided into 48 plots for a randomized block design experiment. Each plot was 6.09 x 3.46 sq. m in area (Figure 3.4). The lower half of the field was divided into 24 plots measuring 12.18 x 6.92 sq. m in area respectively (Figure 3.4). A soil sample consisting of six soil cores was collected from each plot.

Soil and root samples were analysed for densities of P. penetrans (3.1.3-3.1.4). The data were analysed for variance/mean ratios. Other indeces of dispersion including Green's index, the dispersion constant K and the reciprocal of K (1/K) were also calculated. The chisquared test was used to determine whether the distribution was random, aggregate or regular. Goodness of fit test for a negative binomial distribution was applied to test the distribution from the initial sampling scheme (Figure 3.1-3.2).

3.2.2 Incidence of Pratylenchus penetrans in dry bean fields in Michigan

3.2.2.1 Method

In order to determine the significance and nature of nematode problems in Michigan dry bean

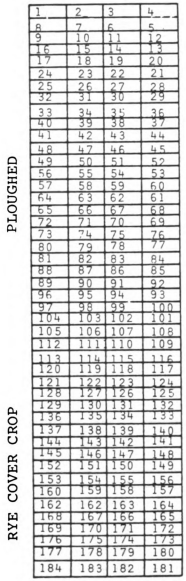


Figure 3.3. Plot plan for the study of the field distribution of Pratylenchus penetrans in the ploughed and unploughed sections of the field.

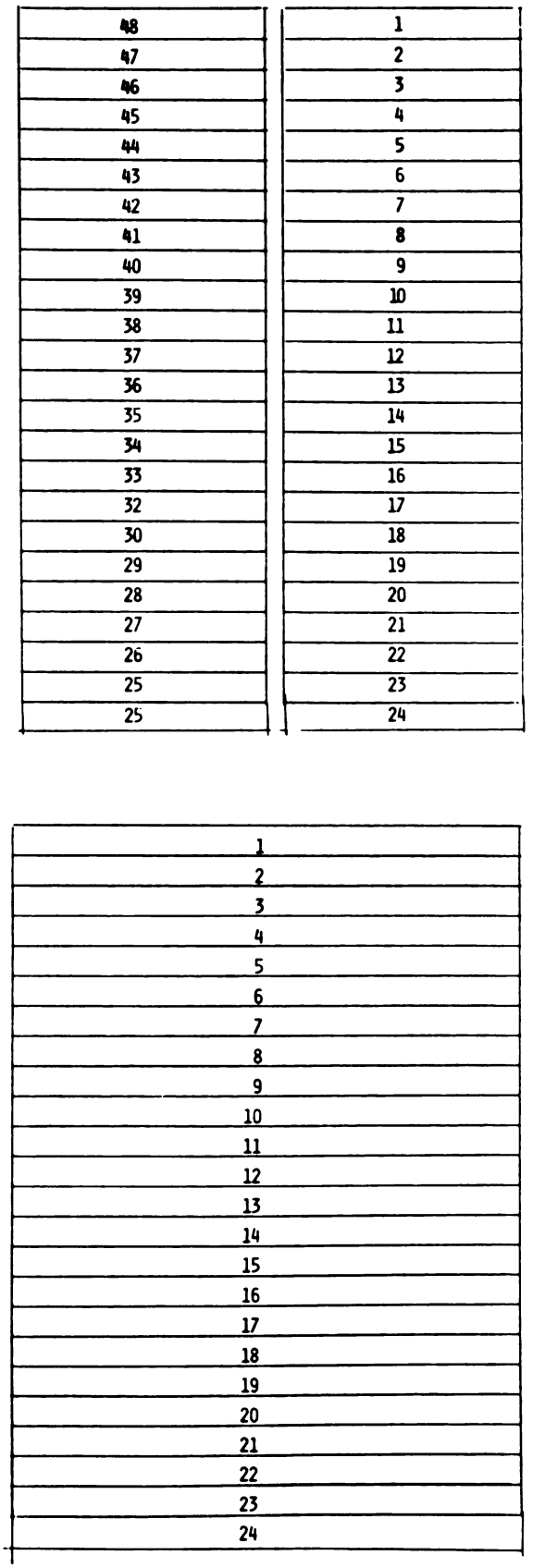


Figure 3.4. Plot plan for the randomized block designs.

production, a survey on the incidence of nematodes in 80 dry bean fields was conducted. The 80 sampling sites were selected from a total of seven counties (Figure 3.5). Fifteen sampling sites were selected in Bay and Montcalm counties respectively. Ten sampling sites were selected in the other five counties of Huron, Saginaw, Tuscola, Sanilac and Gratiot respectively. Each sampling site consisted of one hectare (10,000 sq. m). Two soil and root samples for nematode analysis were collected from each site (3.1.1.1 and 3.1.2.1). Nematodes were extracted, identified and enumerated (3.1.3-3.1.4). Information on associated soil tvpe and bean variety was collected.

The percent occurence of nematode species in each county was determined.

3.2.3 Development of an experimental population of Pratylenchus penetrans

3.2.3.1 Method

A culture of P. penetrans was developed on navy beans to provide a source of inoculum densities for greenhouse experiments. One hundred navy bean plants cv Sanilac were propagated in sterilized sandy clay loam soil in the greenhouse. One week after germination, two holes were made in the soil around the bean roots,

State of Michigan

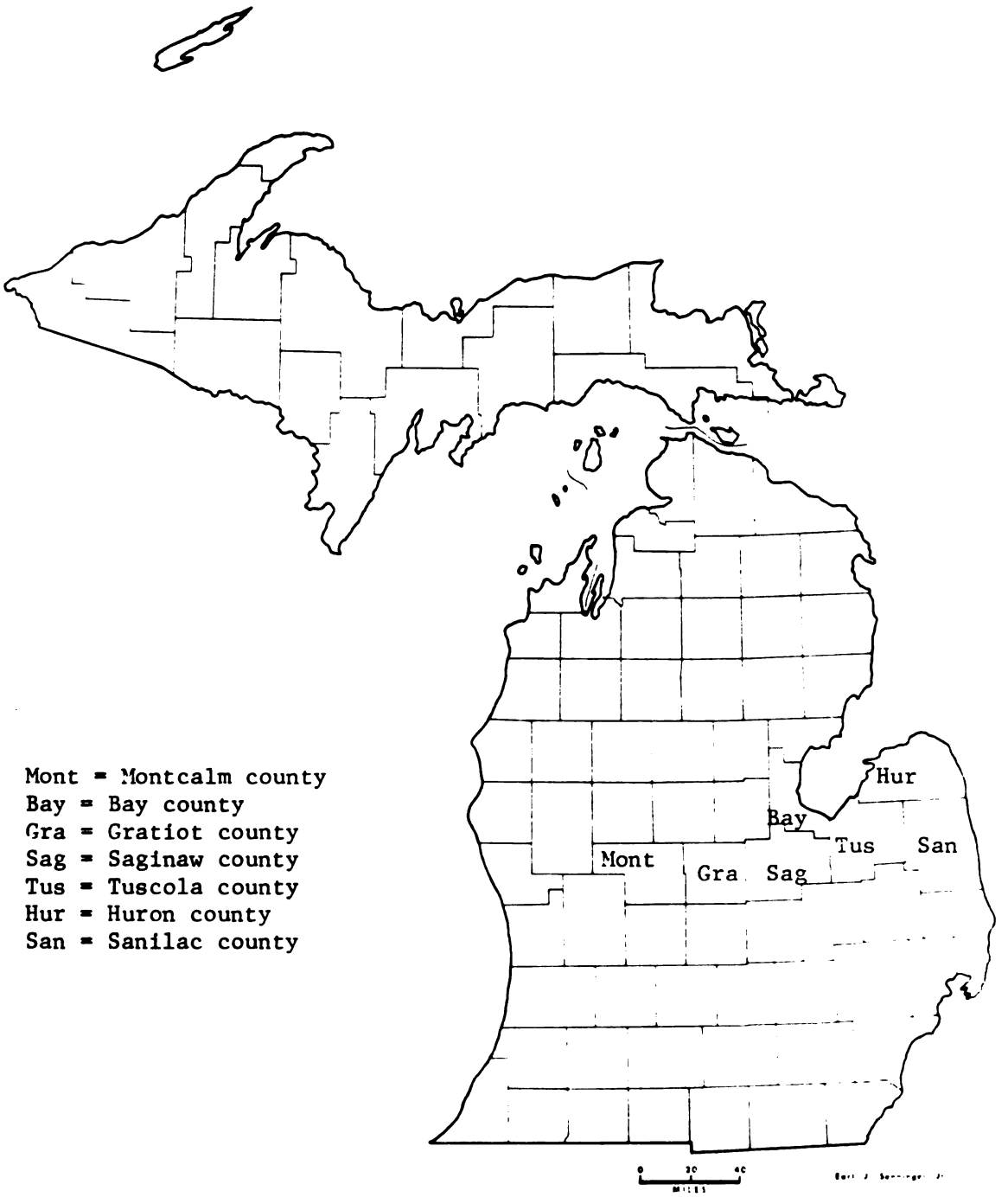


Figure 3.5. Counties included in a survey of P. penetrans in dry bean fields in Michigan.

and one male and one female P. penetrans suspended in 50 ml of water in beakers were added to the holes in the soil. The holes were sealed and plants were watered daily. Population densities were allowed to develop for a period of ten months. Sanilac navy beans were planted three times during this period.

Soil and root samples were taken (3.1.1.2 and 3.1.2.2) and nematodes were extracted, identified and enumerated (3.1.3-3.1.4).

The extracted nematodes from this population were used to inoculate roots of navy bean plants which were propagated in sandy clay loam soil in large culture boxes in the greenhouse. Navy beans were replanted regularly to maintain the population of P. penetrans. Inoculum densities of P. penetrans for greenhouse experiments were obtained from populations developed in these culture boxes.

3.2.4 Identification of the life cycle stages of Pratylenchus penetrans

3.2.4.1 Method

In order to study the population dynamics of P. penetrans it was necessary to identify and develop a key to the different stages in the life cycle of P. penetrans. Navy bean roots were taken from the

culture boxes and P. penetrans were extracted from these roots (3.1.3.2). Temporary slides of different stages (identified visually) were prepared. Morphometric characters of (a) body length (b) body width (c) oesophagus length (d) ovary length and (e) anal length were measured with the use of a calibrated ocular micrometer in a compound microscope. Allometric characters of (1) "a" value (body length/body width) (2) "b" value (body length/oesophagus length) and (3) "c" value (body length/anal length) were calculated.

The biomass of nematodes was calculated as:

$$\left(\frac{(\text{Body width})^2 \times (\text{Body length})}{16 \times 100{,}000}\right)$$ (Andrassy, 1956; Norton, 1977). The data were statistically analysed to determine mean values for each stage, standard deviations and coefficients of variation. Analyses of variance and Student Newman-Keuls test were applied to determine significant differences in morphometric and allometric characters among different stages in the life cycle of P. penetrans. A key to the life cycle stages of P. penetrans based on differences in morphometric and allometric characters was developed.

3.2.5 Results

3.2.5.1 Field distribution of *P. penetrans*

The variance/mean ratios for all sample sets were greater than one by the chi-squared test (Table 3.1). The chi-squared test indicated that the distribution of *P. penetrans* over the whole field (Figure 3.6) was aggregated (Table 3.1A). The distribution was also aggregated in subplots from which 16 samples were taken (Figure 3.7; Table 3.1B). The degree of aggregation was lower in subplots from which soil samples consisting of one soil core was taken (Figure 3.8; Table 3.1C). For two of these sets agreement with a random distribution was obtained by the Pearson Hartley statistic (Elliott, 1973; Table 3.1C). This random distribution was supported by the high reciprocal K values (Table 3.1C).

Goodness of fit test for a negative binomial distribution indicated that the field distribution of *P. penetrans* determined for the sampling scheme involving the whole field (Figure 3.6) was significantly correlated with a negative binomial distribution (Table 3.1).

The distribution of *P. penetrans* in the unploughed section of the field covered with a rye cover crop (Figures 3.9-3.17) was aggregated (Table 3.1D-L) except for one sample set (Table 3.1I). The distribution of total population densities in roots plus soil was of an aggregate

Table 3.1: Analysis of field distribution of Pratylenchus penetrans

Sample level & No.	$\bar{x}$	S^2	$\frac{S^2}{\bar{x}}$	Green's Index	K^2	1/K	X^2	df	Distribution
A 184	13.98	133.50	9.53	0.003	1.63	0.63	9.20	3	Neg B
B_1 16	16.19	288.69	14.12	0.05	1.06	0.94	1.20	1	Neg B
B_2 16	12.25	110.60	9.02	0.04	1.45	0.69	0.54	3	Neg B
B_3 16	11.87	95.32	8.03	0.04	1.61	0.62	7.63	6	Neg B
B_4 16	12.30	83.80	6.81	0.03	2.04	0.49	1.67	1	Neg B
C_1 6	3.66	4.66	1.27	0.01	12.61	0.08	6.39	5	Random
C_2 6	4.33	7.47	12.80	0.50	5.57	0.18	8.62	5	Random
C_3 6	12.16	70.17	5.77	0.07	2.35	0.43	5.24	9	Neg B
C_4 6	9.50	36.30	3.82	0.05	3.14	0.32	3.28	3	Neg B

A-C initial complete sampling scheme

$$K = \frac{\bar{x}^2 - (S^2/n)}{S^2 - \bar{x}}$$

$$S^2 = \frac{\Sigma(x - \bar{x})^2}{n-1}$$

$$\text{Green's index} = \frac{(S^2/\bar{x})-1)}{(\Sigma x - 1)}$$

$$\chi^2 = \frac{S^2(n-1)}{\bar{x}}$$

Table 3.1 con't

Sample level & No.	$\bar{x}$	S^2	$\frac{S^2}{\bar{x}}$	Green's Index	K	1/K	χ^2	Distribution
D 92	25.91	1002.45	38.67	0.001	0.68	1.47	d = 70.92	Aggregate
E_1 16	15.81	395.36	25.00	0.10	0.59	1.69	375.10	"
E_2 16	20.06	272.73	13.59	0.04	1.52	0.66	203.94	"
E_3 16	10.25	261.53	25.52	0.15	0.35	2.86	382.72	"
E_4 16	13.06	140.59	10.76	0.05	1.26	0.79	161.47	"
F_1 6	14.67	202.67	13.81	0.147	0.96	1.04	69.07	"
F_2 6	8.33	82.67	9.92	0.18	0.75	1.34	49.62	"
F_3 6	4.30	68.27	15.80	0.60	0.11	0.09	79.38	"
F_4 6	31.50	125.90	3.99	0.005	10.42	0.10	19.98	"

D-F sampling scheme for lower half of field covered with rye cover crop (soil samples)

$d = (\sqrt{2\chi^2} - \sqrt{2v - 1})$

v = degrees of freedom

Table 3.1 con't

Sample level & No.	$\bar{x}$	S^2	$\frac{S^2}{\bar{x}}$	Green's Index	K	1/K	χ^2	Distribution
G 92	25.65	1262.69	49.69	0.02	0.52	1.93	d = 64.63	Aggregate
H_1 16	14.19	290.16	20.44	0.08	0.66	1.51	306.72	"
H_2 16	30.69	590.09	19.22	0.02	1.61	0.62	288.41	"
H_3 16	8.81	107.49	12.20	0.79	0.71	1.41	183.72	"
H_4 16	18.63	300.78	16.14	0.05	1.16	0.86	242.17	"
I_1 6	5.00	11.20	2.24	0.04	3.73	0.27	11.20	Random
I_2 6	9.00	186.40	20.70	0.40	0.30	3.30	103.33	Aggregate
I_3 6	10.67	143.47	13.45	0.19	0.68	1.47	67.23	"
I_4 6	10.17	196.97	19.36	0.30	0.40	2.50	96.84	"

G-I sample scheme for lower half of field covered with rye (root samples)

Table 3.1 con't

Sample level & No.		$\bar{x}$	S^2	$\frac{S^2}{\bar{x}}$	Green's Index	K	1/K	χ^2	Distribution
J	92	51.11	2413.73	47.22	0.01	1.09	0.91	d = 78.25	Aggregate
K_1	16	30.00	608.53	20.28	0.03	1.48	0.68	304.42	"
K_2	16	50.69	748.09	14.76	0.02	3.16	0.28	221.79	"
K_3	16	19.06	594.06	31.06	0.01	0.57	1.19	467.50	"
K_4	16	31.69	483.29	15.25	0.10	2.16	1.75	228.75	"
L_1	6	19.67	163.47	8.31	0.08	2.50	0.40	41.55	"
L_2	6	17.33	173.47	10.00	0.09	1.73	0.58	50.05	"
L_3	6	15.00	128.00	8.53	0.08	1.80	0.55	42.66	"
L_4	6	41.67	441.07	10.58	0.04	4.16	0.24	52.92	"

J-L sample scheme for the lower half of field covered with rye (soil plus root)

Table 3.1 con't

Sample level & No.	$\bar{x}$	S^2	$\frac{S^2}{\bar{x}}$	Green's Index	K	1/K	χ^2	Distribution
M 92	14.31	245.50	17.78	0.01	1.84	1.19	d = 43.42	Aggregate
N_1 16	17.50	216.00	12.34	0.04	1.47	0.68	185.14	"
N_2 16	9.53	62.76	6.59	0.04	1.63	0.61	98.78	"
N_3 16	15.18	155.63	10.25	0.04	1.59	0.63	153.80	"
N_4 16	10.00	58.80	5.80	0.03	1.85	0.54	88.20	"
O_1 6	12.00	239.60	19.97	0.26	0.46	2.17	99.83	"
O_2 6	4.83	14.96	3.09	0.07	2.05	0.49	15.48	"
O_3 6	10.33	231.06	22.37	0.34	0.31	3.22	111.83	"
O_4 6	8.83	58.50	6.63	0.11	1.37	0.73	33.12	"
P 48	53.41	403.90	7.50	0.003	8.24	0.10	352.78	"
Q 24	63.45	1255.56	19.78	1.58	3.33	0.30	455.01	"

N-O sample scheme for the ploughed half of field
P - sample scheme for the randomized block design of 48 plots
Q - sample scheme for the randomized block design of 24 plots

27	0	36	35
18	16	0	7
13	0	0	3
36	17	0	0
0	7	7	26
32	34	7	10
26	48	5	26
14	0	3	0
11	21	34	3
7	23	21	14
11	6	9	25
8	30	35	0
16	23	7	34
6	9	6	13
17	4	20	30
22	13	39	42
30	12	12	38
13	23	15	30
3	14	14	3
7	4	0	4
11	16	9	25
30	10	10	8
18	13	5	12
7	9	12	4
7	7	15	7
33	7	15	7
17	25	32	31
27	32	31	10
17	22	44	6
0	5	24	19
20	7	7	20
8	38	7	23
17	11	19	6
35	31	4	21
5	21	5	13
0	0	5	2
4	0	6	2
0	2	6	18
0	5	4	18
2	5	14	4
12	10	22	2
13	0	10	22
9	14	0	4
4	5	10	10
0	0	0	42
12	38	14	24
10	3	12	18

Figure 3.6. Distribution of P. penetrans in the field.

B_1 - PLOT 24

14	36	0	6
26	4	8	5
41	11	8	0
20	2	38	40

B_2 - PLOT 52

36	23	11	8
4	10	0	4
0	15	5	15
27	8	5	25

B_3 - PLOT 122

12	17	22	0
15	18	0	4
26	30	19	5
15	2	3	2

B_4 - PLOT 173

6	2	0	30
16	6	23	0
10	2	19	9
19	15	21	18

Figure 3.7. Distribution of P. penetrans in subplots

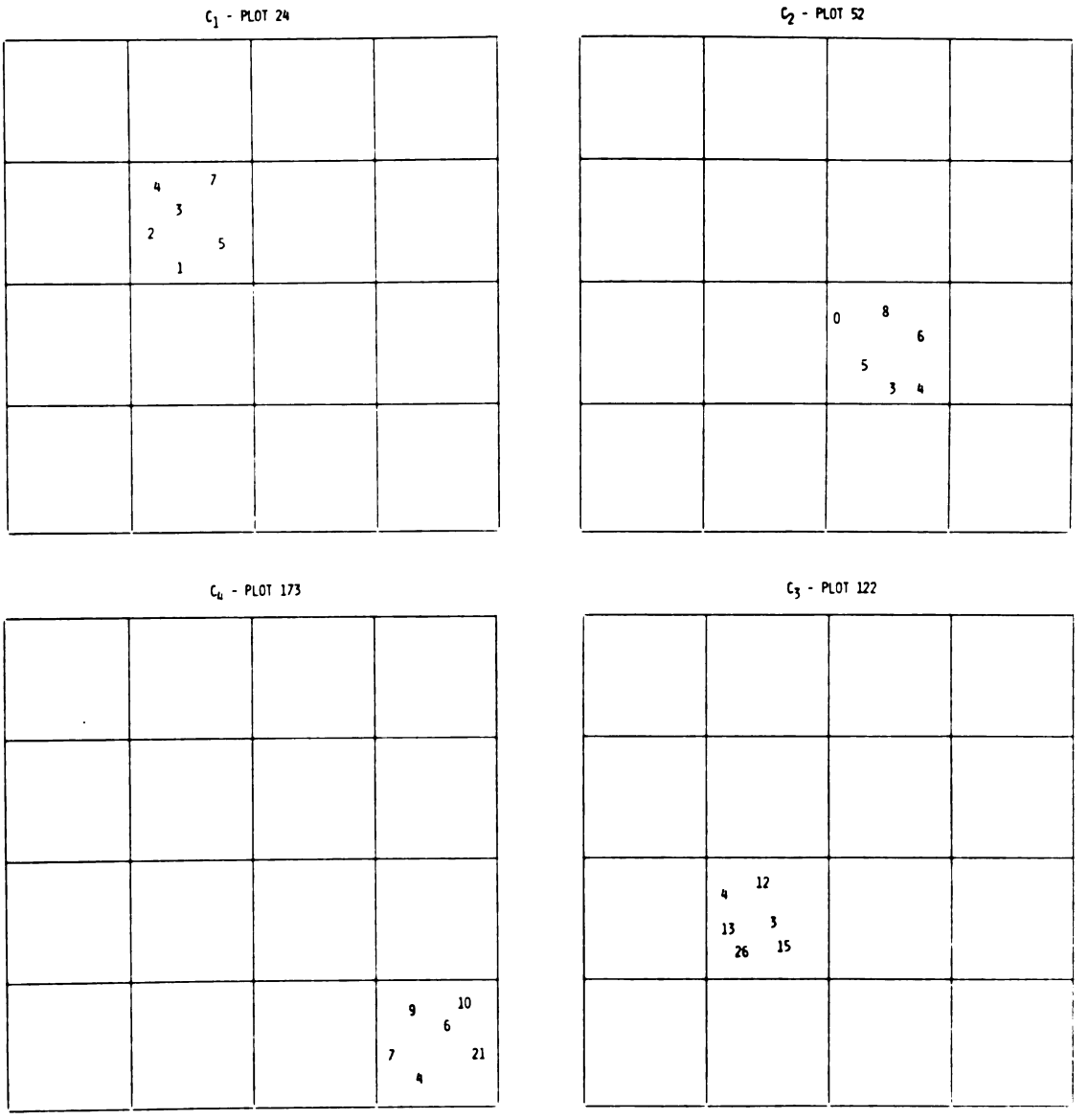


Figure 3.8. Distribution of P. penetrans from samples consisting of one soil core.

15	10	16	0
3	0	79	10
33	0	28	59
0	40	21	0
16	2	8	0
21	0	133	12
0	12	0	6
16	84	19	16
14	2	77	0
4	86	0	23
9	35	31	11
0	2	0	52
66	12	41	15
7	21	114	4
8	0	4	5
0	22	10	45
39	2	1	7
16	0	8	4
65	74	48	94
118	28	52	2
19	34	20	4
85	84	100	7
0	52	30	12

Figure 3.9 Soil distribution of P. penetrans from the section of the field covered with rye.

E_1- PLOT 96 (SOIL)

17	30	4	2
2	21	6	2
0	6	0	14
63	56	30	0

E_2- PLOT 142 (SOIL)

32	0	32	35
24	28	63	6
12	16	28	20
2	7	16	0

E_3 - PLOT 164 (SOIL)

23	9	20	21
14	3	0	10
0	62	0	2
0	0	0	0

E_4 - PLOT 175 (SOIL)

0	0	20	13
7	6	7	0
4	0	32	32
24	20	30	14

Figure 3.10. Soil distribution of P. penetrans in subplots from the section of the field covered with rye.

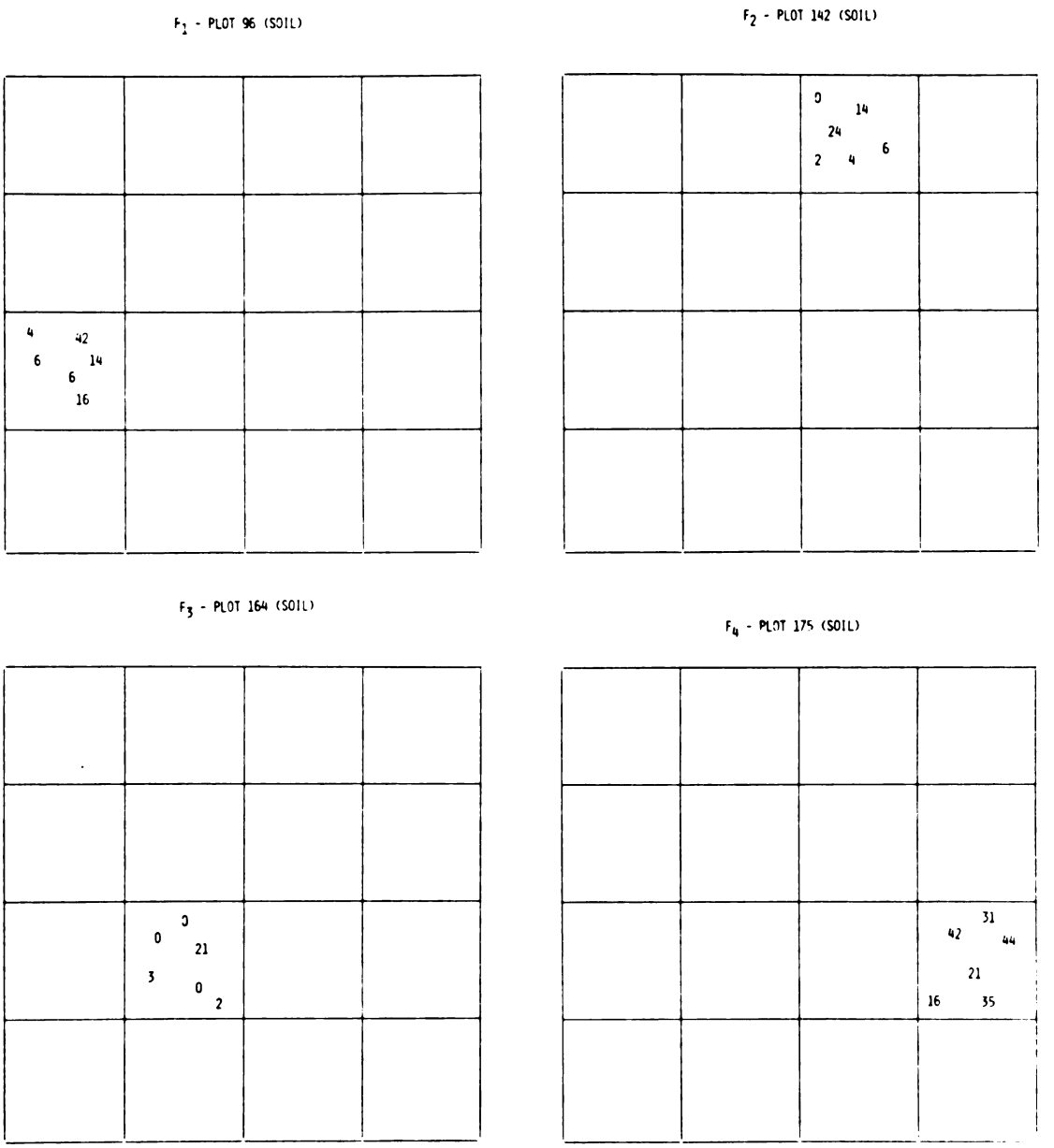


Figure 3.11. Soil distribution of P. penetrans from samples consisting of one soil core from the section of field covered with rye.

16	2	18	16
15	70	164	25
14	27	42	16
2	0	0	68
16	8	35	0
16	4	42	84
8	13	6	102
20	20	0	4
45	0	0	24
12	16	14	2
7	12	0	2
30	28	10	156
80	17	2	2
102	46	50	30
0	10	0	0
6	60	28	31
0	96	180	44
43	34	0	15
4	0	36	38
4	0	20	7
44	5	9	2
46	0	4	14
0	16	1	3

Figure 3.12. Root distribution of P. penetrans in the section of the field covered with rye.

H_1 - PLOT 96 (ROOTS)

0	12	0	2
26	4	24	14
0	0	64	24
28	0	8	21

H_2 - PLOT 142 (ROOTS)

7	35	15	0
21	10	30	37
56	96	56	50
21	16	27	14

H_3 - PLOT 164 (ROOTS)

8	2	0	35
12	4	6	2
4	32	0	6
5	14	4	7

H_4 - PLOT 175 (ROOTS)

12	0	0	0
7	14	18	14
33	20	12	8
28	56	20	56

Figure 3.13. Root distribution of P. penetrans in subplots from the section of the field covered with rye.

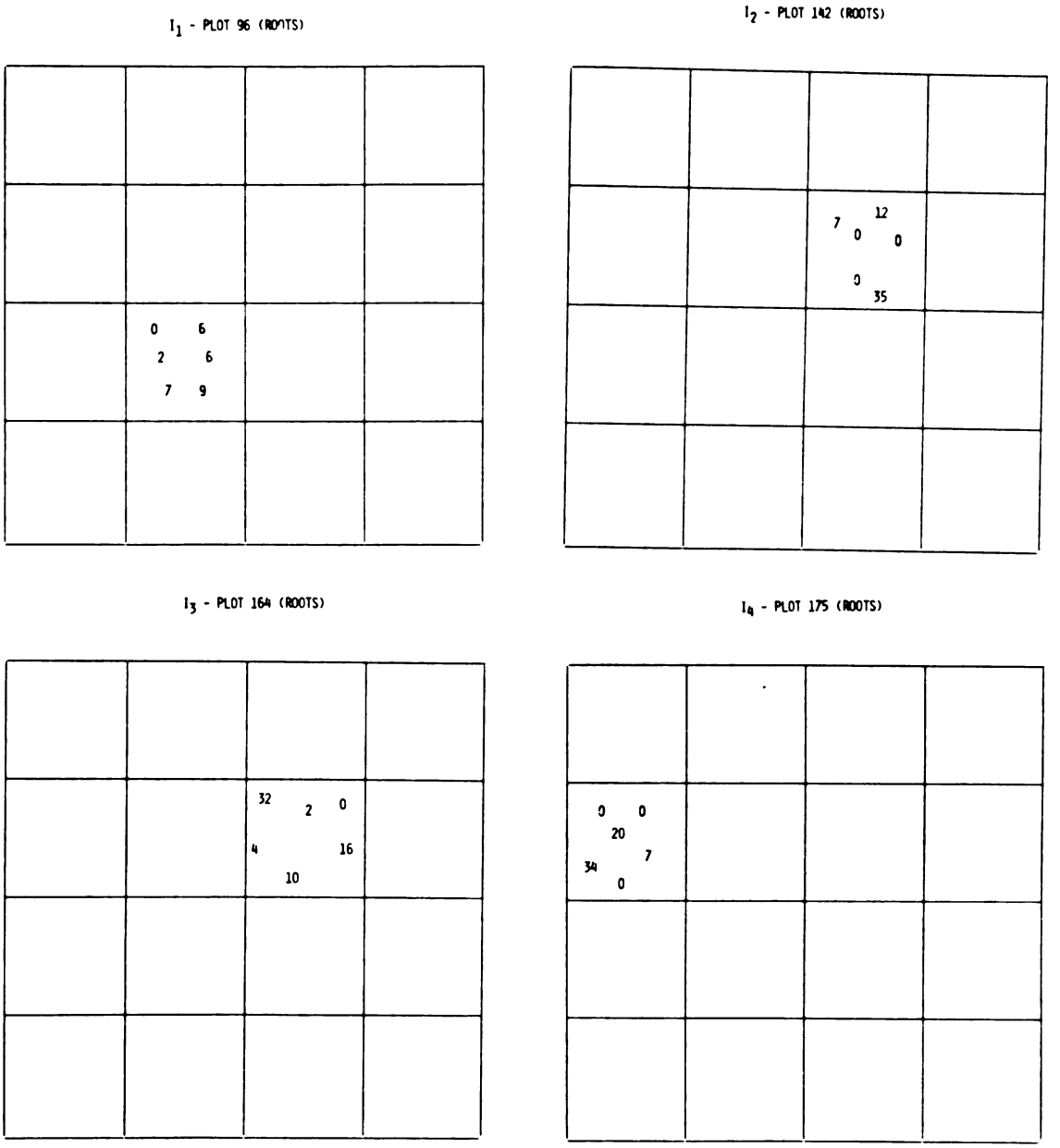


Figure 3. 14. Root distribution of P. penetrans from samples consisting of one core from the section of the field covered with rye.

31	12	34	16
18	70	243	35
47	27	70	75
2	40	21	68
32	10	43	0
37	4	175	96
8	25	6	108
36	104	19	20
59	2	77	24
16	102	14	25
16	47	31	13
30	30	10	208
146	29	43	17
109	67	164	34
8	10	4	5
6	82	38	70
39	98	181	51
59	34	8	19
69	74	48	132
122	28	72	9
63	39	29	6
131	84	104	21
0	68	31	15

Figure 3.15. Distribution of P. penetrans (soil + root) in the section of the field covered with rye.

K_1 - PLOT 96 (SOIL + ROOTS)

17	42	4	4
28	25	30	16
0	6	64	38
91	56	38	21

K_2 - PLOT 142 (SOIL + ROOTS)

39	35	47	35
45	38	93	43
68	112	84	70
22	23	43	14

K_3 - PLOT 164 (SOIL + ROOTS)

31	11	20	56
26	7	6	12
4	94	0	8
5	14	4	7

K_4 - PLOT 175 (SOIL + ROOTS)

12	0	20	13
14	20	25	14
37	20	44	40
52	76	50	70

Figure 3.16. Distribution of P. penetrans (root + soil) in subplots from the section of the field covered with rye.

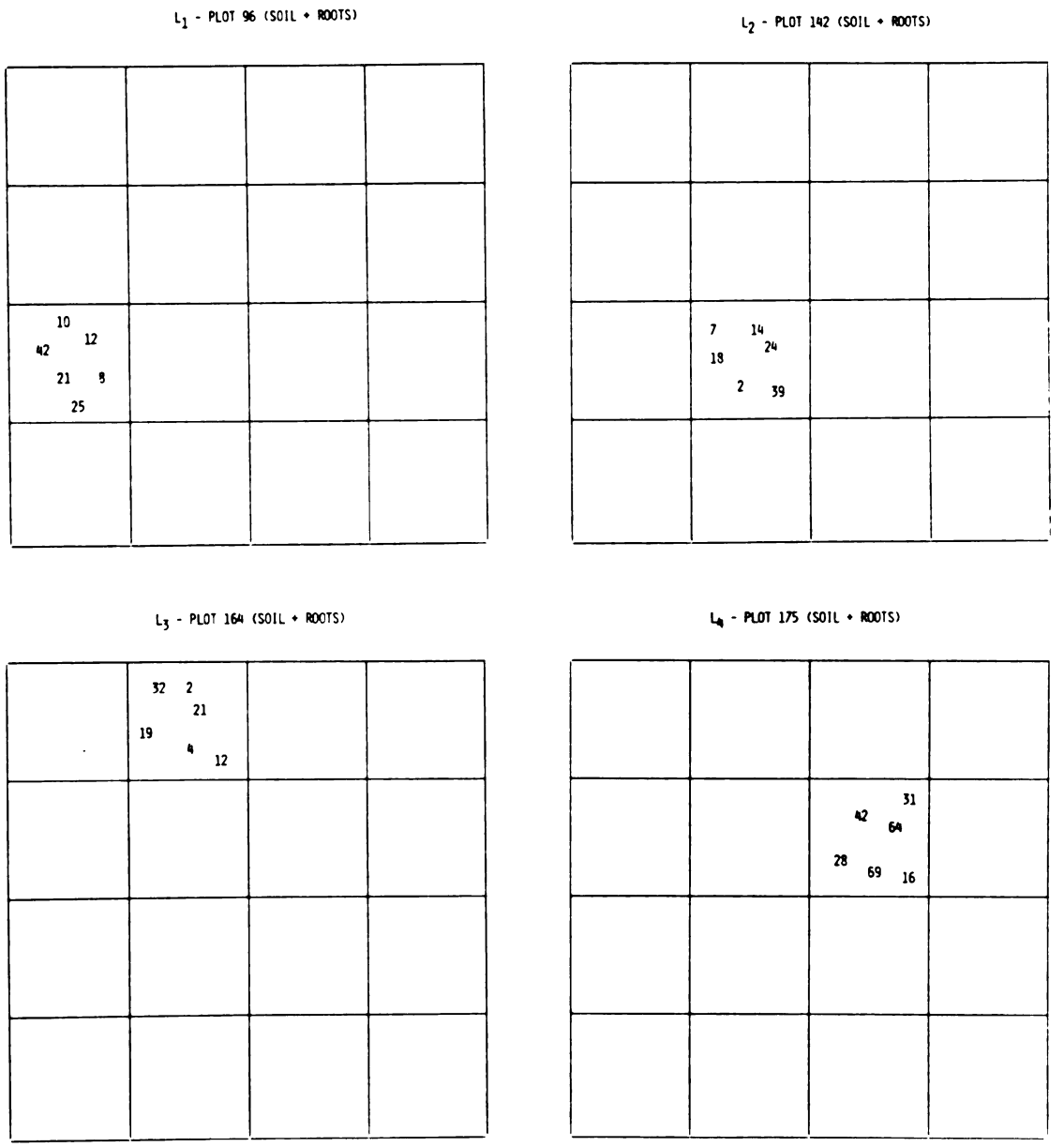


Figure 3.17. Distribution of P. penetrans (root + soil) from samples consisting of one core from the section of the field covered with rye.

nature (Table 3.1J_L).

The mean numbers of P. penetrans in the ploughed section of the field (Figures 3.18-3.20; Table 3.1M, N, O) were higher for the large sample set of 92 plots (Table 3.1M) compared to the mean numbers of P. penetrans from the smaller subplots from which 16 and 6 samples were collected (Table 3.1N, O). The variance/ mean ratios were greater than one indicating an aggregate distribuiton. The distribution in the randomized block design plots was also aggregate (Figure 3.21; Table 3.1P, Q).

3.2.5.2 Incidence of P. penetrans in dry bean fields in Michigan

The survey of 80 dry bean fields in Michigan indicated that plant-parasitic nematodes inhabit dry bean fields. The two most commonly recovered genera were root-lesion nematodes (Pratylenchus spp.) and stunt nematodes (Tylenchorhynchus spp.) (Table 3.2). Pratylenchus spp. were found in 68% of the 80 fields and Tylenchorhynchus spp. were present in 45% of the 80 fields. Pratylenchus penetrans was the most predominant Pratylenchus spp. observed in dry bean fields.

The percent occurrence of Pratylenchus spp. increased by county in the following order: Saginaw > Huron > Sanilac > Gratiot Bay > Tuscola > Montcalm (Table 3.2). This is as expected in the sandy clay loam soil characteristic of Montcalm county.

35	0	3	26
4	0	0	28
0	16	0	23
24	3	7	13
0	70	75	17
0	4	5	12
7	13	0	0
0	75	19	0
17	40	49	22
0	50	2	6
11	28	20	18
10	8	49	7
0	9	13	3
2	2	0	6
8	10	20	15
10	20	0	16
20	10	15	25
2	5	0	40
10	5	6	24
10	5	14	3
5	10	25	5
10	5	5	20
25	15	20	10

Figure 3.18. Distribution of P. penetrans in the ploughed section of the field.

N_1 - PLOT 15 (PLOUGHED)

25	15	0	5
28	19	18	16
5	16	5	28
0	25	15	60

N_2 - PLOT 24 (PLOUGHED)

5	15	0	16
2	17	0	5
18	16	0	25
15	13	10	5

N_3 - PLOT 52 (PLOUGHED)

16	20	0	25
12	5	10	40
20	40	10	5
0	5	25	10

N_4 - PLOT 78 (PLOUGHED)

17	10	5	12
20	5	25	18
0	5	0	16
12	10	5	0

Figure 3.19. Distribution of P. penetrans in subplots in the ploughed section of the field.

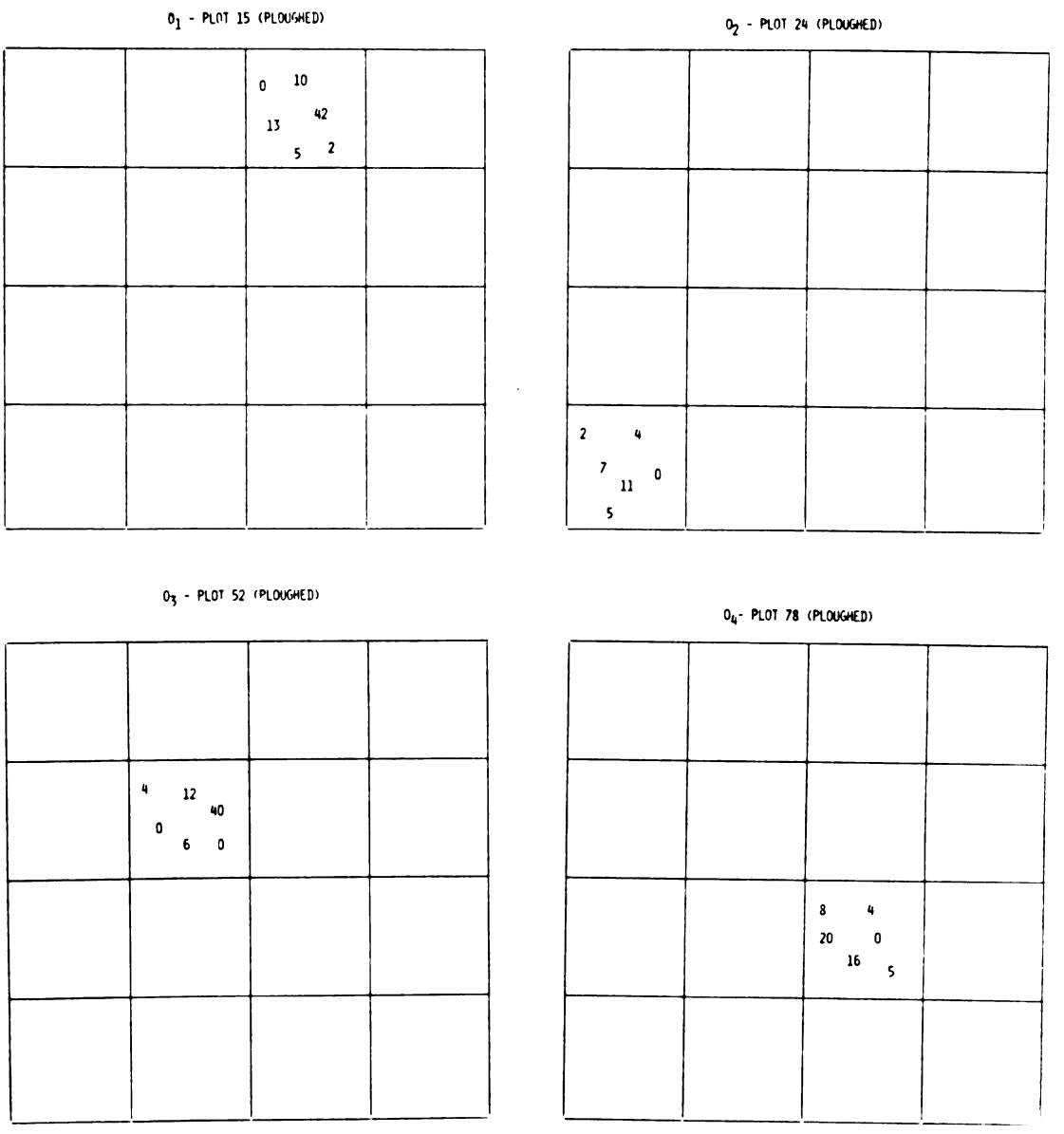


Figure 3.20. Distribution of P. penetrans from samples consisting of one soil core in the ploughed section of the field.

P- (48 PLOTS)

79	82
48	34
68	59
80	81
35	74
57	60
44	50
92	75
22	26
76	56
60	54
65	96
56	52
66	20
57	40
37	6
44	46
35	52
40	55
55	29
8	64
60	70
70	60
40	48

Q- (24 PLOTS)

70
91
84
94
102
61
65
35
31
20
18
38
54
99
133
24
21
66
105
134
68
42
22
46

Figure 3.21. Distribution of P. penetrans in randomized block design plots.

Table 3.2. Occurrence and densities of *Pratylenchus* spp. (root-lesion nematodes) recovered from 80 dry bean fields in Michigan.

County	Fields Sampled	Percent Occurrence	Nematodes per $100cm^3$ soil & g root	Percent Occurence				
				0	0-10	11-50	51-100	100
Montcalm	15	100	150b	0	0	13	40	47
Bay	15	80	72ab	20	20	13	13	33
Sanilac	10	60	19a	40	10	30	20	0
Saginaw	10	10	34a	90	0	0	0	10
Huron	10	50	10a	50	10	40	0	0
Tuscola	10	90	32a	10	20	60	0	10
Gratiot	10	70	18a	30	30	30	10	0

Column means followed by the same letters are not significantly different (P=0.05) according to the Student Newmans Keuls Test.

Higher population densities were generally associated with sandy soils (Table 3.2). Population densities were also higher on kidney beans, and this is related to the soil type as this variety is produced mainly on sandy soils in Bay and Montcalm counties. In Saginaw county a high population density of Pratylenchus spp. was found in one bean field where the soil was characterized as a Granby loamy sand (Table 3.3). In Bay and Montcalm counties Pratylenchus spp. were associated with both colored and navy beans, but the population densities were lower on navy beans in Bay county (Table 3.4). On a state-wide basis 13% of the 80 fields surveyed were infested with population densities > 50 Pratylenchus spp. per 100 cm^3 soil plus 1.0 g root tissue (Table 3.5).

Tylenchorhynchus spp. were found in all seven counties. The frequency of occurrence was lower than for Pratylenchus spp. and population densities were relatively low .(Tables 3.3-3.6).

3.2.5.3 Development of an experimental population of P. penetrans

Thirty-six percent of the 100 Sanilac navy bean plants inoculated with one male and one female Pratylenchus penetrans were infected with this nematode species and produced recoverable nematode populations.

Table 3.3 Occurrence of Plant-parasitic nematodes in relation to soil type and bean variety.

County	Bean variety	Soil type	*Pratylenchus* spp. $100cm^3$ soil + g root tissue	*Tylenchorhynchus* spp. $100cm^3$ soil
Montcalm	Seafarer	Nester Loam	230ab	0
	Seafarer	Nester Loam	146a	0
	Seafarer	Nester Loam	25a	0
	Seafarer	Nester Loam	11a	0
	Seafarer	Nester Loam	105a	20
	Kidney	Nester Loam	56a	0
	Kidney	Isabella Sandy Loam	75a	0
	Kidney	Isabella Sandy Loam	290ab	33
	Kidney	Isabella Sandy Loam	85a	0
	Kidney	Isabella Sandy Loam	60a	0
	Cranberry	Isabella Sandy Loam	45a	0
	Cranberry	Isabella Sandy Loam	450b	40
	Cranberry	Isabella Sandy Loam	290ab	10
	Cranberry	Isabella Sandy Loam	100a	8
	Yellow Eye	Isabella Sandy Loam	275a	
Bay	Sanilac	Kawkawlin Sandy Loam	10a	0
	Sanilac	Kawkawlin Loam	10a	0
	Sanilac	Brookston Loam	0a	0
	Sanilac	Kawkawlin Loam	15a	17

Column means followed by the same letter are not significantly different (P = 0.05) according to Student-Newmans Keuls Test.

Table 3.3 Cont'd.

County	Bean variety	Soil type	*Pratylenchus* spp. $100cm^3$ soil + g root tissue	*Tylenchorhynchus* spp. $100cm^3$ soil
Bay Cont'd.	Seafarer	Kawkawlin Loam	5a	0
	Kidney	Wisner Clay Loam	13a	0
	Kidney	Kawkawlin Sandy Loam	102b	10
	Kidney	Kawkawlin Sandy Loam	216c	0
	Kidney	Iosco Sandy Loam	170c	8
	Kidney	Ogemaw Sandy Loam	0a	20
	Cranberry	Wisner Clay Loam	270d	8
	Cranberry	Iosco Sandy Loam	52ab	0
	Cranberry	Iosco Sandy Loam	0a	0
	Cranberry	Kawkawlin Loam	55ab	6
	Pinto	Wisner Loam	160c	0
Huron	Seafarer	Klimanagh Loam	0a	0a
	Seafarer	Guelph Loam	0a	0a
	Seafarer	Klimanagh Loam	25a	0a
	Seafarer	Shebeon Loam	25a	10ab
	Seafarer	Klimanagh Loam	0a	5a
	Seafarer	Avoca Loam	14a	5a
	Seafarer	Shebeon Loam	20a	10ab
	Seafarer	Klimanagh Loam	0a	10ab
	Seafarer	Shebeon Loam	10a	20b
	Sanilac	Klimanagh Loam	0a	0a

Column means followed by the same letter are not significantly different (P = 0.05) according to Student-Newmans Keuls Test.

Table 3.3 Cont'd.

County	Bean variety	Soil type	*Pratylenchus* spp. $100cm^3$ soil + g root tissue	*Tylenchorhynchus* spp. $100cm^3$ soil
Saginaw	Seafarer	Wisner Clay Loam	0a	0a
	Seafarer	Kibbie Very Fine Sandy Loam	0a	10a
	Seafarer	Granby Loamy Sand	355b	0a
	Seafarer	Sims Clay Loam & Parkhill Loam	0a	10a
	Sanilac	Capac-Parkhill Loam	0a	10a
	Sanilac	Parkhill-Klimanagh Loam	0a	0a
	Sanilac	Sloan Loam	0a	0a
	Sanilac	Saranac Silty Clay Loam	0a	0a
	Sanilac	Charity Silty Clay Loam	0a	0a
	Sanilac	Sloan-Shoals Loam	0a	0a
Tuscola	Seafarer	ND	132b	0a
	Seafarer	"	35a	15a
	Seafarer	"	0a	10a
	Seafarer	"	10a	5a
	Seafarer	"	25a	10a
	Seafarer	"	10a	0a
	Seafarer	"	27a	0a
	Sanilac	"	15a	0a
	Sanilac	"	30a	5a
	Sanilac	"	30a	0a

Column means followed by the same letter are not significantly different (P = 0.05) according to Student-Newmans Keuls Test.

Table 3.3 Cont'd.

County	Bean variety	Soil type	*Pratylenchus* spp. / $100cm^3$ soil + g root tissue	*Tylenchorhynchus* spp. / $100cm^3$ soil
Sanilac	Seafarer	ND	0a	0a
	Seafarer	"	35a	15a
	Seafarer	"	0a	0a
	Seafarer	"	0a	0a
	Seafarer	"	15a	0a
	Seafarer	"	12a	11a
	Sanilac	"	60a	0a
	Sanilac	"	0a	10a
	Sanilac	"	6a	0a
	Sanilac	"	60a	2a
Gratiot	Sanilac	Parkhill Loam	0a	10a
	Sanilac	Parkhill Loam	10a	5a
	Sanilac	Parkhill Loam	63b	5a
	Sanilac	Selridge Loamy Sand	12a	0a
	Sanilac	Senawee Clay Loam	0a	10a
	Sanilac	Parkhill Loam	40ab	10a
	Sanilac & Seafarer	Parkhill Loam	30ab	5a
	Kidney	Capac Loam	0a	0a
	Kidney	Breckenridge Sand Loam	10a	10a
	Gratiot	Metmora Sandy Laom	20a	0a

Column means followed by the same letter are not significantly different (P = 0.05) according to Student-Newmans Keuls Test.
ND = not determined

Table 3.4. *Pratylenchus* spp. (root-lesion nematodes) associated with navy and colored beans in Bay and Montcalm counties.

Bean type	County	Fields sampled	Percent occurrence	*P. Penetrans*/ $100cm^3$ soil + g root	Percent Occurrence				
					0	0-10	11-50	51-100	100
Navy beans	Montcalm	5	100	103	0	0	40	20	60
Navy beans	Bay	5	90	8	20	60	20	0	0
Colored beans	Montcalm	10	100	145	0	10	10	50	30
Colored beans	Bay	10	80	104	20	0	10	20	50

Table 3.5. Occurrence of plant-parasitic nematodes recovered from 80 dry bean fields in Michigan in 1978.

Nematode	Nematodes per $100cm^3$ soil + g root	Percent Occurrence	Percent Occurrence				
			0	1-10	11-50	51-100	100
Root-lesion nematode (*Pratylenchus* spp.)	56	68	31.3	11.2	27.5	12.5	17.5
Stunt nematode (*Tylenchorynchus* spp.)	5	45	55.0	33.8	11.2	0	0

Table 3.6 Occurrence and population density of Tylenchorhynchus spp. (stunt nematode) recovered from 80 Michigan dry bean fields in 1978.

County	Fields Sampled	Percent Occurrence	Nematodes per $100cm^3$ soil + g root	Percent Occurrence				
				0	11-10	11-50	51-100	100
Montcalm	15	33	8a	66	13	20	0	0
Bay	15	40	5a	60	26	13	0	0
Sanilac	10	40	3a	60	20	20	0	0
Saginaw	10	20	2a	80	20	0	0	0
Huron	10	40	4a	40	5	10	0	0
Tuscola	10	50	5a	50	40	10	0	0
Gratiot	10	70	6a	30	60	10	0	0

Column means followed by the same letters are not significantly different (P = 0.05) according to the Student-Newmans Keuls Test.

The total population densities in soil and roots associated with navy bean plants varied considerably (Figure 3.22). The symbols above the X axis represent plants infected with P. penetrans, while the large proportion of symbols on the X axis represents non-infected plants. The highest population density was 250 P. penetrans per 100 cm^3 soil plus 1.0 g root tissue (Figure 3.22).

3.2.5.4 Identification of the life cycle stages of P. penetrans

Four morphometric characters were significantly different (P = 0.05) among the five stages of P. penetrans which were studied (Figure 3.23). Considerable variation in body length of females from the experimental population was recorded. The mean length of a female was 566.3 µm with a standard deviation of 55.8 µm (Table 3.7). Differences in body width were significant (P = 0.05), (Table 3.8).

Oesophagus length and stylet length were also significantly different (P = 0.05) among stages, but the range in values for all stages was relatively narrow (84.8-137.0 µm) for oesophagus length and (10.2-17.3 µm) for stylet length (Table 3.7). Significant differences in allometric characters were observed among stages

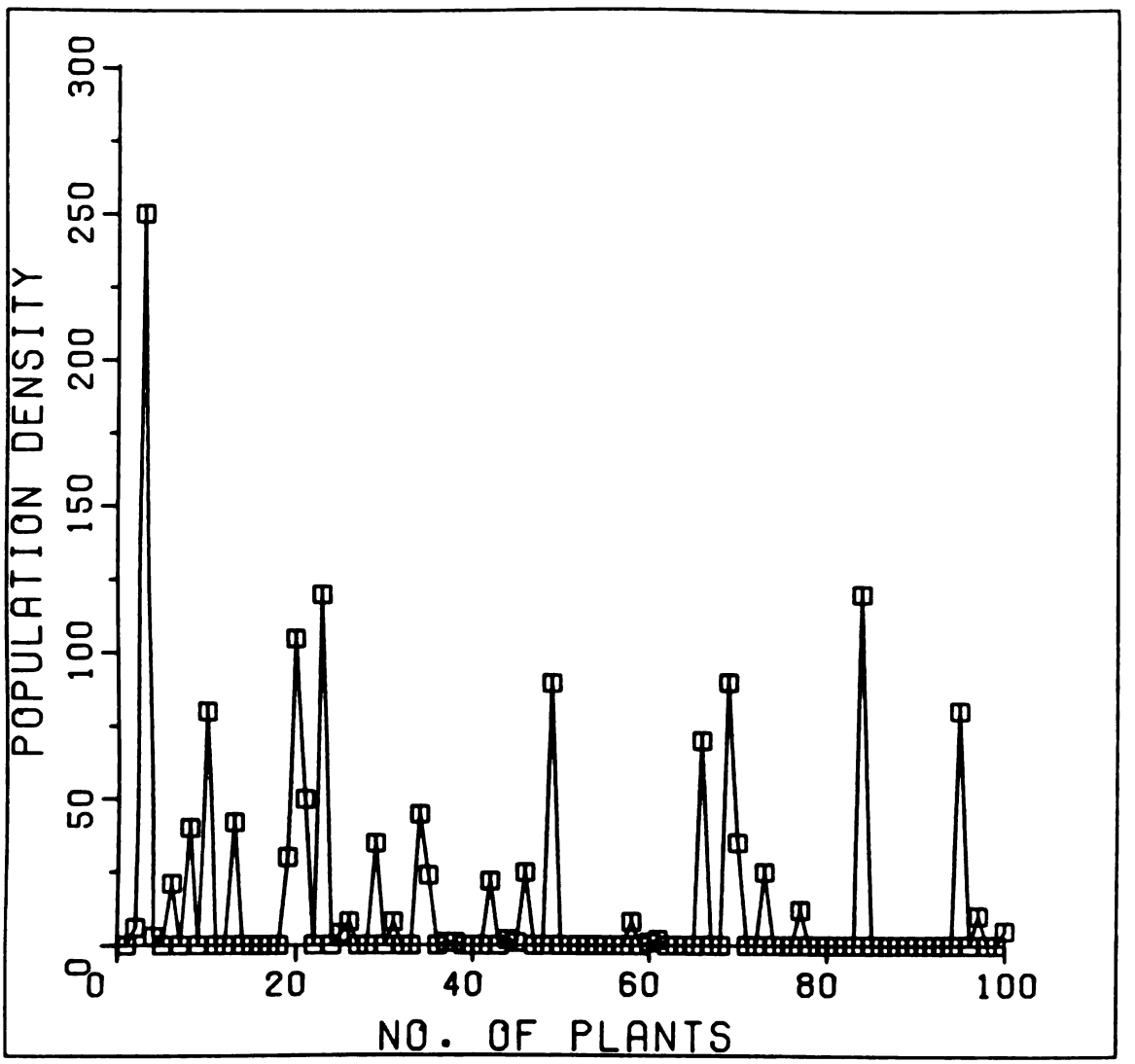


Figure 3.22. Total soil and root population densities of Pratylenchus penetrans associated with navy beans exposed to an initial density of one female and one male P. penetrans.

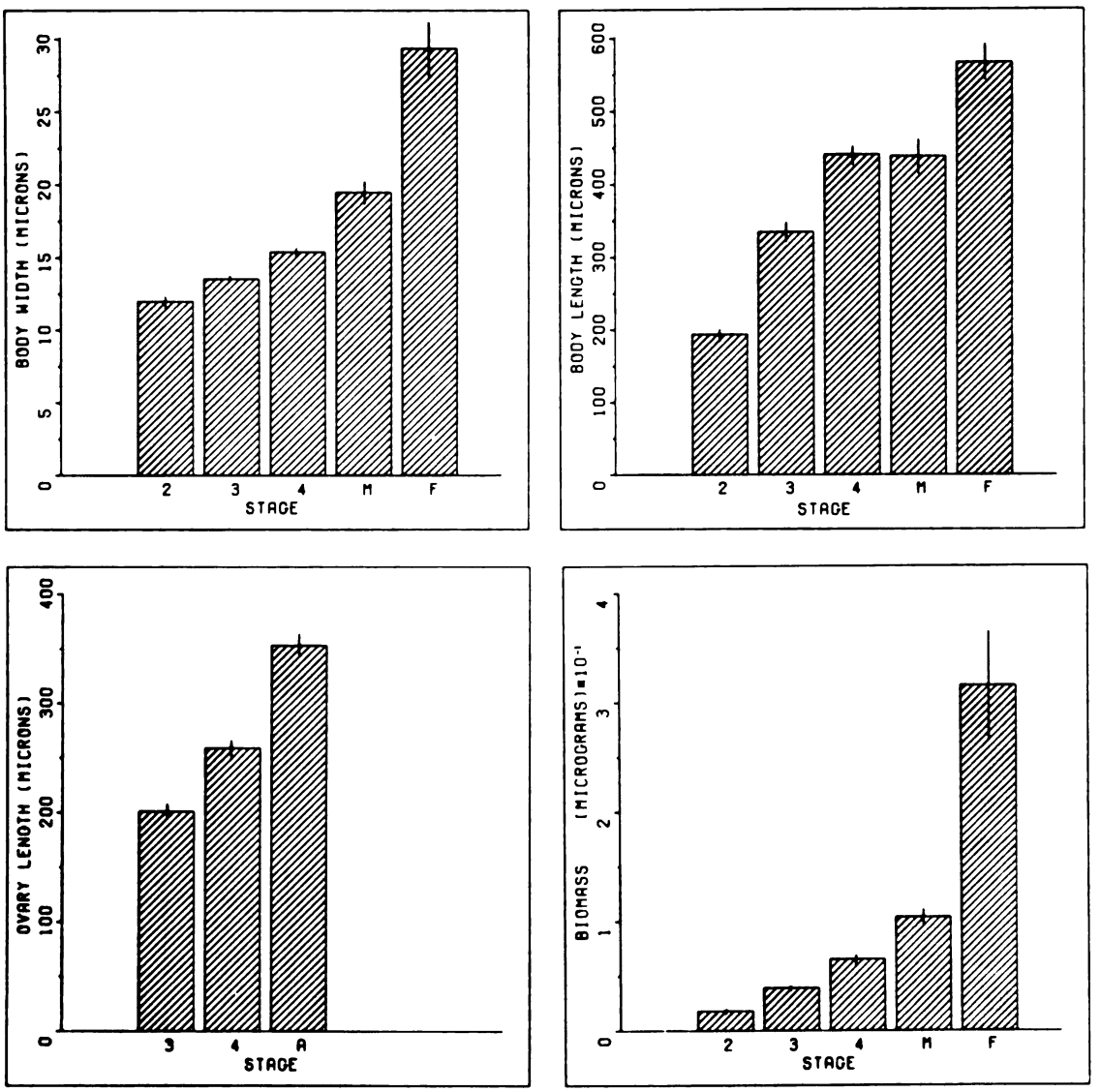


Figure 3.23. Morphometric characters and biomass of life cycle stages of Pratylenchus penetrans. Vertical bars represent 95 % confidence intervals.

Table 3.7 Morphometric characters of the life cycle stages of *Pratylenchus penetrans* associated with navy beans.

Character	Life cycle stage				
	2nd	3rd	4th	Male	Female
Morphometric					
Body length	193.3	334.4	440.2	437.8	566.3
(SD)	18.4	30.6	28.9	52.7	55.8
(CV) (%)	9.5	9.2	6.6	12.0	9.9
Body width	12.0	13.6	15.4	19.5	29.4
(SD)	0.9	0.6	0.7	1.9	4.2
(CV) (%)	7.8	4.1	4.4	9.5	14.4
Oesophagus length	84.8	113.6	123.1	127.9	137.0
(SD)	7.1	6.0	4.2	5.9	8.9
(CV((%)	8.4	5.2	3.4	4.6	6.5
Stlyet length	10.2	13.7	15.4	15.0	17.3
(SD)	1.4	0.7	0.5	0.8	1.4
(CV) (%)	13.5	5.4	3.1	5.1	8.2
Tail length	10.8	15.6	23.6	24.8	30.1
(SD)	0.8	0.7	2.9	1.0	5.7
(CV) (%)	7.8	4.4	12.1	4.1	18.8
Ovary length		201.8	258.5		352.5
(SD)		14.6	18.0		21.6
(CV) (%)		7.3	6.9		6.1

Table 3.8 Morphometric characters of Pratylenchus penetrans life cycle stages.

Life cycle stage	Body Length	Body Width	Oeaophagus Length	Stylet Length	Tail Length	Ovary Length
2nd	193.3a	12.0 a	84.8	10.2a	10.8a	___
3rd	334.4b	13.6b	113.6b	13.7b	15.6b	201.8a
4th	440.2c	15.4c	123.Ic	15.4c	23.6c	258.5b
Adult Males	437.8c	19.5d	127.9d	15.0c	24.8c	____
Adult Females	566.3d	29.4e	137.0e	17.3d	30.1d	352.5c

Column means followed by the same letter are not significantly different (P = 0.05) according to the Student Newman Keuls test.

(Table 3.9-3.10).

3.2.6 Discussion

The study of the field distribution of Pratylenchus penetrans indicated that an aggregate-type distribution approximating a negative binomial type distribution was characteristic for the distribution of P. penetrans in the field. The nature and distribution of nematodes in the field is of great importance in determining sampling pattern, and number of replicates to use in experimental procedures. The nature of statistical analysis and transformations which should be applied to data are also to some extent dependent on the nature of the distribution of the pest (Beall, 1941; Kleczkowski, 1955; Wayman, 1959; Hayman and Lowe, 1961; Taylor, 1961; Kendall, 1948; Elliott, 1973). Logarithmic transformations involving coding of data containing zero values are useful in analysing nematode data (Wallace, 1973; Barker and Nusbaum, 1971).

The number of samples which should be taken is dependent on the degree of precision desired and this in turn is limited by the relative economics involved. The results from the nematode distribution study indicated that large variations are encountered in sampling nematode populations in the field. Use of small numbers of samples

Table 3.9 Allometric characters of the life cycle stages of *Pratylenchus penetrans* associated with navy beans.

	life cycle stage				
Character	2nd	3rd	4th	Males	Females
Allometric					
1					
a value	16.2	24.7	28.6	22.7	19.5
(SD)	1.7	2.2	2.1	4.2	2.4
(CV) (%)	10.3	8.8	7.4	18.5	12.3
2					
b values	2.3	2.9	3.6	3.1	4.1
(SD)	0.2	0.4	0.2	0.3	0.4
(CV) (%)	8.5	11.9	5.4	10.1	9.6
3					
c value	17.8	21.4	18.6	17.6	19.2
(SD)	1.0	1.6	2.2	1.6	2.6
(CV) (%)	5.8	7.7	11.8	9.1	13.8
4					
Biomass (G)	0.018	0.038	0.065	0.104	0.316
(SD)	0.004	0.005	0.008	0.017	0.108
(CV) (%)	22.43	14.01	12.39	16.83	34.6

1 = Body length/Body width
2 = Body length/ Oesophagus length
3 = Body length/ tail length

$$4 = \frac{\text{Body width} \times \text{Body length}}{16 \times 100{,}000}$$

Table 3.10. Differences in allometric characters of *Pratylenchus penetrens* life cycle stages.

Stage	Allometric character			
	"a" value[2]	"B" value[3]	"c" value[4]	Biomass (ug)[5]
2nd	16.2a	2.3a	17.8ab	0.018a
3rd	24.7d	2.9b	21.40c	0.038a
4th	28.56e	3.6c	18.6ab	0.065b
Adult Males	22.7c	3.4c	17.6a	0.104c
Adult Females	19.5b	4.1d	19.2b	0.326d

[1]Column means followed by the same letter are not significantly different (P = 0.05) according to the Student Newman Keuls test.

[2]Body length/body wieght

[3]Body length/oesophagus length

[4]Body length/tail length

[5]$\frac{\text{Body width x body length}}{16 \times 100.000}$

in experimental procedures could therefore lead to inaccuracies. The most desirable procedure is to take large numbers of samples usually greater than 50 (Langdon, 1963; Elliott, 1973; Goodell, 1978). Unfortunately while large sample numbers ensure relatively accurate biological information, there are disadvantages associated with time and cost involved in taking and processing large numbers of samples.

Therefore a compromise must be made between statistical accuracy, labor and cost to determine the optimum sample size. First it is necessary to determine the degree of experimental error which can be tolerated and still retain a substantial amount of accuracy. The percent error can be expressed as the standard error of the mean (S.E.). The ratio of the standard error to the mean (S.E./ $\bar{x}$) represents an index of precision (D) (Elliott, 1973). The calculation of the index varies depending on the nature of the distribution, i.e. whether normal, poisson or aggregated (negative binomial). For the normal or random distribution the index of precision is calculated as:

$$D = S.E_{\bar{x}} / \bar{x}$$

$$D = \frac{1}{\bar{x}}\sqrt{\frac{S^2}{n}}$$

and the number of samples which should be taken is calculated from this equation as:

$$n = \frac{S^2}{D^2\bar{x}^2}$$

For a poisson type distribution the index of precision is calculated as:

$$D = \frac{1}{\bar{x}}\sqrt{\frac{\bar{x}}{n}}$$

and the number of samples which should be taken is calculated as:

$$n = \frac{\bar{x}}{D^2\bar{x}^2}$$

The calculation of the index of precision for an aggregate type distribution approximating a negative binomial distribution involves calculation of the parameter K which is an index of dispersion (Elliott, 1973). Various methods for calculation of K can be employed (Elliott, 1973). The choice of method is to some extent dependent on the mean values, number of samples and degree of aggregation. With a calculated K value the index of

precision for a negative binomial distribution can be calculated as:

$$D = \frac{1}{\bar{x}} \sqrt{\frac{\bar{x}}{n} + \frac{\bar{x}^2}{n\,K}}$$

$$D = \sqrt{\frac{1}{n\,\bar{x}} + \frac{1}{n\,K}}$$

and the number of samples which should be taken is calculated as:

$$n = \frac{1}{D^2} \left(\frac{1}{\bar{x}} + \frac{1}{K} \right)$$

For example if a standard error of the mean equal to 20% can be tolerated then

$$D = 0.2$$

and

$$n = \frac{1}{0.2^2} \left(\frac{1}{13.98} + \frac{1}{1.63} \right)$$

$$n = 17$$

for the sample size which should be taken for sample level A of Table 3.1 where the mean value was 13.98 and K was 1.63. In this analysis K was calculated according to the moment method (Elliott, 1973) from the equation:

$$K = \frac{\bar{x}^2}{S^2 - \bar{x}}$$

where $\bar{x}$ is the arithmetic mean and S^2 is the variance of the sample. In this study a sample size of 184 was employed for estimating the mean value of the population of P. penetrans in the field for this sample level. Calculations indicate that allowing for a standard error of 20% of the mean, a sample size of 17 could be employed. The sample size would however increase as the degree of precision is increased. For example if a standard error of only 5% of the mean could be tolerated then

$$D = 0.05$$

and

$$n = \frac{1}{0.05^2} \left(\frac{1}{13.98} + \frac{1}{1.63} \right)$$

$$n = 308$$

Therefore to obtain a precision of a 5% error the optimum sample size is 308. This is larger than the sample size employed. The relative cost of taking and processing these samples however limited the sample size to 184.

Calculation of a desirable sample size based on the degree of error which can be tolerated is valuable however for initial decisions on choice of sample size.

Experimental procedures for the survey of 80 bean fields in Michigan involved collecting two samples of six soil cores from one hectare size areas within bean fields. With this sampling procedure Pratylenchus spp. were found in 68% of the fields and Tylenchorhynchus spp. were present in 45 % of the 80 fields. The results of the study on field distribution of Pratylenchus penetrans indicated that nematodes are generally found in an aggregated-type distribution in the field, and therefore detection of nematodes through use of random sampling procedures should involve use of large sample sizes. However the economic and time factors involved in conducting this survey limited the sample size to two replicates. This allowed for only one degree of freedom in analysis of variance, and large within field variances were obtained resulting in a few significant differences ($P = 0.05$) among population densities within a field (Table 3.3). The absence of plant parasitic nematodes in some fields could be related to the inability to detect populations from an aggregate-type distribution with the use of random sampling procedures.

The results, however, indicated the presence of plant parasitic nematodes in bean fields and can be viewed as an "alert", which should not be neglected. The highest population densities were generally associated with sandy soils. This is expected and in agreement with report findings on relationships between nematode population densities and soil types (Oostenbrink, 1966; Norton, 1978).

Information from this survey can be useful in conjunction with information on economic thresholds of P. penetrans. The population densities in fields in different counties together with an economic threshold density could be used to estimate economic losses due to this nematode species in dry bean production in the counties examined. The data though useful has its limitations in that the observed densities are related to a particular time of the season and may be higher or lower at other periods. The dynamic nature of the nematode species must also be considered in estimating losses. The data provides a basis for thought for research on interactions of Pratylenchus spp. and dry beans.

The development of an experimental population of P. penetrans was necessary to ensure that individuals

used in preparing inoculum densities for research experiments were obtained from similar genetic source and should be typical of one race of this species. The population densities obtained at the time of sampling is no indication of the maximum reproductive potential of this species on beans. The length of the life cycle varies depending on the temperature and the associated host crop. The absence of populations associated with 64% of the 100 bean plants could be due to the high mortality, detection procedure inefficiency (Kotcon, 1979), or to the life cycle stage at the time of sampling. Nematodes could have been present in the egg stage or first stage larvae within the eggs and samples were not processed for detection of these stages. The presence of P. penetrans on 36% of the bean plants indicated that these nematodes were able to survive, move towards susceptible roots, penetrate, feed and reproduce within these roots. While some of the females may have been fertilized before inoculation, males were added to increase the likelihood of fertilization.

Morphometric characters of nematodes are influenced to a large extent by the environmental conditions of moisture, temperature and also the host crop. Tarte

and Mai (1976) observed considerable variation in morphometric characters of P. penetrans developed on alfalfa callus tissue. Comparison of morphometric characters of the population of P. penetrans developed on Sanilac navy beans in culture boxes in the greenhouse at a temperature of 77 ± 10 C with the original population of P. penetrans described by Sher and Allen (1953) and Loof (1960) indicated some differences. The mean length, "a" value and "b" value for the female described by these taxonomists were 530 µm, 26 and 5.8 respectively, while values of 566 µm, 19.5 and 4.1 were obtained for similar morphometric and allometric characters of the female from the population developed for research experiments in the greenhouse.

Although differences in body width were statistically significant (P = 0.05), identification of life cycle stages through use of this morphometric character is not feasible because of the narrow range in values and small size involved. The narrow range in values obtained for oesophagus and stylet lengths respectively limit the usefulness of these characters for identification of stages. Because of the significant differences and wide ranges in values for body length, ovary length, biomass, "a" value, "b" value and "c" value these

morphometric and allometric characters were used to develop a key to the life cycle stages of Pratylenchus penetrans (Table 3.11). The egg and first stage larvae were not easily recovered and can be readily identified if found. These two stages were not included in the key because they were not extracted and enumerated in the sampling procedures.

Table 3.11 Key to the life cycle stages of *Pratylenchus penetrans*

1. Spicules absent, body length 193.3-566.3 µm . . . 2
   Spicules present, body length, 437.8 ± 52.7 µm biomass, 0.104 ± 0.017 µg, "a" value, 22.7 ± 4.2 . . . . . Adult males
2. Body length, 193.3 ± 9.5 µg, ovary not visible, biomass, 0.018 ± 0.001 µg, "a" value, 16.2 ± 1.7, "b" value 2.3 ± 0.2, vulva not conspicuous . . . . . Second-stage juveniles
   Ovary present, body length greater than 193.3 ± 9.5 µm 3
3. Ovary length, 201.8 ± 14.6 µm "a" value, 24.7 ± 2.2, "b" value, 2.9 ± 0.4, ovary slightly conspicuous . . . . . Third-stage juveniles
   Body length greater than 334.4 ± 30.6 µm, vulva highly conspicuous, ovary well-developed . . . 4
4. Body length, 440.2 ± 28.9 µm, ovary length, 258.5 ± 18 µm, biomass, 0.065 ± 0.008 µg, "a" value, 28.6 ± 2.1 . . . . . Fourth-stage juveniles
   Body length, 566.3 ± 55.8 µm, ovary length, 352.5 ± 21.6 µm, vulva highly conspicuous, ovary well-developed, spermatheca present, "a" value, 19.5 ± 2.4, "b" value, 4.1 ± 0.4, "c" value, 19.2 ± 2.6, biomass, 0.316 ± 0.108 µg . . . . . Adult female

3.3 Pest-crop Interactions

3.3.1 Pathogenicity

A survey on the incidence of nematodes in dry bean production in Michigan indicated that root-lesion nematodes (*Pratylenchus* spp.) were present in bean fields and *P. penetrans* was the most predominant plant parasitic nematode species encountered. The objective of this study was to evaluate the pathogenicity of *Pratylenchus penetrans* on dry beans.

3.3.1.1 Method

The experiment involved a completely randomized design of six replicates of six treatments including population densities of 0, 25, 50, 100, 150 and 300 *P. penetrans* per 100 cm^3 soil. Thirty-six 4.72 cm clay pots were filled with 3000 cm^3 sandy clay loam soil containing the desired densities which were obtained by mixing steam sterilized sandy clay loam soil with *P. penetrans* infested soil from culture boxes in the greenhouse. Three navy bean seeds cv Sanilac were planted in the soil in each pot. Plants were thinned out two days after germination leaving one seedling in each pot. The plants were watered daily and maintained at 80 ± 10 C in the greenhouse for a period of 95 days. Plant height, leaf area, shoot fresh weight, root weight, root length

and dry bean yield were recorded after this growth period. Shoot systems were oven dried at 30 ± 5 C and shoot dry weight was recorded. Soil and root samples were taken for nematode analyses (3.1.1.2 and 3.1.2.2). P. penetrans were extracted and enumerated (3.1.3-3.1.4).

3.3.2 Susceptibility of six navy bean varieties to Pratylenchus penetrans

Because of genetic variability the response to infection by plant parasitic nematodes may vary among cultivars of plant species. The discovery of nematode resistant or tolerant bean varieties is important for development of nematode control practices in dry bean production. This study was designed to determine the effect of P. penetrans on six navy bean cultivars.

3.3.2.1 Method

The experiment involved a completely randomized design of three replicates of six bean varieties. One hundred and twenty-six 2.36 cm clay pots were filled with 1000 cm^3 noninfested P. penetrans steam sterilized sandy clay loam soil, and 126 similar clay pots were filled with 1000 cm^3 sandy clay loam soil containing densities of 150 P. penetrans per 1000 cm^3 soil respectively. The desired densities were obtained by mixing steam sterilized

sandy clay loam soil with appropriate quantities of P. penetrans infested soil obtained from culture boxes. Three navy bean seeds of each variety - Sanilac, Seafarer, Gratiot, Saginaw, Kentwood and Tuscola respectively were planted in the soil in each pot. Plants were thinned out two days after germination leaving one seedling in the soil in each pot. Plants were watered daily and maintained at 75 ± 10 C in the greenhouse for a period of 108 days. Plant height, shoot dry weight, leaf area and yield were recorded at seven intervals during this growth period. Relative growth rates were calculated (3.1.8). Soil and root samples were taken for nematode analyses (3.1.1.2 and 3.1.2.2) and P. penetrans were extracted and enumerated (3.1.3-3.1.4).

3.3.3 Responses of Sanilac navy beans to infection with different initial population densities of Pratylenchus penetrans

Plants are subject to inherent ontogenic drifts, and responses to pests and diseases vary at different stages in the growth and development of plants. The objective of this study was to examine the responses of navy bean plants to infection with varying densities of P. penetrans at different periods during the growth and development of these plants, and to examine the population

dynamics of P. penetrans associated with navy beans.

3.3.3.1 Method

The experiment consisted of four replicates of eight treatments including population densities of 0, 5, 10, 20, 40, 80, 160 and 320 P. penetrans per 100 cm^3 soil. Three hundred and eight 2.36 cm clay pots were filled with 1000 cm^3 steam sterilized sandy clay loam soil. P. penetrans were extracted from roots of navy bean plants removed from culture boxes in the greenhouse and a suspension containing a calculated density of P. penetrans was prepared. The desired densities for this experiment were then added to the soil in respective pots. Forty-four 2.36 cm clay pots were filled with steam sterilized sandy clay loam soil to serve as controls. Three navy bean seeds cv Sanilac were planted in the soil in each pot. Plants were thinned out two days after germination leaving one seedling in the soil in each pot. Plants were watered daily and maintained at 80 ± 10 C in the greenhouse for a period of 95 days. Plant height, leaf area, shoot fresh weight and root weight of plants were recorded at 10 intervals during the growth period. Shoot systems were oven dried at 30 ± 5 C and shoot dry weight was recorded.

Dry bean yield was taken at the end of the 95 day

growth period. Soil and root samples were taken at 11 intervals (3.1.1.2 and 3.1.2.2) and P. penetrans were extracted and enumerated (3.1.3-3.1.4). Data on shoot dry weight were used to calculate the relative growth rates of plants (3.1.8). Initial nematode mortality was calculated for each initial density of P. penetrans. Sampling dates were converted to accumulated degree days (3.1.7).

3.3.4 Results

3.3.4.1 Pathogenicity

Final root and soil population densities of P. penetrans were significantly (P = 0.05) higher than initial population densities (Figure 3.24). Regression of the log of the final root population densities on log of the initial population densities of P. penetrans indicated a significant linear correlation and the equation for the relationship is:

$$\log Y = 0.10 + 0.99 (\log X)$$

$$R = 0.99$$

where Y = log of final densities of P. penetrans plus one and X = log of initial densities of P. penetrans plus one. The regression line for this relationship indicated that population densities in navy bean roots increased with increase in initial soil population densities of

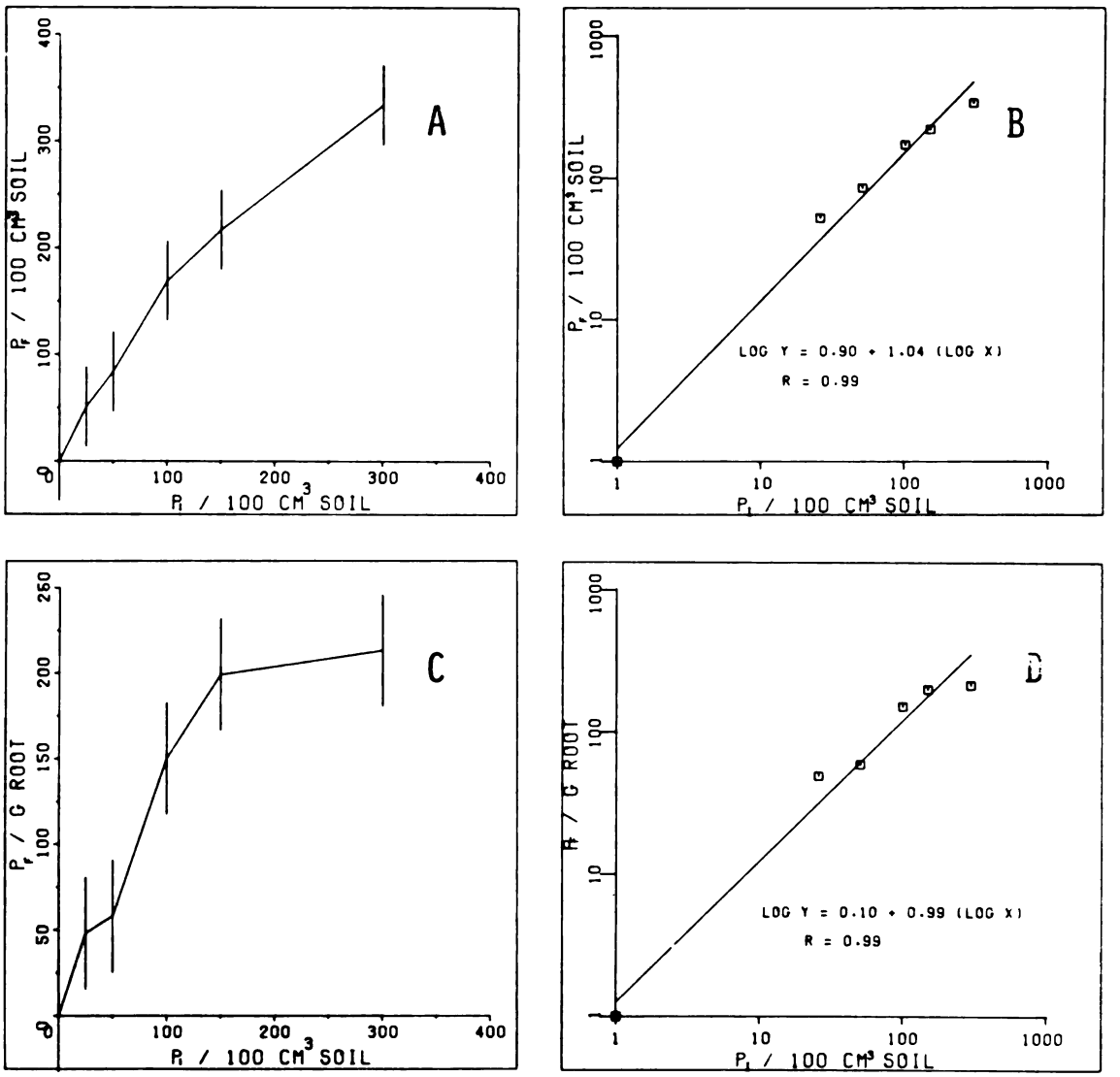


Figure 3.24. Influence of initial soil population densities of P. penetrans on final soil population densities (A & B), and final root population densities (C & D) of P. penetrans associated with navy beans.
Vertical bars represent 95 % confidence intervals.

P. penetrans (Figure 3.24D).

Final soil population densities increased with increase in initial soil population densities (Figure 3.24C). Regression of the log of initial soil densities on soil final densities of P. penetrans indicated a significant linear relationship with a high correlation coefficient value (R = 0.99) (Figure 3.24B). The equation for the relationship is:

$$\text{Log } Y = 0.90 + 1.04 \text{ (log } X)$$

$$R = 0.99$$

where Y = log of final densities of P. penetrans plus one and X = log of initial densities of P. penetrans plus one.

The growth and yield of plants exposed to initial soil densities of 50, 100, 150 and 300 P. penetrans per 100 cm^3 soil were significantly (P = 0.05) lower than that of noninfected plants exposed to an initial soil density of 0 P. penetrans (Figures 3.25-3.27). At the time of harvest the initial density of 25 P. penetrans per 100 cm^3 soil had no significant (P = 0.05) effect on plant height, shoot fresh weight, leaf area and root length. Shoot dry weight was significantly (P = 0.05) decreased by this density while root weight and root length were significantly (P = 0.05) increased by 25 P. penetrans per 100 cm^3 soil (Figure 3.26B,C & D).

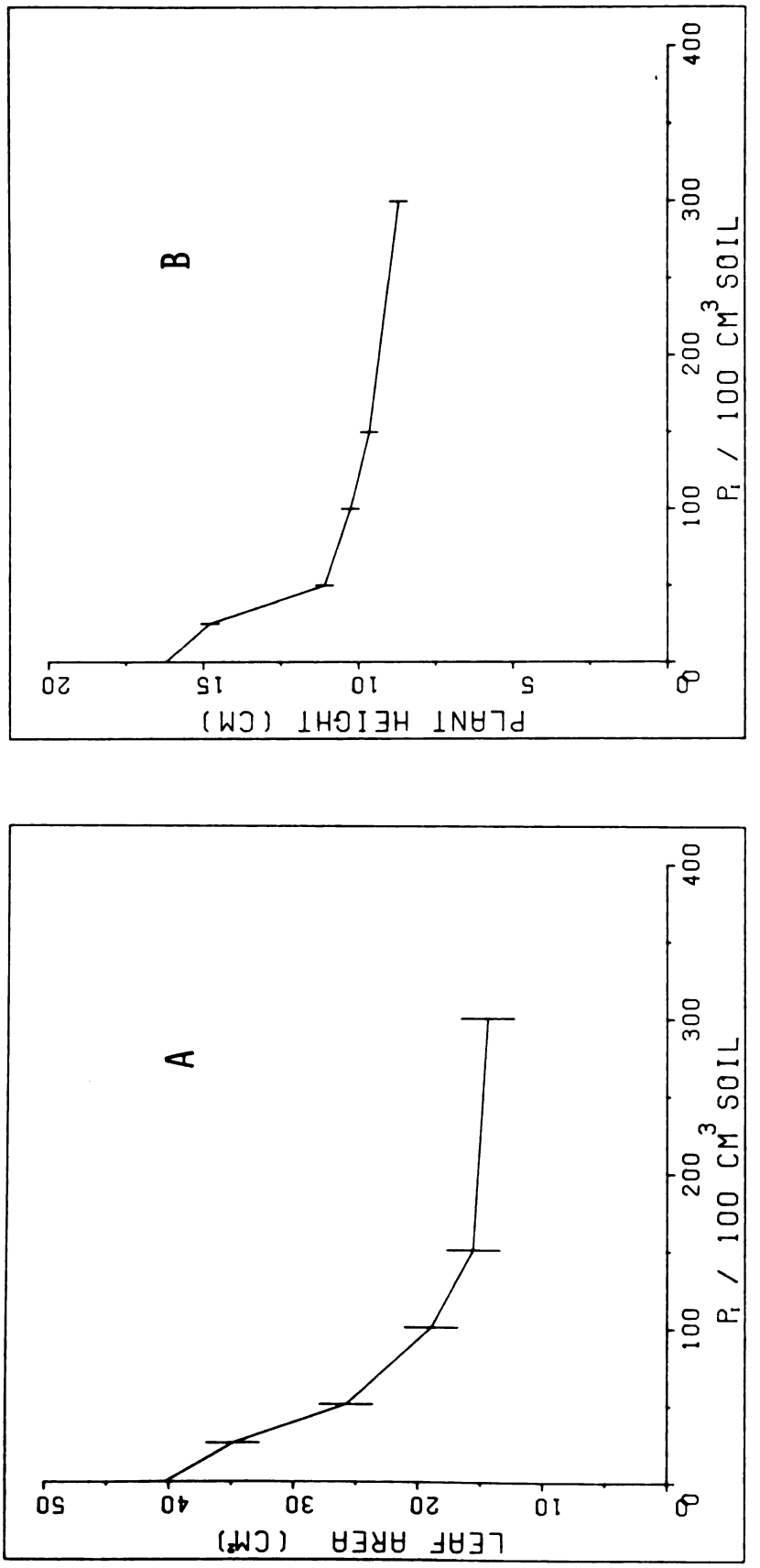


Figure 3.25. Influence of different initial population densities of P. penetrans on leaf area (A) and height (B) of navy bean plants.

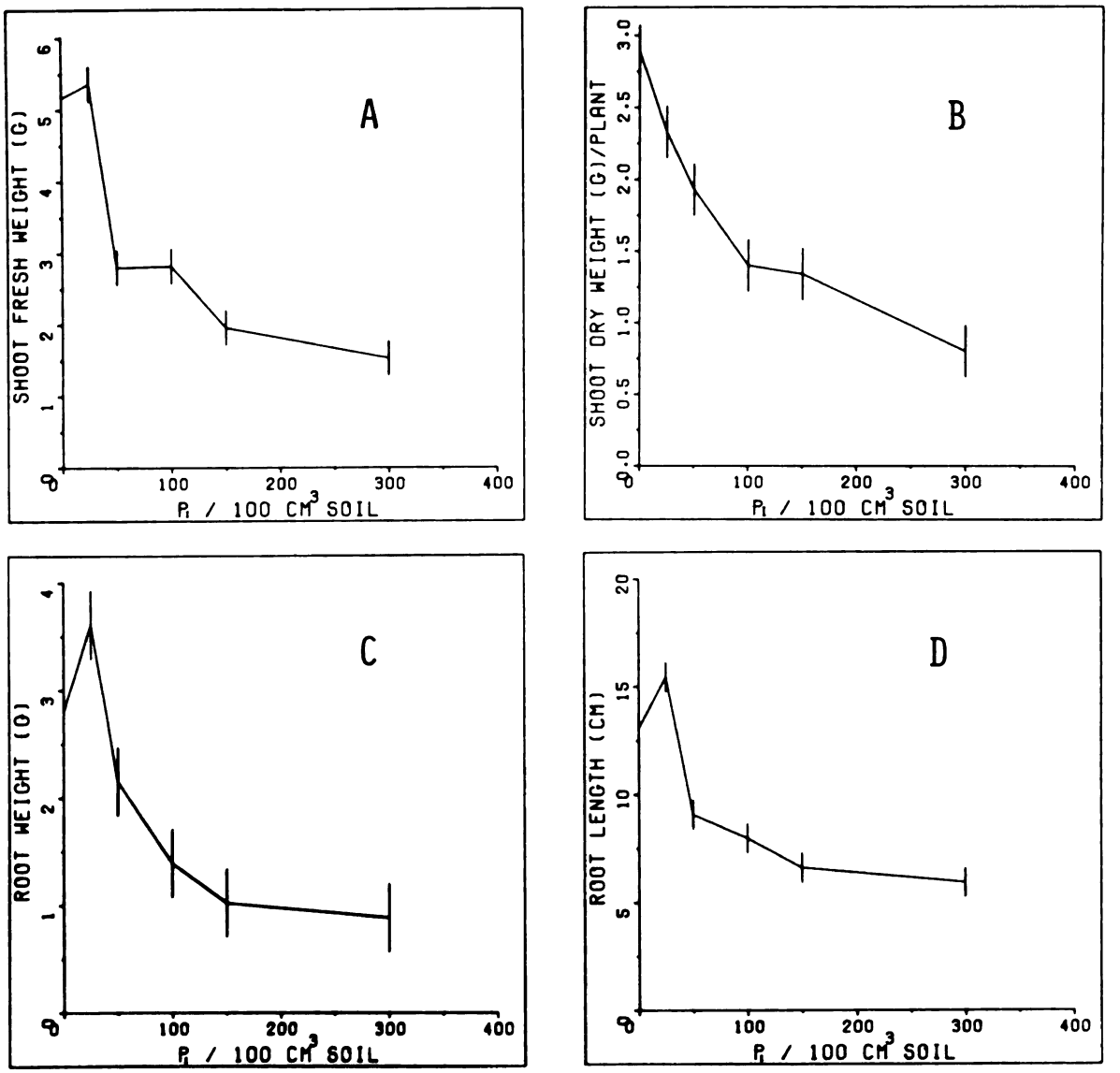


Figure 3.26. Effect of different initial population densities of P. penetrans on shoot fresh weight (A), shoot dry weight (B), root weight (C), and root length (D) of navy beans .
Vertical bars represent 95 % confidence intervals.

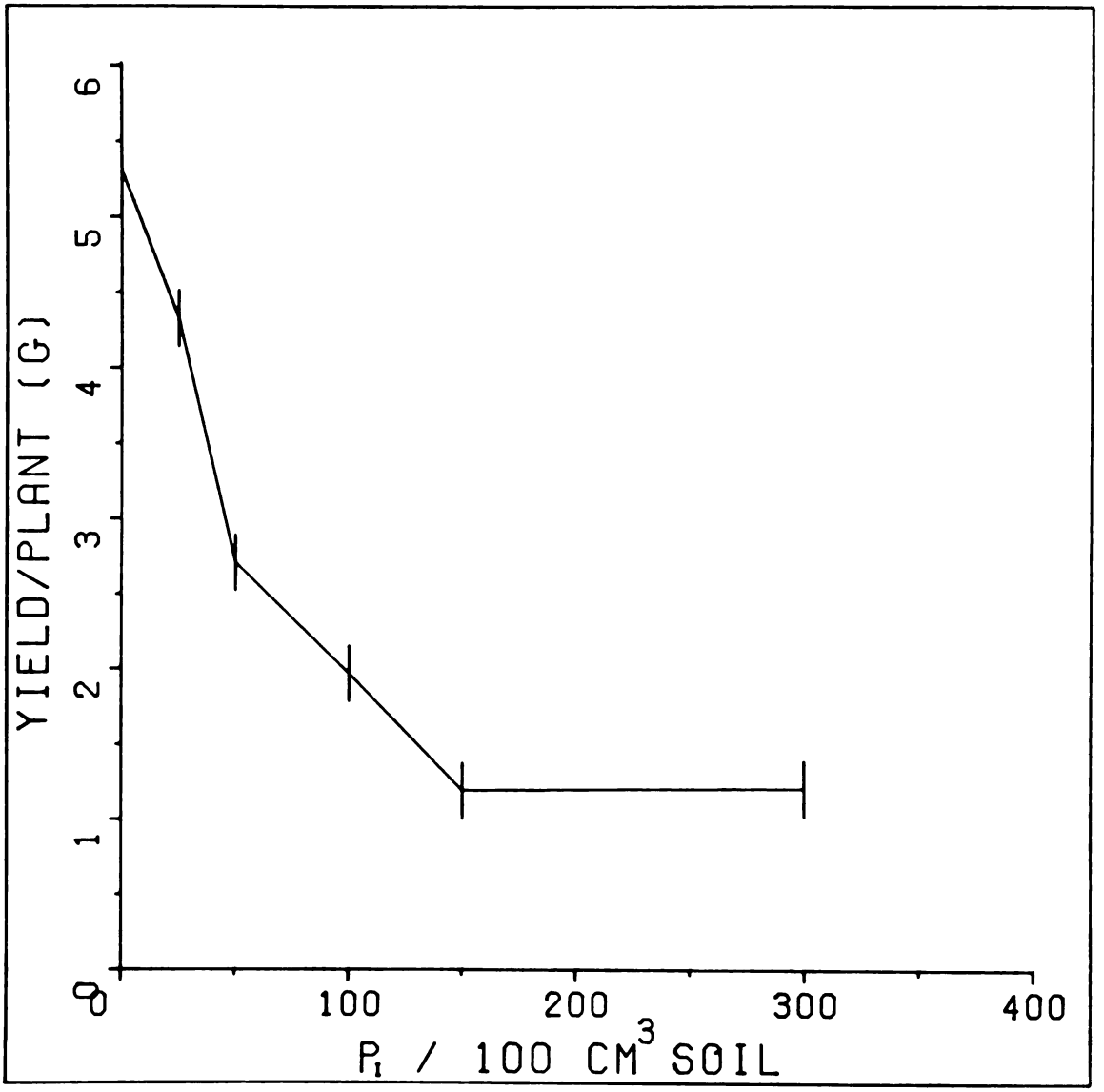


Figure 3.27. Effect of different initial population densities of P. penetrans on navy bean yield. Vertical bars represent 95 % confidence intervals.

3.3.4.2 Susceptibility of six navy bean varieties to Pratylenchus penetrans

P. penetrans were recovered from roots of all six bean varieties. Higher total root and soil densities of P. penetrans were associated with Sanilac, Seafarer and Tuscola varieties compared to Gratiot, Saginaw and Kentwood varieties (Figure 3.28). Three maxima in population densities were evident at 357, 927 and 1132 DD 10 C respectively on Sanilac, Seafarer and Tuscola varieties. Population densities associated with Gratiot and Kentwood varieties initially decreased until 340 DD 10 C and then steadily increased reaching maxima 785 DD 10 C (Figure 3.28). This was followed by another decrease at 927 DD 10 C and then an increase at the end of the growth period (Figure 3.28).

Plant heights were significantly lower for P. penetrans infected plants of Sanilac, Seafarer and Tuscola bean varieties (Figure 3.29A-C; Table A1). Plant heights increased with increase in degree days reaching a plateau at 1110 DD 10 C (Figure 3.29). The difference in response to infection by P. penetrans is evident from the equations for the relationship. For noninfected Tuscola plants the equation for plant height is:

$$Y = 36.79 - 6152/X \quad (R^2 = 0.99)$$

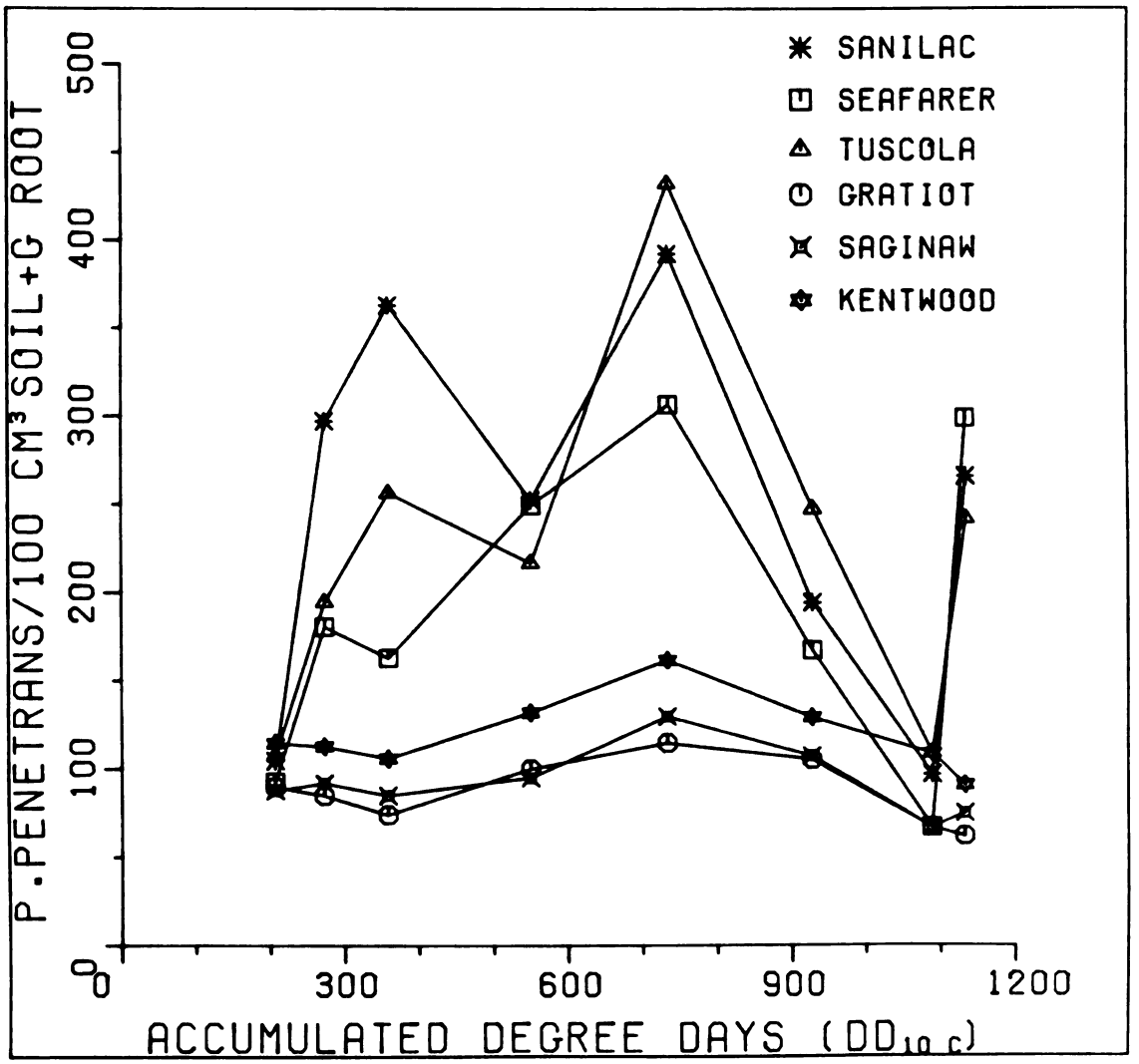


Figure 3.28. Population dynamics of P. penetrans associated with six navy bean varieties.

Figure 3.29. Influence of P. penetrans on height of six navy bean varieties over the growth period.

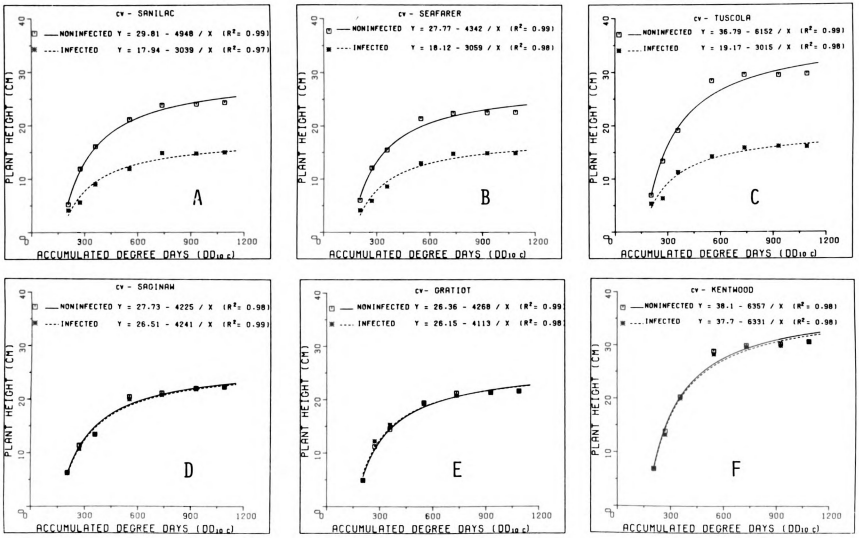

cv - SANILAC
NONINFECTED Y = 29.81 - 4948 / X (R²= 0.99)
INFECTED Y = 17.94 - 3039 / X (R²= 0.97)
A
cv - SEAFARER
NONINFECTED Y = 27.77 - 4342 / X (R²= 0.99)
INFECTED Y = 18.12 - 3059 / X (R²= 0.98)
B
cv - TUSCOLA
NONINFECTED Y = 36.79 - 6152 / X (R²= 0.99)
INFECTED Y = 19.17 - 3015 / X (R²= 0.98)
C
cv - SAGINAW
NONINFECTED Y = 27.73 - 4225 / X (R²= 0.98)
INFECTED Y = 26.51 - 4241 / X (R²= 0.99)
D
cv- GRATIOT
NONINFECTED Y = 26.36 - 4268 / X (R²= 0.99)
INFECTED Y = 26.15 - 4113 / X (R²= 0.98)
E
cv - KENTWOOD
NONINFECTED Y = 38.1 - 6357 / X (R²= 0.98)
INFECTED Y = 37.7 - 6331 / X (R²= 0.98)
F
PLANT HEIGHT (CM)
ACCUMULATED DEGREE DAYS (DD10 C)
0
10
20
30
40
300
600
900
1200

Figure 3.29.

where Y = plant height and X = accumulated degree days at base 10 C. For P. penetrans infected Tuscola plants, however, the equation for the relationship is:

$$Y = 19.17 - 3015/X \quad (R^2 = 0.98)$$

The comparison of the two equations show that plant heights were lower in P. penetrans infected plants. For P. penetrans infected Gratiot plants the relationship between plant height and accumulated degree days is:

$$Y = 26.36 - 4268/X \quad (R^2 = 0.99)$$

and for noninfected Gratiot plants the equation for the relationship is:

$$Y = 26.15 - 4113/X \quad (R^2 = 0.98)$$

Comparison of these two equations show that heights of Gratiot plants were not significantly influenced by P. penetrans.

The relationship between root weight and accumulated degree days correlated well with a second degree polynomial type relationship as expressed by the curves in Figure 3.30A-F. Root weight increased to maxima at 750 DD 10 C and then decreased rapidly until 1088 DD 10 C (Figure 3.30). Root weights of Sanilac, Seafarer and Kentwood varieties were significantly lower (P = 0.05) in P. penetrans infected plants compared to those of noninfected plants, while for Gratiot, Saginaw and Kentwood varieties there

Figure 3.30. Influence of P. penetrans on root weight of six navy bean varieties over the growth period.

Equations for the relationships between root weight and accumulated degree days at base 10 C.

Y = root weight ; X = accumulated degree days.
NI = noninfected ; I = P. penetrans infected

cv- Sanilac

NI: $Y = -2.76317835468 + 0.021347254052\,X - 0.000001659285771\,X^2$ $(R^2 = 0.92)$

I: $Y = -0.93304277061 + 0.00924446617497\,X - 0.000007408234021\,X^2$ $(R^2 = 0.86)$

cv- Seafarer

NI: $Y = -2.84413943365 + 0.021960513683\,1\,X - 0.0000170987044\,X^2$ $(R^2 = 0.87)$

I: $Y = -0.810740336604 + 0.00841788236324\,X - 0.000006740109478\,X^2$ $(R^2 = 0.87)$

cv- Tuscola

NI: $Y = -2.92376327034 + 0.0234429064198\,X - 0.00001790035985\,X^2$ $(R^2 = 0.92)$

I: $Y = -0.87282288469 + 0.00981501061033\,X - 0.0000078876075\,X^2$ $(R^2 = 0.87)$

cv- Saginaw

NI: $Y = -2.39974783238 + 0.0196105924317\,X - 0.00001514828469\,X^2$ $(R^2 = 0.96)$

I: $Y = -2.44222442166 + 0.0199420467434\,X - 0.00001556483007\,X^2$ $(R^2 = 0.97)$

cv- Gratiot

NI: $Y = -2.33094449815 + 0.019195936554\,X - 0.00001478955799\,X^2$ $(R^2 = 0.90)$

I: $Y = -1.99770667355 + 0.0183378954379\,X - 0.00001444678826\,X^2$ $(R^2 = 0.90)$

cv- Kentwood

NI: $Y = -2.8314348122 + 0.0250758319854\,X - 0.00001946851258\,X^2$ $(R^2 = 0.87)$

I: $Y = -2.65487564121 + 0.0241572456405\,X - 0.00001882603424\,X^2$ $(R^2 = 0.89)$

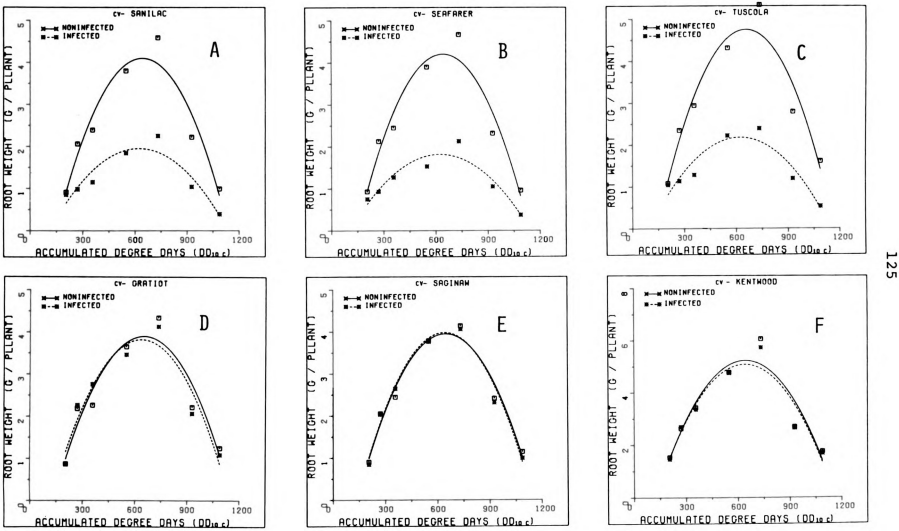

CV- SANILAC
NONINFECTED
INFECTED
A
ROOT WEIGHT (G / PLANT)
ACCUMULATED DEGREE DAYS (DD10 C)
CV- SEAFARER
B
CV- TUSCOLA
C
CV- GRATIOT
D
CV- SAGINAW
E
CV - KENTWOOD
F

Figure 3.30.

were no significant (P = 0.05) differences in root weight of noninfected and P. penetrans infected plants (Figure 3.30; Table A2).

Leaf area of Sanilac, Seafarer and Tuscola plants were significantly (P = 0.05) decreased by P. penetrans while differences in leaf area in noninfected and P. penetrans infected Saginaw, Gratiot and Kentwood varieties were less marked (Table A3).

Dry bean yield from Sanilac, Seafarer and Tuscola varieties were significantly (P = 0.05) lower in P. penetrans infected plants than in noninfected plants (Figure 3.31). For Gratiot, Saginaw and Kentwood varieties there were no significant (P = 0.05) differences in dry bean yield in P. penetrans infected and noninfected plants (Figure 3.31).

For the varieties Sanilac, Seafarer and Tuscola the relative growth rates of P. penetrans infected plants were lower than those of noninfected plants (Figure 3.32A, B, C). For Sanilac plants, relative growth rate was higher in noninfected plants throughout the growth period (Figure 3.32A), while growth rate of noninfected plants of Seafarer and Tuscola varieties were higher than that of P. penetrans infected plants from initial growth up to 930 DD 10 C, after which there was no difference in

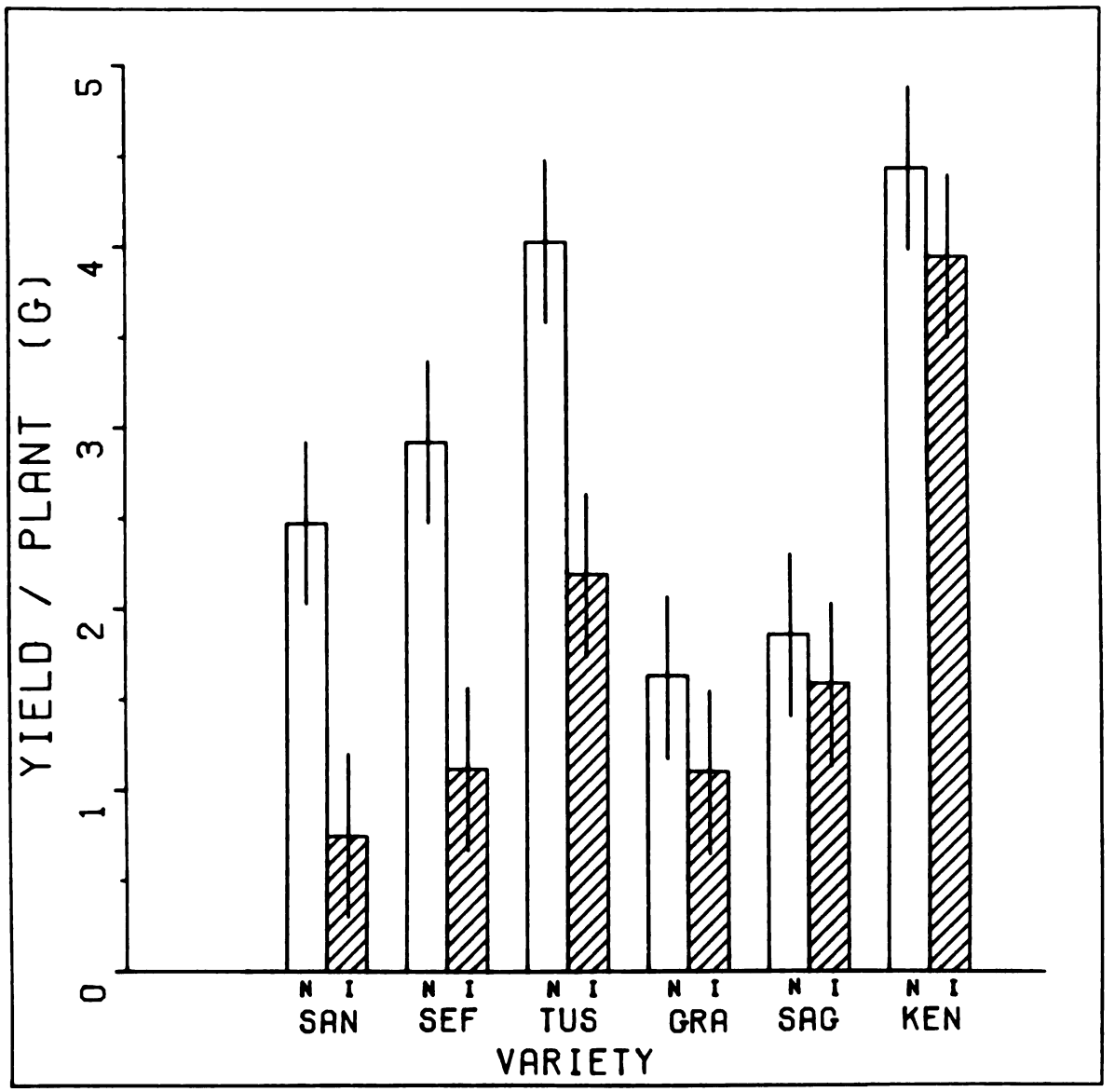


Figure 3.31. Effect of P. penetrans on yield of six navy bean varieties.
Vertical bars represent 95 % confidence intervals.
N = noninfected ; I = P. penetrans infected
San = Sanilac, Sef = Seafarer, Tus = Tuscola
Gra = Gratiot, Sag = Saginaw, Ken = Kentwood.

Figure 3.32. Effect of P. penetrans on relative growth rate of six navy bean varieties over the growth period.

Equations for the relationships between relative growth and accumulated degree days at base 10 C.

Y = relative growth rate per week ; X = accumulated degree days.
NI = noninfected ; I = P. penetrans infected

cv- Sanilac

NI: $Y = 0.0755662541602 + 0.0009430491099\ X^2 - 0.000001340226071\ X^2$ $(R^2 = 0.89)$

I: $Y = 0.0575269502686 + 0.00108419798777\ X - 0.000001352304453\ X^2$ $(R^2 = 0.92)$

cv- Seafarer

NI: $Y = 0.0789468044517 + 0.0009585056417\ X - 0.000001357854103\ X^2$ $(R^2 = 0.85)$

I: $Y = 0.02323289969 + 0.0009318011136\ X - 0.000001231264458\ X^2$ $(R^2 = 0.85)$

cv- Tuscola

NI: $Y = 0.0705445316036 + 0.0009825407043\ X - 0.000001353147372\ X^2$ $(R^2 = 0.78)$

I: $Y = 0.0026517726648 + 0.00104944243762\ X - 0.0000013249396614\ X^2$ $(R^2 = 0.86)$

cv- Saginaw

NI: $Y = 0.0640298556787 + 0.0010262552332\ X - 0.000001387527968\ X^2$ $(R^2 = 0.80)$

I: $Y = 0.0708459814593 + 0.00100470707048\ X - 0.0000013917.98334\ X^2$ $(R^2 = 0.79)$

cv- Gratiot

NI: $Y = 0.0800559470947 + 0.00101491572655\ X - 0.000001412741105\ X^2$ $(R^2 = 0.85)$

I: $Y = 0.080009763156 + 0.0009800761301\ X - 0.000001407212762\ X^2$ $(R^2 = 0.89)$

cv- Kentwood

NI: $Y = 0.0405285386304 + 0.00106061667648\ X - 0.000001423001624\ X^2$ $(R^2 = 0.89)$

I: $Y = 0.028449637433 + 0.00107961761902\ X - 0.000001439563895\ X^2$ $(R^2 = 0.88)$

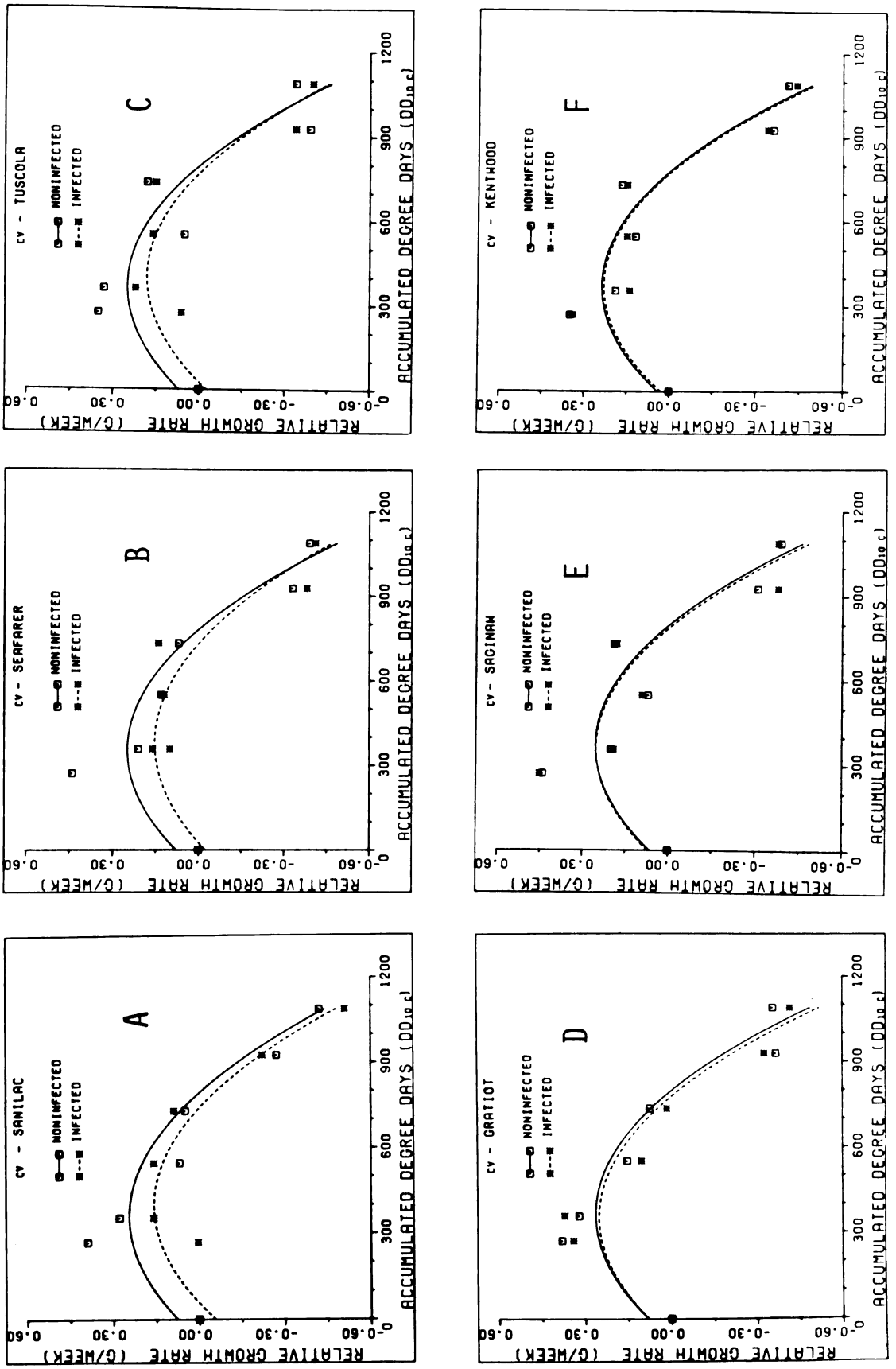

A
cv - SANILAC
B
cv - SEAFARER
C
cv - TUSCOLA
D
cv - GRATIOT
E
cv - SAGINAW
F
cv - KENTWOOD
NONINFECTED
INFECTED
RELATIVE GROWTH RATE (G/WEEK)
ACCUMULATED DEGREE DAYS (DD10 C)
0.60
0.30
0.00
-0.30
-0.60
0
300
600
900
1200

Figure 3.32.

relative growth rates in noninfected and P. penetrans infected plants (Figure 3.32).

Relative growth rates of P. penetrans infected and noninfected Saginaw, Gratiot and Kentwood bean plants were similar (Figure 3.32D-F). The relationship between relative growth rate and degree days correlated well with a second degree polynomial type relationship as indicated by the equations and curves for the relationships between relative growth rate and accumulated degree days (Figure 3.32).

For Sanilac noninfected plants the equation for the relationship is:

$$Y = 0.0755662541602 + 0.0009430491099\ X - 0.000001340226071\ X^2 \quad (R^2 = 0.89)$$

while the equation for Sanilac P. penetrans infected plants is:

$$Y = 0.057526902686 + 0.00108419798777\ X - 0.000001352304453\ X^2 \quad (R^2 = 0.92)$$

where Y = relative growth rate per week and X is accumulated degree days at base 10 C. The comparison of the equations shows the differences in growth rate of infected and noninfected plants.

A comparison of equations expressing the relationship between relative growth rate and accumulated degree

days for noninfected and infected plants of Gratiot variety indicated that there was no significant difference in relative growth rates of noninfected and P. penetrans infected plants. For noninfected plants the equation for the relationship is:

$$Y = 0.0800559470947 + 0.00101491572655\ X - 0.000001412741105\ X^2 \quad (R^2 = 0.85)$$

and for P. penetrans infected plants the equation for the relationship is:

$$Y = 0.080009763156 + 0.0009800761301\ X - 0.000001407212762\ X^2 \quad (R^2 = 0.89)$$

3.3.4.3 Responses of Sanilac navy beans to infection with different densities of Pratylenchus penetrans

Final total population densities in roots and soil associated with navy beans increased with increase in initial population densities of P. penetrans and the relationship between the log of initial and the log of final densities was correlated with a linear function (Figure 3.33) and expressed by the equation:

$$\text{Log } Y = 0.34 + 0.93\ (\log X) \quad (R = 0.96)$$

where Y = log of final densities of P. penetrans plus one and X = log of initial densities of P. penetrans plus one. The percentage initial mortality was 20%, 20%, 50%, 11%, 24% and 38% for initial densities of 5, 10, 20, 80, 160

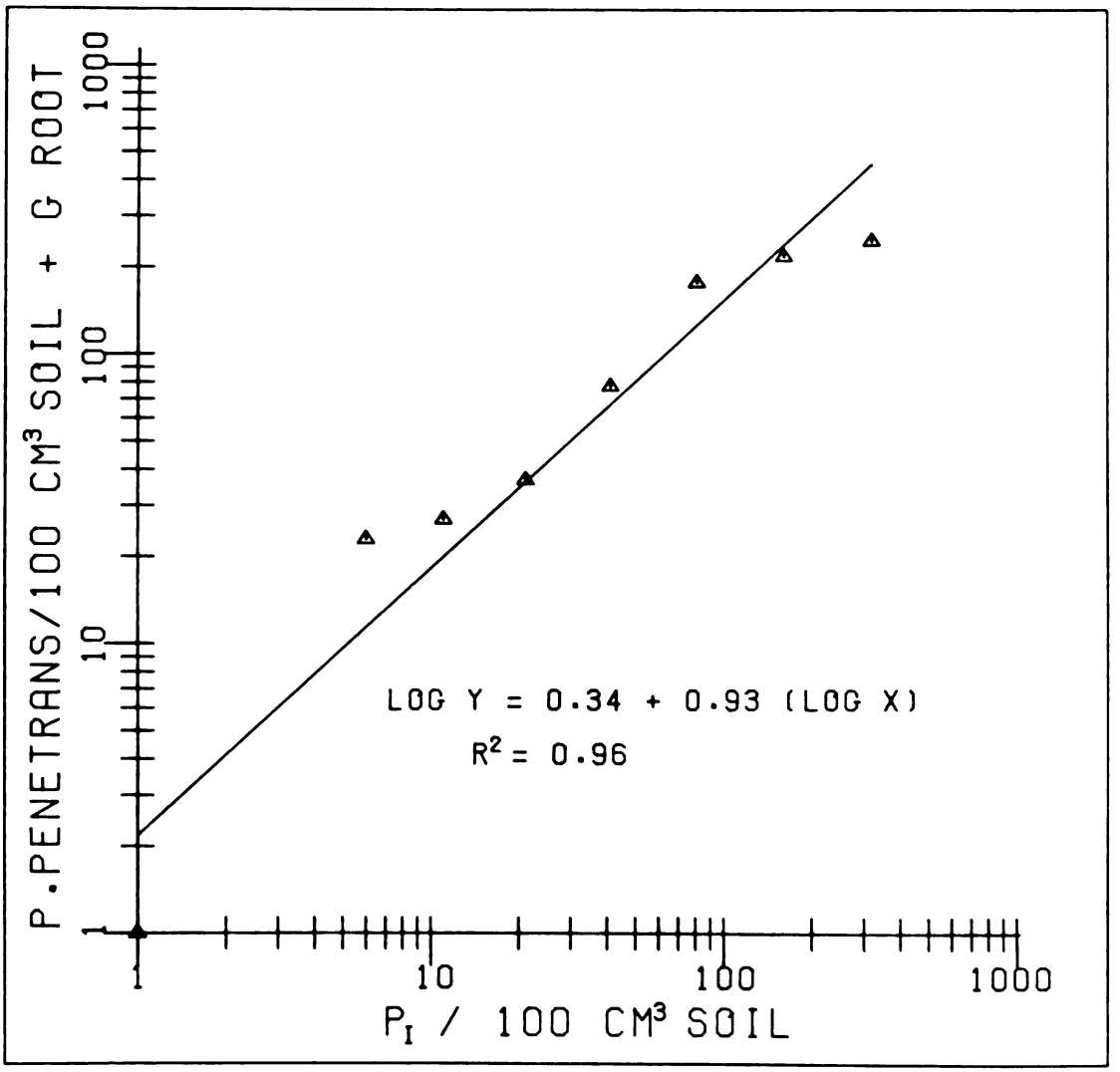


Figure 3.33. Relationship between total (Root + soil) final population densities of P. penetrans and initial soil population densities of P. penetrans.

and 320 P. penetrans per 100 cm^3 soil respectively. For an initial density of 40 P. penetrans per 100 cm^3 soil the initial mortality was not obtained as population densities were higher than initial density at the time of sampling at 254 DD 10 C (Tables A4-1,2 & 3).

Population densities fluctuated over time. Two maxima in root population densities were evident and three maxima in soil population densities were observed (Figure 3.34) for populations associated with an initial density of 320 P. penetrans per 100 cm^3 soil. Root population densities increased steadily from initial growth until 523 DD 10 C and then decreased until 603 DD 10 C. Densities increased after this period reaching the second maxima at 865 DD 10 C (Figure 3.34). In the soil, densities decreased initially as nematodes entered the roots until 341 DD 10 C. The three maxima in population densities were observed at 434, 603 and 1094 DD 10 C (Figure 3.34).

Lesions were present on roots of plants exposed to P. penetrans (Figures 3.35-3.36). These lesions are characteristic of the damage caused by root lesion nematodes.

The heights of plants exposed to initial densities of 20, 40, 80, 160 and 320 P. penetrans per 100 cm^3 soil

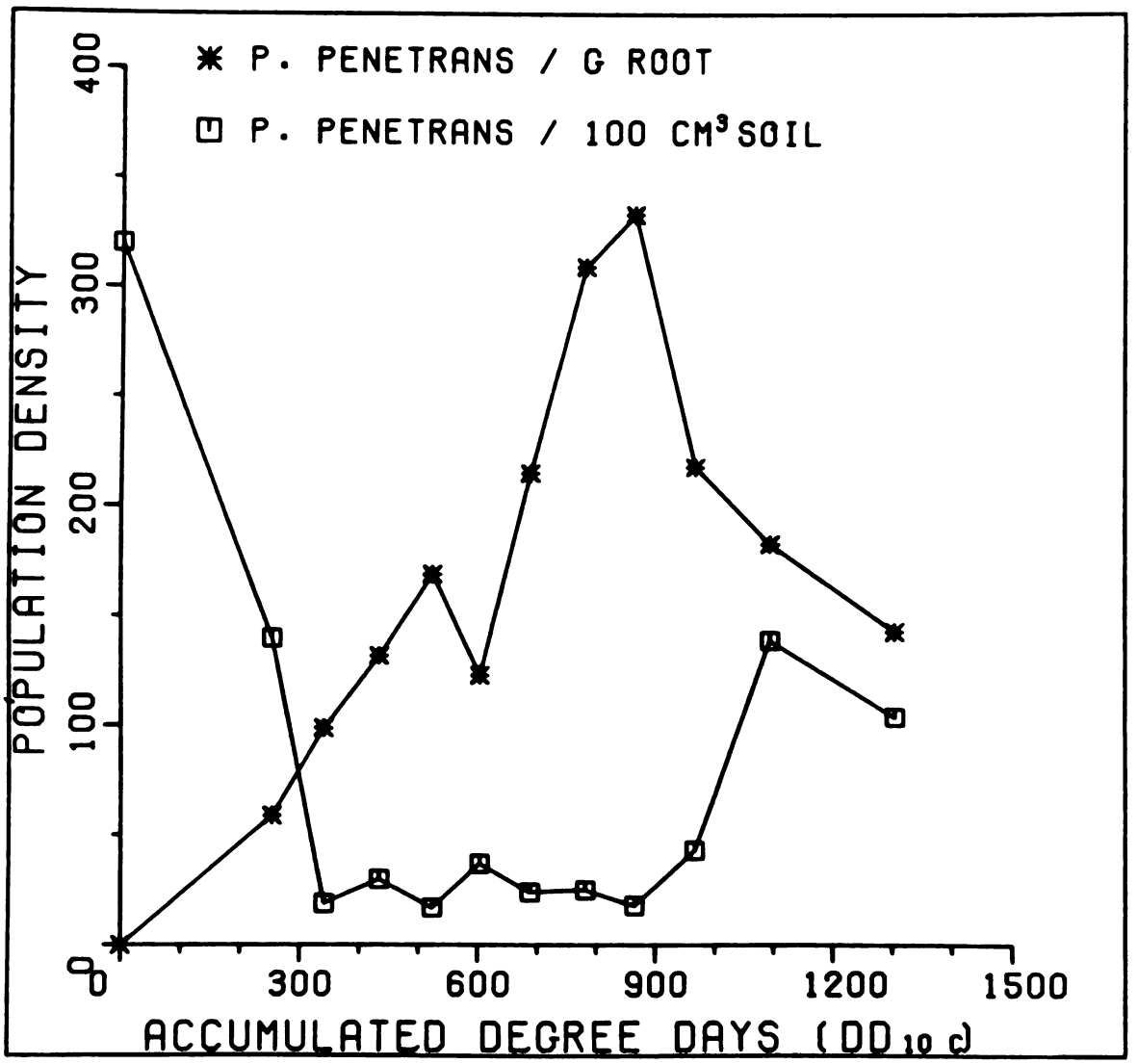


Figure 3.34. Population dynamics of P. penetrans associated with navy beans exposed to an initial density of 320 P. penetrans per 100 cm^3 soil.

Figure 3.35. Root-lesions produced by P. penetrans on navy bean roots.
P_i = initial population density per 100 cm^3 soil.
Le = lesion

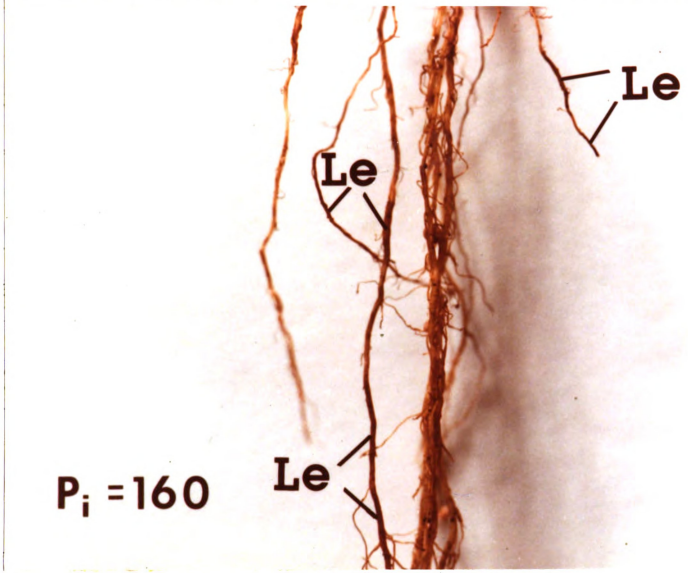


Figure 3.35

Figure 3.36. Comparison of a noninfected and a P. penetrans infected navy bean root system.
Le = lesion.

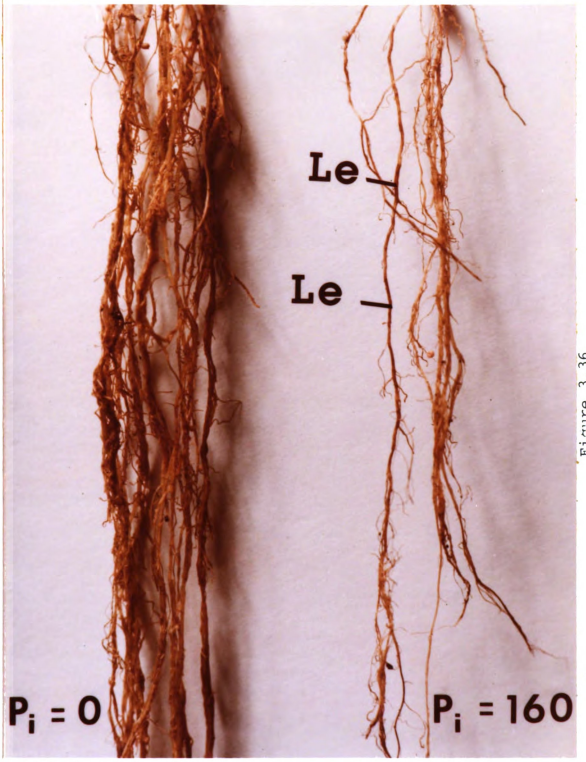


Figure 3.36

were lower than the heights of noninfected plants (Figures 3.37-3.40). The relationship between plant height and log of initial population density was adequately expressed by linear functions with significant correlation coefficients (R) values for six time periods (341, 688, 782, 865, 967 and 1094 DD 10 C) (Figure 3.37). However for the time periods associated with 434, 523 and 603 DD 10 C the relationship between plant height and the log of initial population densities was correlated to second degree polynomial relationships (Figure 3.38). The curves for these relationships indicated increases in plant height at low initial population densities of P. penetrans. These increases in plant height were not evident at the other six time periods of growth.

The relationship between plant height and accumulated degree days was curvilinear indicating increases in plant height with increase in degree days (Figures 3.39-3.40).

Initial population densities above 20 P. penetrans per 100 cm^3 soil significantly (P = 0.05) reduced root area of plants (Figures 3.41-3.42). The relationship between the log of initial population densities of P. penetrans and root area of navy beans was expressed

Figure 3.37, Relationships between navy bean plant height and initial soil population density of P. penetrans at different periods of growth.

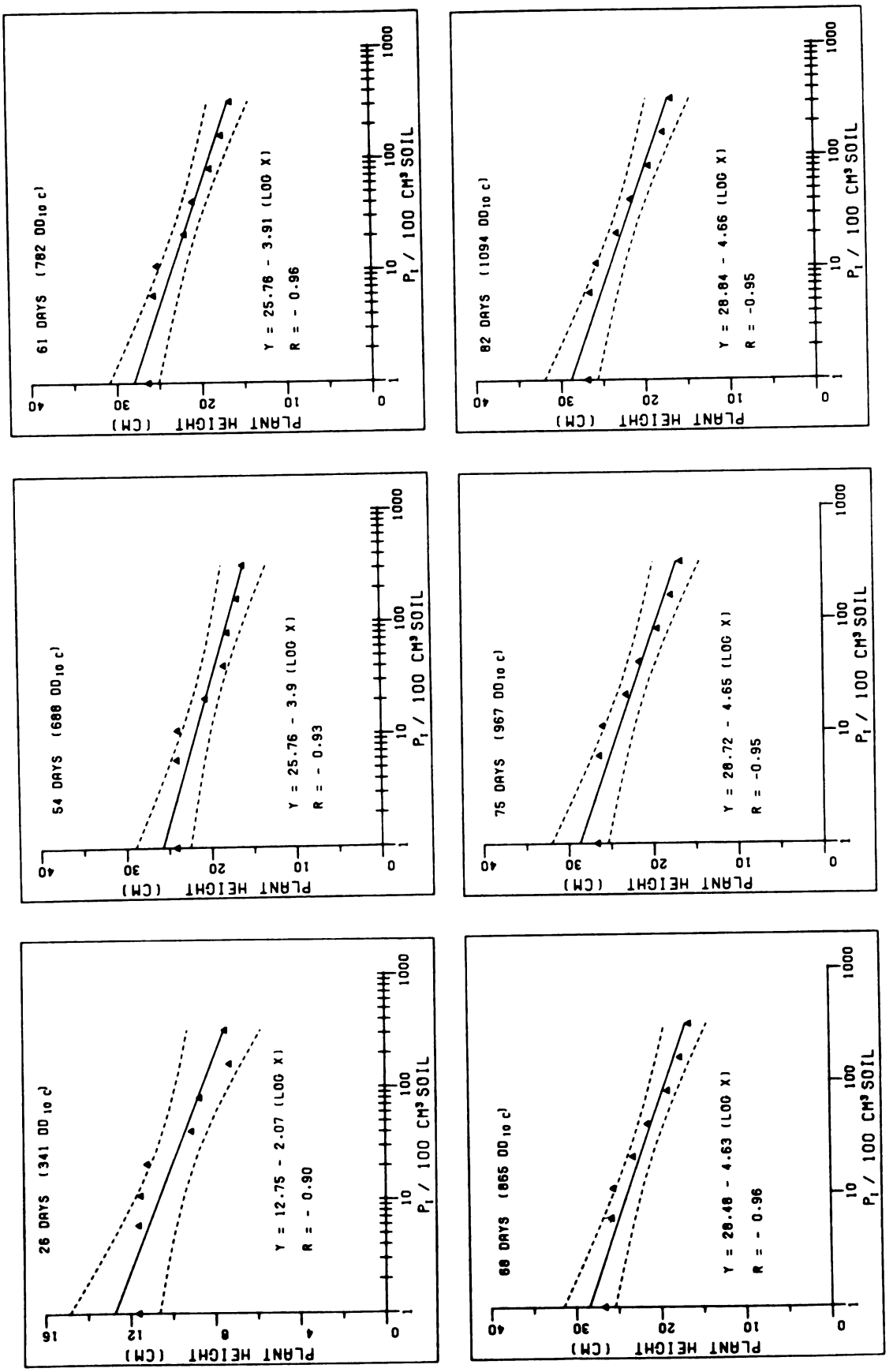

26 DAYS (341 DD10 C)
Y = 12.75 - 2.07 (LOG X)
R = - 0.90
54 DAYS (600 DD10 C)
Y = 25.76 - 3.9 (LOG X)
R = - 0.93
61 DAYS (782 DD10 C)
Y = 25.78 - 3.91 (LOG X)
R = - 0.96
68 DAYS (865 DD10 C)
Y = 28.48 - 4.63 (LOG X)
R = - 0.96
75 DAYS (967 DD10 C)
Y = 28.72 - 4.65 (LOG X)
R = -0.95
82 DAYS (1094 DD10 C)
Y = 28.84 - 4.66 (LOG X)
R = -0.95
PLANT HEIGHT (CM)
P1 / 100 CM3 SOIL

Figure 3.37.

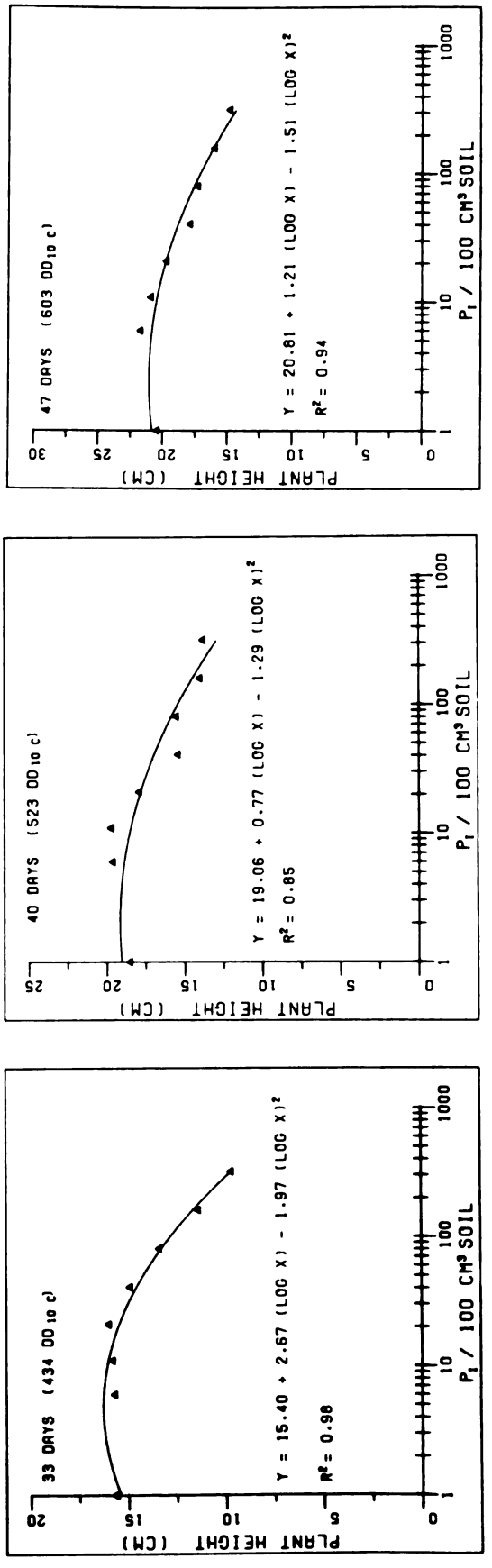


Figure 3. 38. Relationship between height of navy bean plants and initial population density of P. penetrans at different growth periods.

Figure 3.39. Effect of P. penetrans on height of navy bean plants over the growth period.

Equations for the relationships between plant height and accumulated degree days at base 10 C.

Y = plant height ; X = accumulated degree days
P_i = initial soil population density of P. penetrans per 100 cm^3 soil.

$P_i = 0$ Y = 34.21 - 7519 / X (R = - 0.99)

$P_i = 5$ Y = 33.94 - 7369 / X (R = - 0.99)

$P_i = 10$ Y = 33.32 - 7176 / X (R = - 0.99)

$P_i = 20$ Y = 29.52 - 6064 / X (R = - 0.99)

$P_i = 40$ Y = 27.34 - 5759 / X (R = - 0.99)

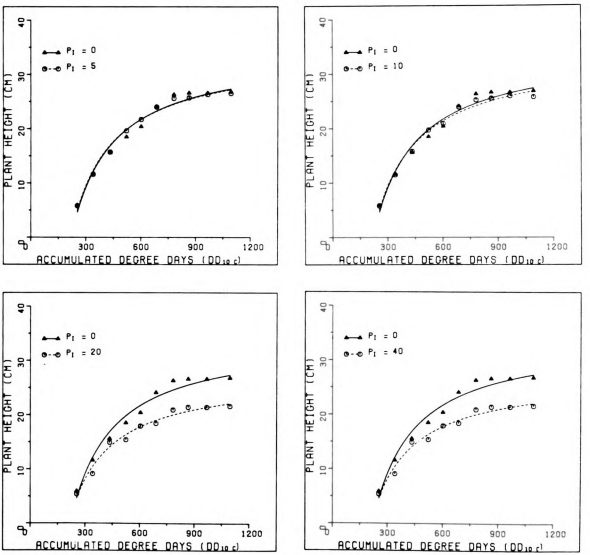

PLANT HEIGHT (CM)
ACCUMULATED DEGREE DAYS (DD10 C)
P1 = 0
P1 = 5
P1 = 10
P1 = 20
P1 = 40
0
10
20
30
40
300
600
900
1200

Figure 3.39.

Figure 3.40. Effect of P. penetrans on heights of navy bean plants over the growth period.

Equations for the relationships between plant height and accumulated degree days at base 10 C.

Y = plant height ; X = accumulated degree days.
P_i = initial soil population density of P. penetrans per 100 cm^3 soil.

$P_i = 0$ Y = 34.21 - 7519 / X (R = -0.99)

$P_i = 80$ Y = 24.84 - 5042 / X (R = -0.99)

$P_i = 160$ Y = 22.87 - 4724 / X (R = - 0.98)

$P_i = 320$ Y = 21.40 - 4374 / X (R = -0.98)

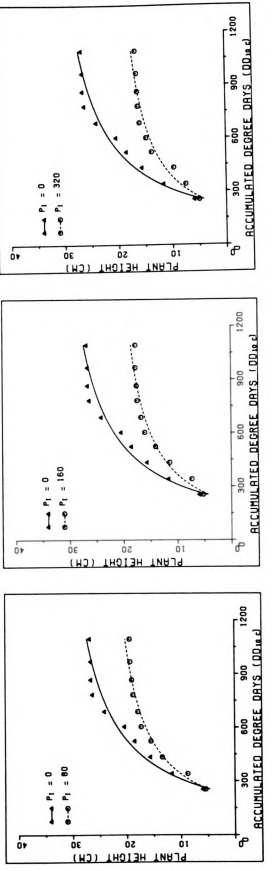

PLANT HEIGHT (CM)
ACCUMULATED DEGREE DAYS (DD$_{10,4}$)
P_I = 0
P_I = 80
P_I = 160
P_I = 320
0
10
20
30
40
300
600
900
1200

Figure 3.40.

Figure 3.41. Effect of different initial population densities of P. penetrans on root area of navy bean plants.

Figure 3.41

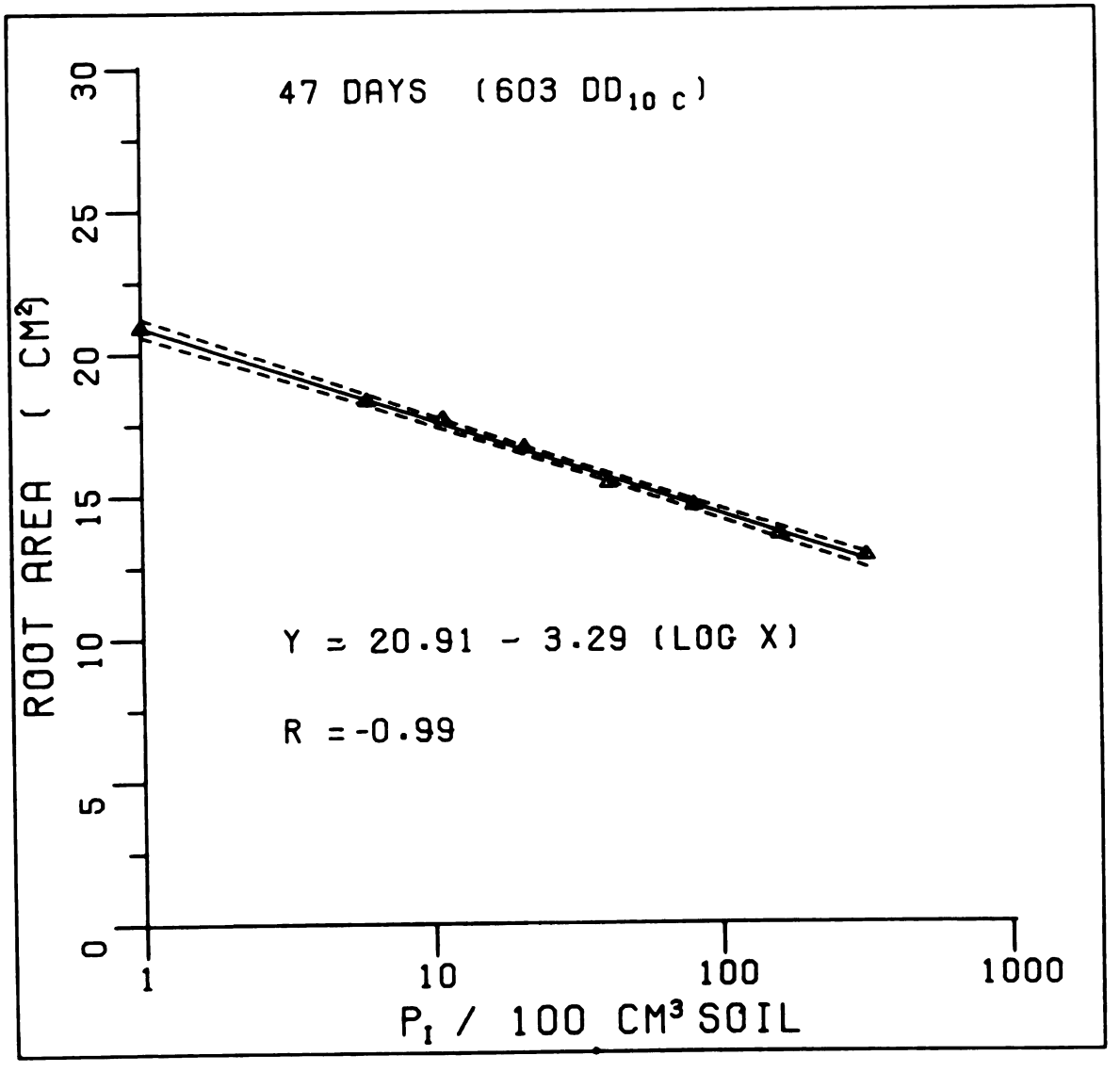


Figure 3.42. Relationship between root area of navy bean plants and the log of initial density of P. penetrans at 688 DD 10 C.

as a linear function indicating decreases in root area with increase in initial population densities of P. penetrans. This is supported by the high correlation coefficient R =-0.99 (Figure 3.42).

The relationship between root area and accumulated degree days was first examined as a linear function from 254 to 688 DD 10 C and from 782 to 1094 DD 10 C (Figure 3.43). The low degree of correlation expressed by the R value, however indicated that a linear function did not adequately express the relationship. Second degree polynomial functions were developed to express the relationships between root area and accumulated degree days (Figures 3.43-3.45).

Leaf area, shoot fresh weight, shoot dry weight and root weight were significantly (P = 0.05) decreased by initial population densities above 40 P. penetrans per 100 cm^3 soil (Tables A5-A8). Dry bean yield was significantly reduced by initial population densities above 40 P. penetrans per 100 cm^3 soil (Figure 3.46). The relationship between initial densities of P. penetrans and dry bean yield was expressed by a linear function (Figure 3.47) and the equation for the relationship is:

$$Y = 3.16 - 0.73 (\log X) \quad (R = -0.97)$$

where Y = dry bean yield and X = initial density of

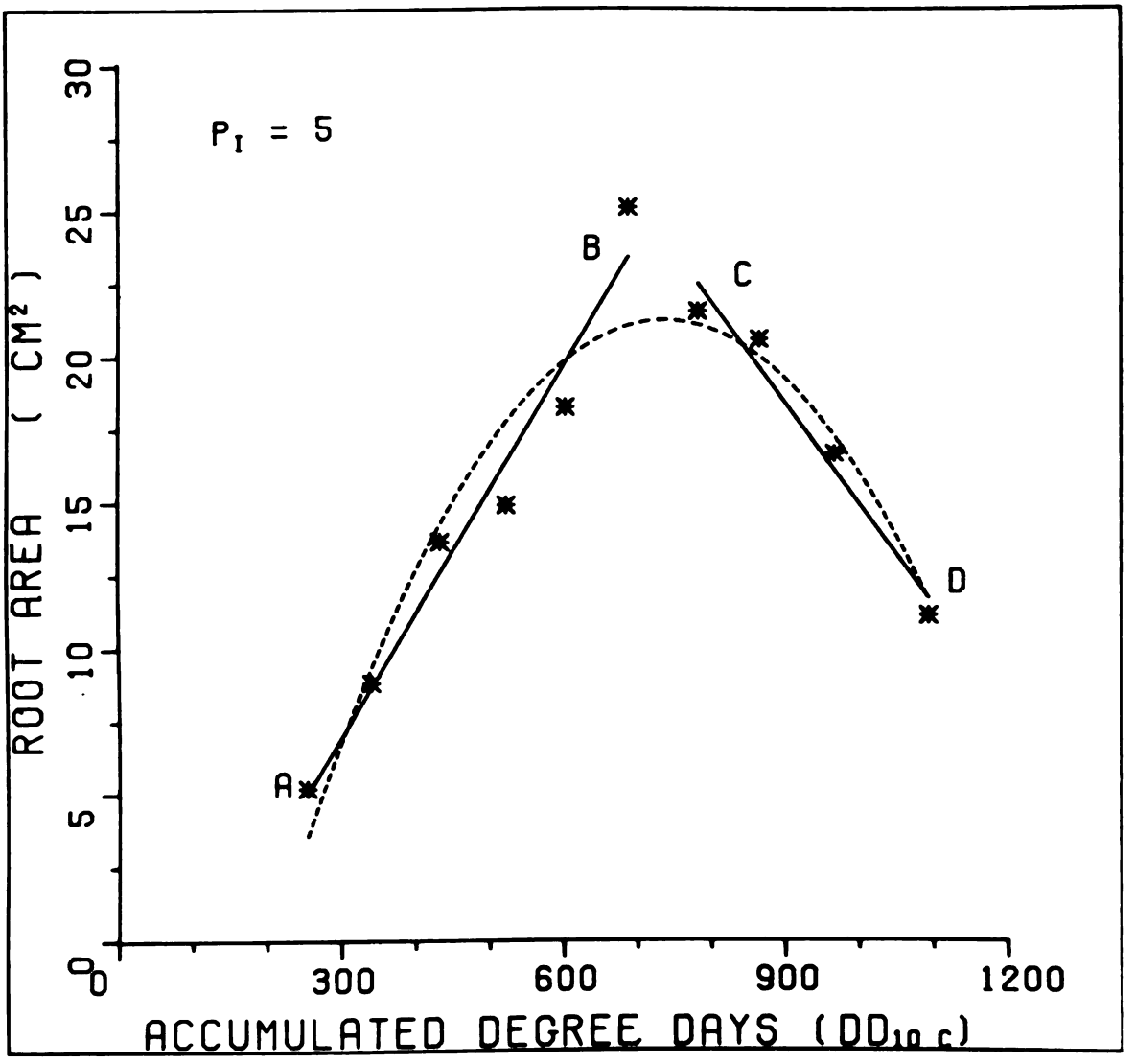


Figure 3.43. Comparison of linear regression functions and a second degree polynomial function for the relationship between root area of navy bean plants and accumulated degree days.

Figure 3.44. Influence of different initial population densities of P. penetrans on root area of navy bean plants over the growth period.

Equations for the relationships between root area and accumulated degree days at base 10 C.

Y = root area ; X = accumulated degree days.

P_i = initial soil population density of P. penetrans per 100 cm^3 soil

$P_i = 0$ $Y = -21.0092565907 + 0.12148432406\ X - 0.0008441463627\ X^2$ $(R^2 = 0.89)$

$P_i = 5$ $Y = -19.8948515196 + 0.111595512098\ X - 0.000075622876\ X^2$ $(R^2 = 0.91)$

$P_i = 10$ $Y = -18.7327810622 + 0.108994759853\ X - 0.00007494743561\ X^2$ $(R^2 = 0.92)$

$P_i = 20$ $Y = -16.667328816 + 0.0969584251\ X - 0.00006708621327\ X^2$ $(R^2 = 0.94)$

$P_i = 40$ $Y = -13.1817518989 + 0.0816703379272\ X - 0.00005761614299\ X^2$ $(R^2 = 0.92)$

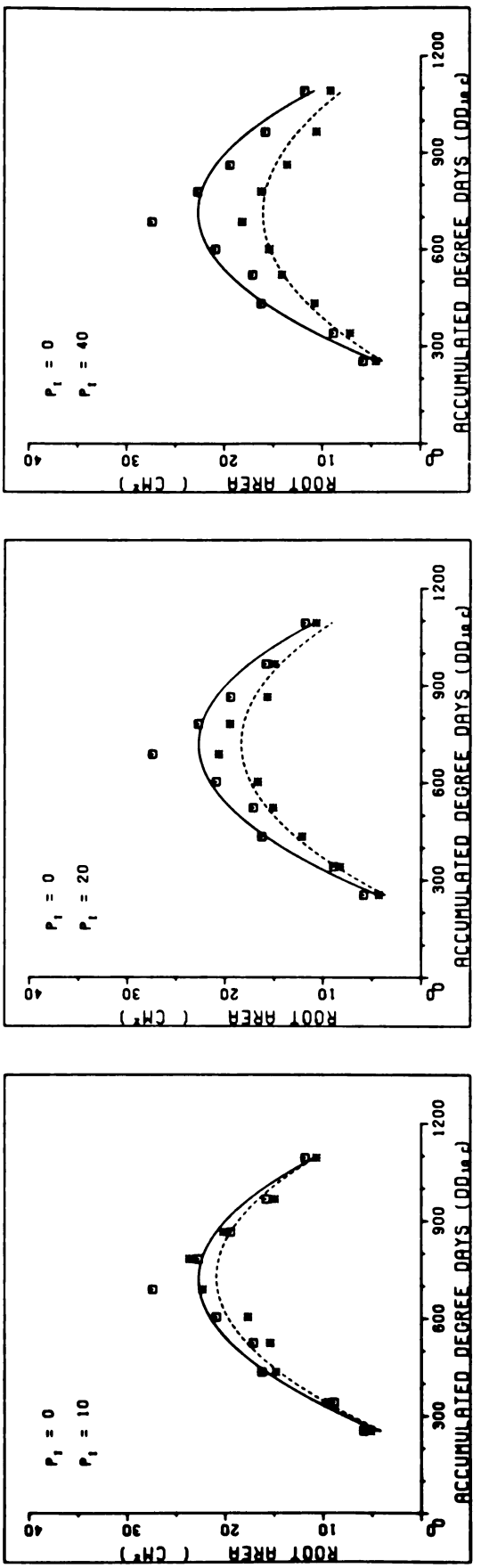

ROOT AREA (CM²)
ACCUMULATED DEGREE DAYS (DD₁₀ₑC)
P₁ = 0
P₁ = 10
P₁ = 20
P₁ = 40
0
10
20
30
40
300
600
900
1200

Figure 3.44.

Figure 3.45. Influence of initial population densities of P. penetrans on root area of navy bean plants over the growth period

Equations for the relationships between root area and accumulated degree days at base 10 C.

Y = root area ; X = accumulated degree days

P_i = initial soil population density of P. penetrans per 100 cm^3 soil.

$P_i = 0$ $\quad Y = -21.0092565907 + 0.12148432406\ X - 0.0008441463627\ X^2 \quad (R^2 = 0.89)$

$P_i = 80$ $\quad Y = -9.65024395178 + 0.0677302399367\ X - 0.00004783616595\ X^2 \quad (R^2 = 0.89)$

$P_i = 160$ $\quad Y = -9.58037983025 + 0.0655903000395\ X - 0.00004671772711\ X^2 \quad (R^2 = 0.87)$

$P_i = 320$ $\quad Y = -9.75174063684 + 0.0640076154808\ X - 0.000045979134\ X^2 \quad (R^2 = 0.89)$

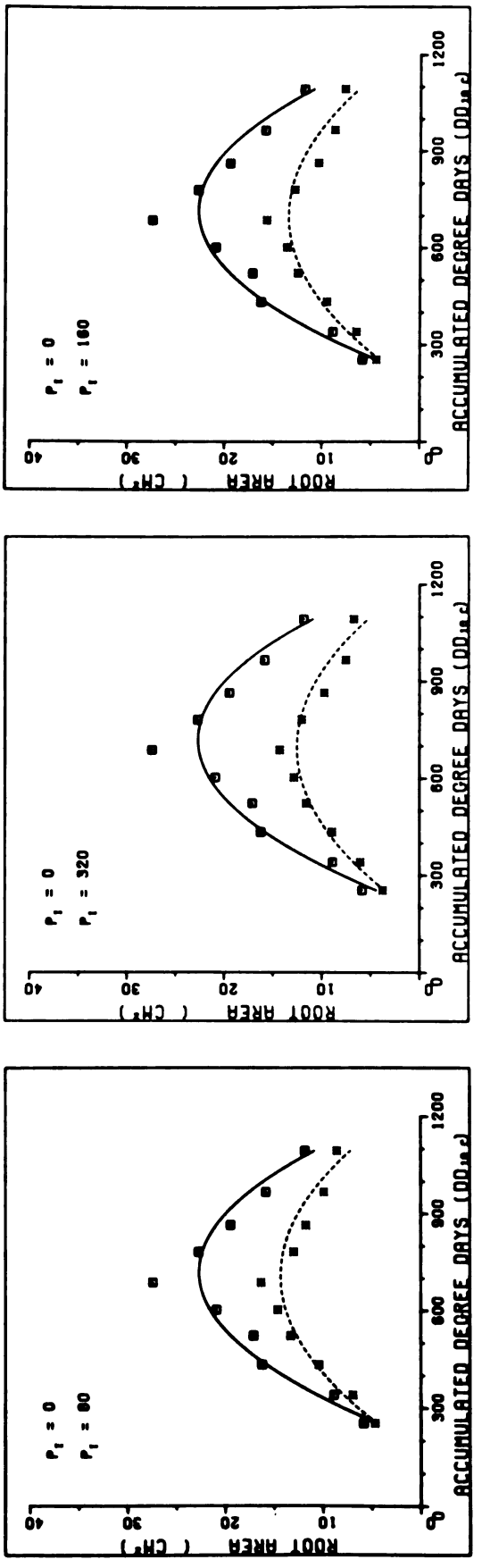

P_i = 0
P_i = 80
P_i = 160
P_i = 320
ROOT AREA (CM²)
ACCUMULATED DEGREE DAYS (DD$_{base}$)
0
10
20
30
40
300
600
900
1200

Figure 3.45.

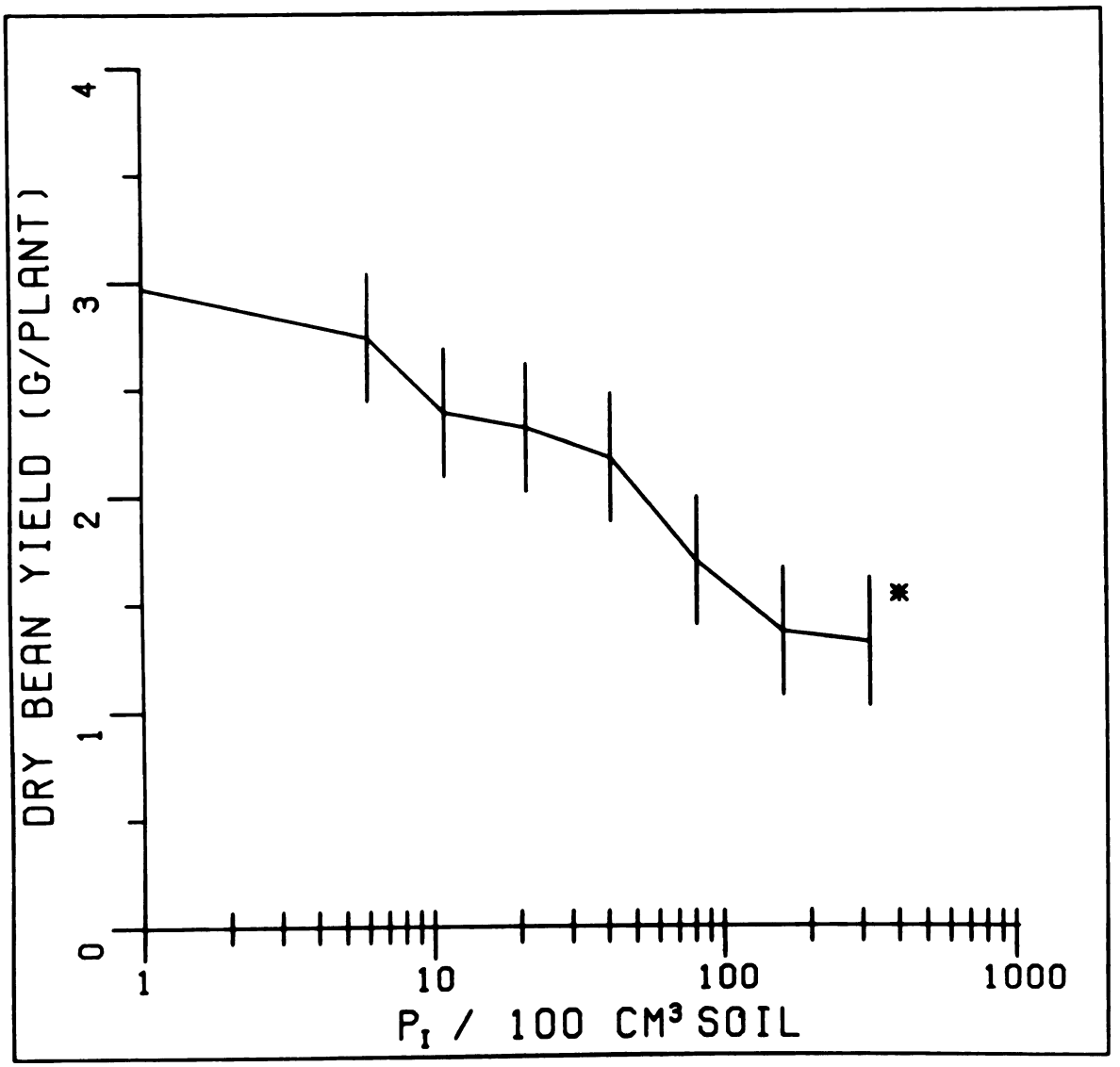


Figure 3.46. Effect of different initial population densities of P. penetrans on yield of navy beans.
Vertical bars represent 95 % confidence intervals.

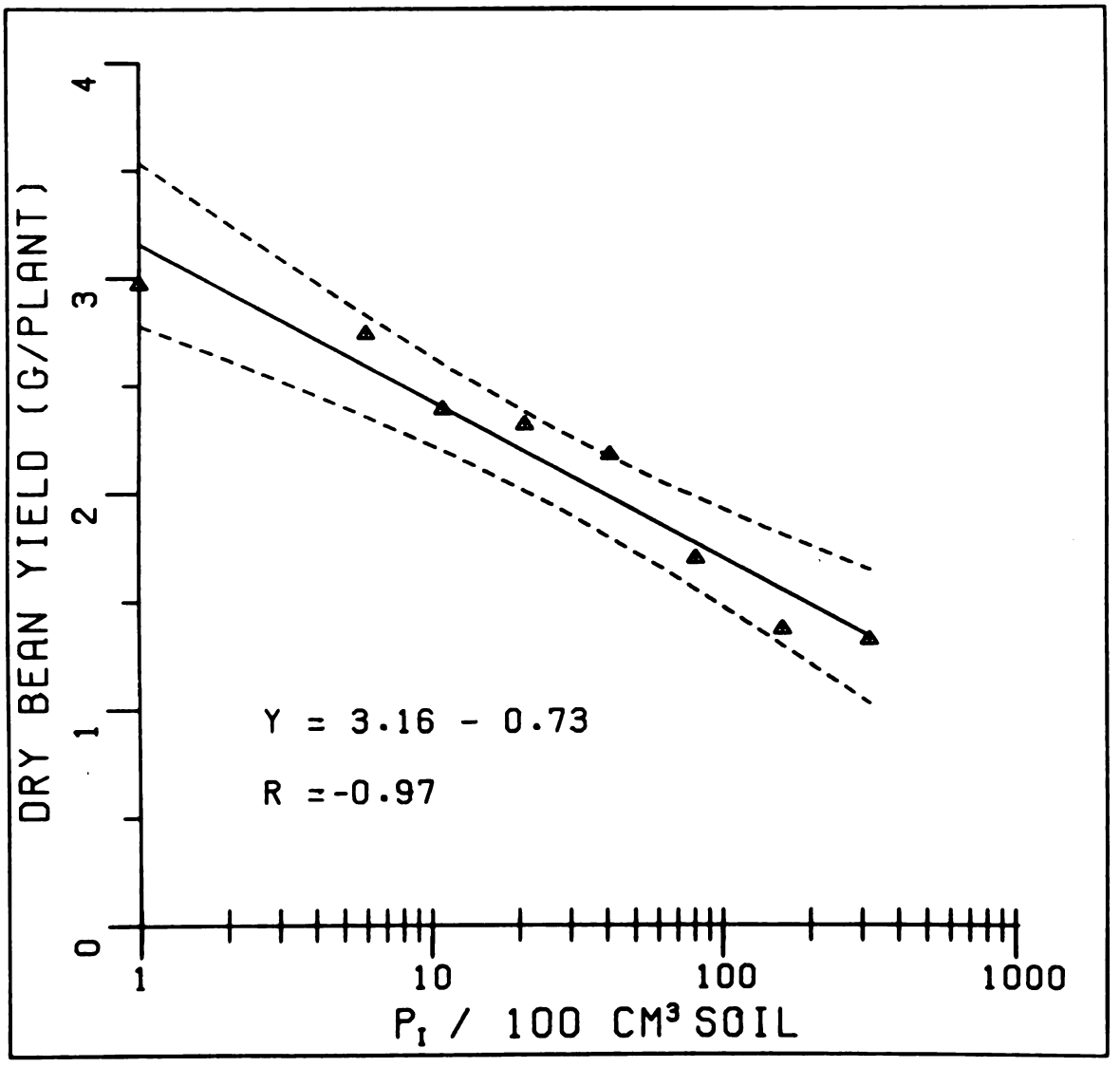


Figure 3.47. Relationship between yield of navy beans and log of initial population density of P. penetrans

P. penetrans plus one. The signficant degree of correlation and confidence intervals (Figure 3.47) indicated that the relationship was appropriately described by this linear function.

The growth response of plants varied depending on the initial population density of P. penetrans (Figure 3.48-3.49). Growth was not significantly reduced by low initial densities (Figure 3.48) but significant reduction in growth was observed at higher densities (Figure 3.48-3.49).

The relative growth rate of plants was reduced by population densities above 20 P. penetrans per 100 cm^3 soil (Figures 3.50-3.51). The relative growth rate of noninfected plants and plants exposed to an initial density of 5 P. penetrans per 100 cm^3 soil followed similar trends over the growth period (Figure 3.50A). The relationship between relative growth rate and accumulated degree days was expressed as second degree polynomials (Figure 3.50-3.51). The equation for the relationship for noninfected plants is:

$$Y = 0.105434974483 + 0.00142888178201\ X - 0.000001991528545\ X^2 \quad (R^2 = 0.67)$$

while the equation for the relationship for plants exposed to an initial density of 5 P. penetrans per 100 cm^3 soil is:

Figure 3.48. Effect of P. penetrans on growth of navy bean plants.

Figure 3.48

Figure 3.49. Comparison of growth of navy bean plants in the absence of P. penetrans and in the presence of an initial density of 320 P. penetrans per 100 cm^3 soil.

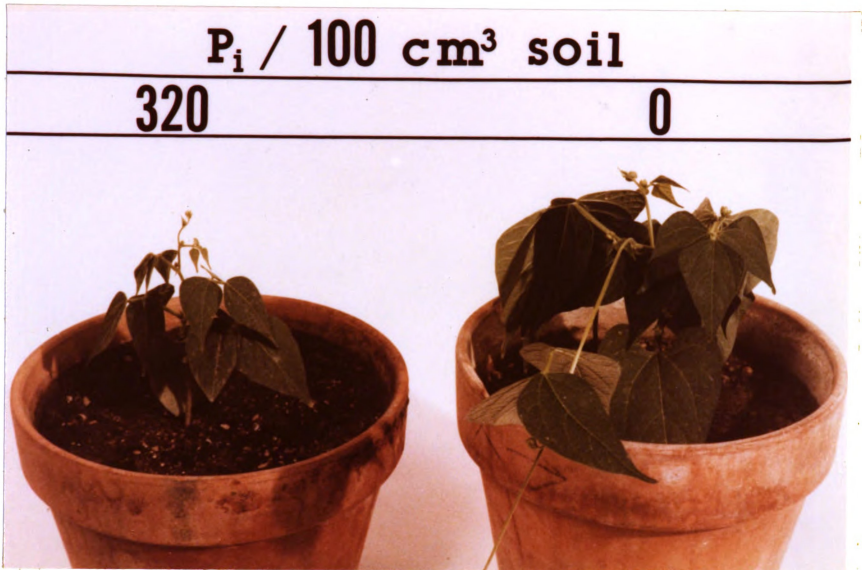


Figure 3.49

Figure 3.50. Influence of different initial population densities of P. penetrans on relative growth rate of navy bean plants over the growth period.

Equations for the relationships between relative growth rate and accumulated degree days at base 10 C

Y = relative growth rate per week ; X = accumulated degree days.

P_i = initial soil population density of P. penetrans per 100 cm^3 soil.

$P_i = 0$ $\quad Y = 0.105434974483 + 0.00142888178201\ X - 0.000001991528545\ X^2 \quad (R^2 = 0.67)$

$P_i = 5$ $\quad Y = 0.0942405452017 + 0.00151169833398\ X - 0.000002072951014\ X^2 \quad (R^2 = 0.69)$

$P_i = 10$ $\quad Y = 0.0291013809244 + 0.00186911335134\ X - 0.000002266413232\ X^2 \quad (R^2 = 0.67)$

$P_i = 20$ $\quad Y = 0.116545193601 + 0.00129545095131\ X - 0.000001922417876\ X^2 \quad (R^2 = 0.58)$

$P_i = 40$ $\quad Y = 0.0450555327553 + 0.00172991654509\ X - 0.000002540119343\ X^2 \quad (R^2 = 0.63)$

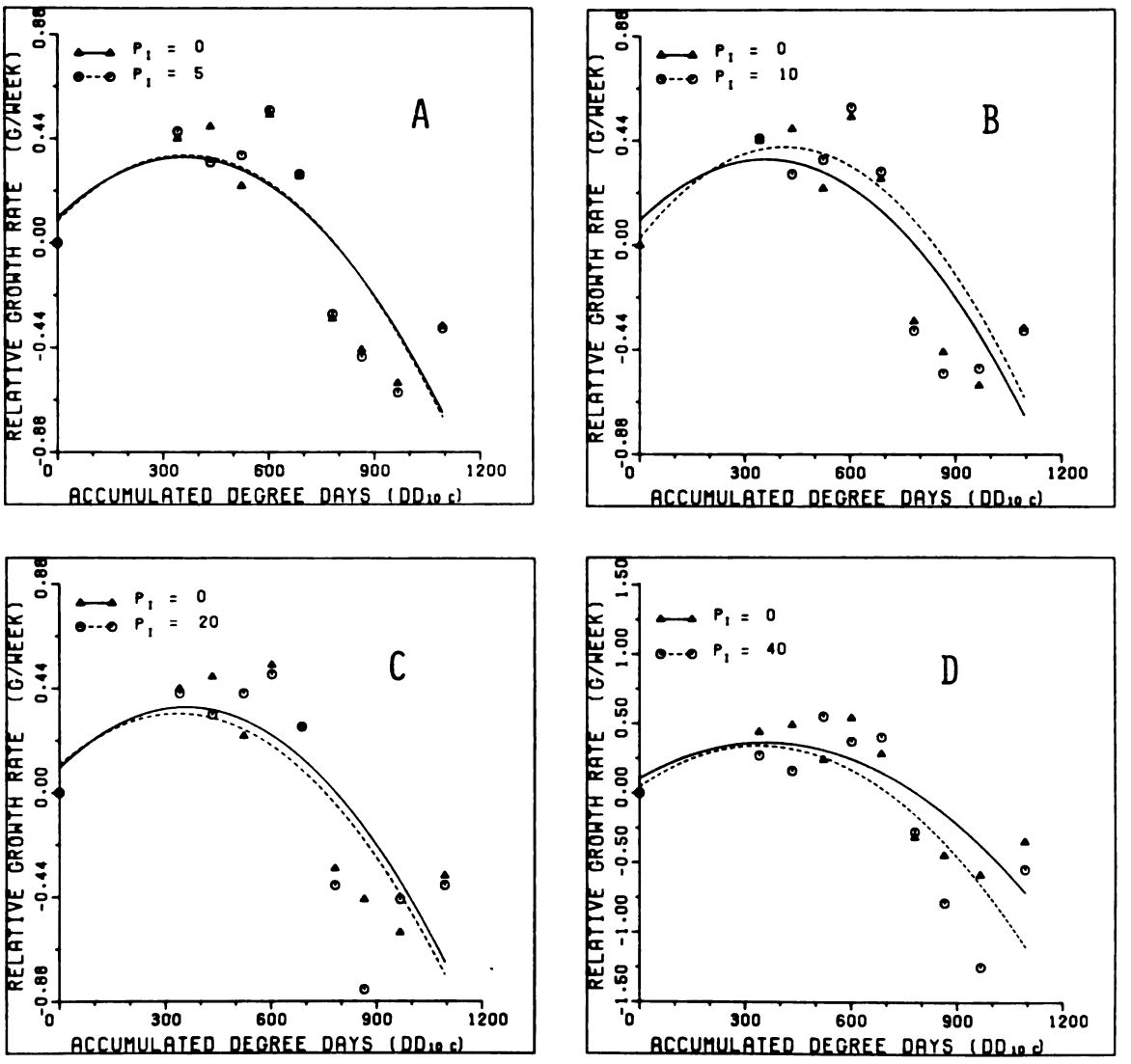

A
P_1 = 0
P_1 = 5
B
P_1 = 0
P_1 = 10
C
P_1 = 0
P_1 = 20
D
P_1 = 0
P_1 = 40
RELATIVE GROWTH RATE (G/WEEK)
ACCUMULATED DEGREE DAYS ($DD_{10\,C}$)
0.88
0.44
0.00
-0.44
-0.88
1.50
1.00
0.50
-0.50
-1.00
-1.50
0
300
600
900
1200

Figure 3.50.

Figure 3.51. Influence of different initial population densities of P. penetrans on relative growth rate of navy beans over the growth period.

Equations for the relationships between relative growth rate and accumulated degree days at base 10 C.

Y = relative growth rate per week; X = accumulated degree days

P_i = initial soil population density of P. penetrans per 100 cm^3 soil.

$P_i = 0$ $\quad Y = 0.105434974483 + 0.00142888178201\ X - 0.000001991528545\ X^2 \quad (R^2 = 0.67)$

$P_i = 80$ $\quad Y = 0.02864789416 + 0.00150419931867\ X - 0.000002090975285\ X^2 \quad (R^2 = 0.50)$

$P_i = 160$ $\quad Y = 0.\ 0.0362586010281 + 0.0012996133828\ X - 0.000001903869134\ X^2 \quad (R^2 = 0.59)$

$P_i = 320$ $\quad Y = 0.0128353084284 + 0.00161252592496\ X - 0.000002408870322\ X^2 \quad (R^2 = 0.73)$

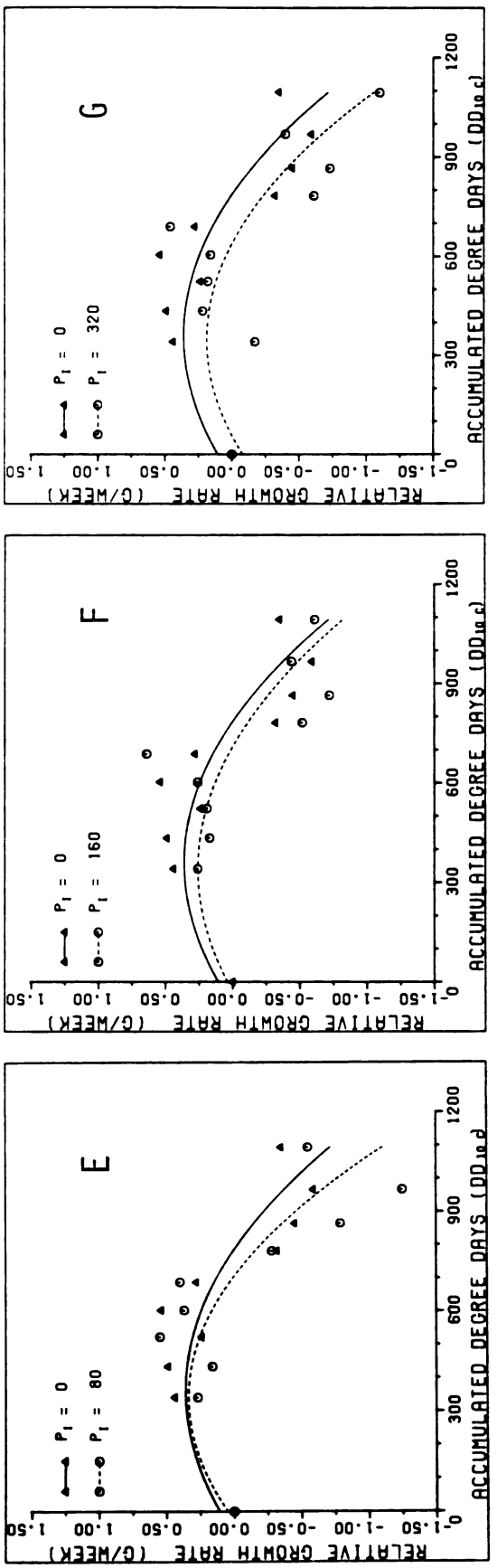

E
F
G
P_I = 0
P_I = 80
P_I = 160
P_I = 320
RELATIVE GROWTH RATE (G/WEEK)
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
ACCUMULATED DEGREE DAYS ($DD_{10\,C}$)
0
300
600
900
1200

Figure 3.51

$$Y = 0.0942405452017 + 0.00151169383398\ X - 0.000002072951014\ X^2 \quad (R^2 = 0.69)$$

This indicated the similarity in growth response between noninfected plants and plants exposed to an initial density of 5 P. penetrans per 100 cm^3 soil.

A comparison of relative growth rates of noninfected plants and plants exposed to an initial density of 10 P. penetrans per 100 cm^3 soil indicated that initially the relative growth rate of infected plants was lower than that of noninfected plants (Figure 3.50B). After 260 DD 10 C, however, the growth rate of infected plants increased above that of noninfected plants (Figure 3.50B). The differences in relative growth rates for these two treatments (0 and 10 P. penetrans per 100 cm^3 soil) are also evident from the equations for the relationships. For plants exposed to an initial density of 10 P. penetrans per 100 cm^3 soil the equation is:

$$Y = 0.0291013809244 + 0.00186911335134\ X - 0.000002266413232\ X^2 \quad (R^2 = 0.67)$$

and the equation for noninfected plants is:

$$Y = 0.105434974483 + 0.00142888178201\ X - 0.000001991528545\ X^2 \quad (R^2 = 0.67)$$

Comparison of the first terms of these two equations indicates the initial lower growth rate in infected plants,

while comparison of the second terms of the equations indicates the increase in relative growth rate in infected plants after 260 DD 10 C.

The relative growth rate of plants exposed to initial densities of 20 and 40 P. penetrans per 100 cm^3 soil respectively followed similar relative growth rate trends as that of noninfected plants from initial growth until 175 DD 10 C and 325 DD 10 C respectively. After these periods the relative growth rate of infected plants were lower than that of noninfected plants (Figures 3.50C, D).

The relative growth rate of plants exposed to an initial density of 80 P. penetrans per 100 cm^3 soil was slightly lower than that of noninfected plants (Figure 3.51E). Growth rates were similar at 300 DD 10 C following which the growth rate of infected plants remained lower than that of noninfected plants (Figure 3.51E). The relative growth rate of plants exposed to an initial density of 160 and 320 P. penetrans per 100 cm^3 soil respectively were lower than that of noninfected plants throughout the growth period (Figure 3.51F, G). For plants exposed to an initial density of 320 P. penetrans per 100 cm^3 soil the equation for the relationship between relative growth rate and accumulated degree days is:

$$Y = 0.0128353084284 + 0.00161252592496\ X - 0.000002408870322\ X^2 \quad (R^2 = 0.73)$$

and the equation for the relationship in noninfected plants is:

$$Y = 0.105434974483 + 0.0014288178201\ X - 0.000001991528545\ X^2 \quad (R^2 = 0.67)$$

Comparison of these two equations indicates the decrease in growth rate in plants exposed to an initial density of 320 P. penetrans per 100 cm^3 soil. Growth rates were lowest in plants exposed to the highest initial density of 320 P. penetrans per 100 cm^3 soil (Figure 3.51G).

3.3.5 Discussion

Studies on the pathogenicity of Pratylenchus penetrans on navy beans indicated that this plant parasitic nematode species can penetrate navy bean roots, feed and reproduce. The plant response to infection by this nematode varied depending on the bean variety and the initial population density of P. penetrans. The results of the study on pathogenicity (3.3.4.1) indicated that densities of P. penetrans above 25 per 100 cm^3 soil can affect the physiological functioning of plants resulting in detrimental growth and significant reduction in dry bean yield of Sanilac bean variety.

In this study the lowest initial population

density included in experimental procedures was 25 *P. penetrans* per 100 cm^3 soil. Examination of the regression of the log of initial density of *P. penetrans* on the log of final densities of *P. penetrans* indicated the necessity for studies involving lower initial densities of *P. penetrans*. The importance of initial population density in relation to final density and yield of plants has been stressed (Wallace, 1973; Oostenbrink, 1966; Seinhorst, 1966; Norton, 1978). The need to examine effects over the growth period was also evident. Evans, (1972) pointed out that in considering relationships between plants and their environments the complete cycle should be examined. Studies over time could assist in elucidating critical periods when some state of the environment, the pest and plant species interact to determine the functioning of the ecosystem.

Sanilac, Seafarer and Tuscola navy bean varieties were highly susceptible to infection by *P. penetrans*, while Gratiot, Kentwood and Saginaw varieties were more tolerant to infection by this nematode species. *P. penetrans* penetrated roots of all varieties and reproduced. The response to infection, however, differed among varieties, in that growth parameters such as plant height, root weight, and relative growth rate were not significantly decreased

in Gratiot, Saginaw and Kentwood varieties, while detrimental effects on these growth parameters were observed for Sanilac, Seafarer and Tuscola varieties.

The yield of dry beans from Sanilac, Seafarer and Tuscola varieties respectively were reduced by infection with P. penetrans while there was no significant decrease in yield from P. penetrans infected Saginaw, Gratiot and Kentwood varieties. All varieties were exposed to similar initial densities of 150 P. penetrans per 100 cm^3 soil. The lower population densities maintained on Saginaw, Gratiot and Kentwood varieties and the observation that these densities had no significant detrimental effect on growth and yield of these varieties indicate that these three varieties are to some extent tolerant to P. penetrans.

The plants' response to infection was such that the reproductive potential of P. penetrans was reduced on Saginaw, Gratiot and Kentwood varieties compared to the reproductive potential on Sanilac, Seafarer and Tuscola varieties respectively.

If the number of generations of P. penetrans is related to the number of maxima in population densities, three generations were evident on Sanilac, Seafarer and Tuscola varieties respectively and, two generations on

Saginaw varieties and one generation on Kentwood variety (Figure 3.28). However because of the overlapping nature of life cycles of P. penetrans the number of generations associated with a particular crop is not always determined by the number of maxima in population densities of P. penetrans.

The discovery of bean varieties tolerant to P. penetrans is critical for development of optimum integrated management strategies in bean production. The choice of variety however is dependent on other factors such as effects of other pests, yields and economics of production. For example while Gratiot bean variety is tolerant to P. penetrans it has not gained economic importance in Michigan, and this is related to the yields and time to maturity of bean seeds (Adams, 1978). In the study on responses of Sanilac navy beans to infection with different initial population densities of P. penetrans at different intervals during the growth period (3.3.2.1) the initial densities ranged from 5 to 320 P. penetrans per 100 cm^3 soil. The low range was chosen to observe effects which were not studied in the experiment on pathogenicity (3.3.1.1). Sanilac navy bean variety was chosen as it appeared to be highly susceptible to P. penetrans. The significance of initial

nematode density as a determining factor on yield and population dynamics of nematodes has been noted. Olthof and Potter (1973) observed a positive correlation between yield and initial density. Robbins et al. (1978) reported on an inverse relationship between yield and Pratylenchus spp.

A salient feature of the research findings is that low densities of P. penetrans can cause increases in plant growth. This was also evident from the study on pathogenicity (3.3.1.1) where root weight and root length of navy beans were increased by population densities of 25 P. penetrans per 100 cm^3 soil (Figure 3.25). Increased growth responses to infection by low densities of nematodes have been observed (Wallace, 1973), and is related to a resistance response of the plant to infection by P. penetrans.

The threshold density for damage was 40 P. penetrans per 100 cm^3 soil. The threshold density is however dependent on temperature, soil moisture and the associated host crop (Wallace, 1973; Norton, 1978). While all replicates of treatments did not respond to the same degree, typical responses are evident in Figures 3.36, 3.41, 3.48 & 3.49 Some degree of stunting was observed but this is not always evident in the field.

The periods of sampling were converted to degree

days as this concept of degree days allows for correlation between a physiological determination factor of temperature with physiological development of plants and organisms.

The relative growth rate of plants was studied by sampling at close intervals during the growth period. Because of the small size of plants, changes over one day periods would not be measurable hence the choice of weekly sampling intervals. Examination of relative growth rates allows broad generalized observations on the growth pattern of plant species over time. Relative growth rate is a physiological growth index and examination of the relationship between this growth index and a physiological time parameter of degree days is appropriate as the growth of plants is influenced to a large extent by temperature. There are however practical difficulties associated with the use of the physiological index of relative growth rate (Evans, 1972). In practice it is not possible to use the same plant to determine initial dry weight and final dry weight for any two growth or sampling periods. This requires use of two different plants which may not be identical in growth form and genetic makeup. The use of large numbers of replicates and uniform genetic planting material can, however reduce the error associated with application of relative growth rates.

The results from studies on relative growth rate indicated that generally at low population densities of P. penetrans, relative growth rates were initially lower than in noninfected plants, but with time the P. penetrans infected plants were able to overcome the detrimental effects associated with infection by P. penetrans and relative growth rates were similar in P. penetrans infected and noninfected bean plants during the latter phases of plant growth. Exceptions to this were observed. In one case infection by low densities of 10 P. penetrans per 100 cm^3 soil increased the relative growth rate of bean plants (Figure 3.50B). This could be related to a resistance response of the plant to infection. At high densities relative growth rate was generally lower in infected plants throughout the growth period. Relative growth rate responses vary depending on the plant species. Slinger (1976) observed initial decreases followed by increases and then further decreases in relative growth rate of carrots (Daucus carota L) over the growth period. The initial decrease however can be correlated with changes in source-sink relationships associated with formation of the tap root. For navy beans relative growth rate initially increased reaching a peak during the growth period and then decreased at the onset of senescence.

3.4 Influence of Environmental parameters of Temperature and Moisture

3.4.1 Influence of Temperature

Growth, development and activity of organisms are influenced by temperature. For most organisms there is a threshold temperature below which reproduction and development cannot take place, and above which detrimental effects on growth results. Temperature can be considered as a source of heat units or energy available to facilitate biological processes. The following studies were designed to examine the effect of temperature on P. penetrans associated with navy beans.

3.4.1.1 Effect of different temperatures and different initial densities of Pratylenchus penetrans on growth and yield of navy beans and on final population densities of Pratylenchus penetrans

3.4.1.1.1 Method

The experiment consisted of a 2 x 2 factorial design of three replicates of four treatments of P. penetrans at four temperatures. P. penetrans treatments included densities of 0, 25, 150 and 300 per 100 cm^3 soil. Temperatures studied included 15, 20, 25 and 30. Forty-eight 2.36 cm clay pots were filled with 1000 cm^3 sterilized

sandy clay loam soil. Four temperature control chambers were arranged to hold 12 of these clay pots respectively. The temperature control chambers were maintained at 15, 20, 25 and 30 C respectively. P. penetrans were extracted from roots of Sanilac navy bean plants propagated in culture boxes in the greenhouse. A suspension containing a calculated density of P. penetrans was prepared. The appropriate densities for this study were added to the soil in pots by extracting calculated aliquants of the suspension and transferring these to the soil in pots. Three navy bean seeds were planted in the soil in each pot. Two days after germination, plants were thinned out leaving one seedling in the soil in each pot. Plants were watered daily as required and maintained in the temperature chambers in the greenhouse for a period of 96 days. Plant height, shoot dry weight, root weight and dry bean yield were recorded after this period. Soil and root samples were taken for nematode analyses (3.1.1.2 and 3.1.2.2) and P. penetrans densities were determined (3.1.3-3.1.4).

3.4.1.2 Interactions of temperature and *P. penetrans* associated with navy beans over the growth period

3.4.1.2.1 Method

A 2 x 2 factorial design of three replicates of two densities of *P. penetrans* (0 and 150 per 100 cm^3 soil) and four temperatures (15, 20, 25 and 30 C) was used in this study. Twenty-four 2.36 cm clay pots containing 1000 cm^3 sandy clay loam soil were arranged in each of the four temperature chambers maintained at 15, 20, 25 and 30 C respectively. *P. penetrans* were extracted from roots of navy bean plants which were propagated in culture boxes in the greenhouse. A suspension containing a calculated density of *P. penetrans* was prepared. Calculated aliquants of this suspension were added to soil in 12 of these pots to obtain an initial population density of 150 *P. penetrans* per 100 cm^3 soil. The soil in the other 12 pots served as controls. Three navy bean seeds cv Sanilac were planted in the soil in each pot. Plants were thinned out three days after germination leaving one seedling in the soil in each pot. Plants were watered daily and maintained at the 15, 20, 25 and 30 C respectively in the greenhouse for a period of 91 days.

Shoot fresh weight, leaf area, plant height, root

area, root weight and root length were recorded at four intervals during the growth period. Shoot systems were oven dried at 30 ± 5 C and shoot dry weight was recorded. Dry bean yield was recorded after the 91 day growth period. Soil and root samples were taken at 4 intervals for nematode analysis (3.1.1.2 and 3.1.2.2) and P. penetrans densities were determined (3.1.3-3.1.4).

3.4.1.3 Results

3.4.1.3.1 Effect of different temperatures and different initial densities of P. penetrans on growth and yield of navy beans and on final population densities of P. penetrans

Final soil population densities of P. penetrans were lower than root densities (Figure 3.52; Tables A9-A11). Population densities increased with increase in temperature reaching maximum densities at 25 C and then decreasing above this temperature (Figures 3.52-3.53). The highest densities were associated with soil infested with the highest initial density of 300 P. penetrans per 100 cm^3 soil. Interactions of temperature and P. penetrans had a significant effect on final population densities (Figure 3.53). For all sampling periods and at all temperatures the highest percent of the population cohort consisted of females (Table 3.12). The percentage of

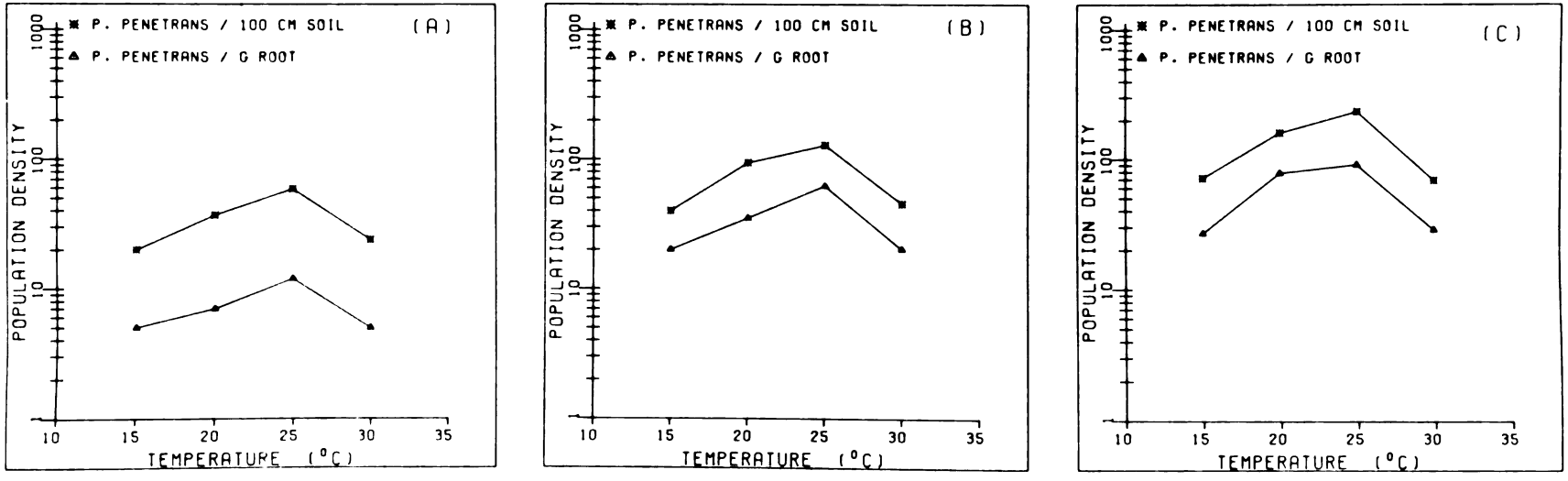


Figure 3.52. Influence of temperature on population densities of P. penetrans associated with navy beans.
(A) = initial density of 25 P. penetrans per 100 cm^3 soil
(B) = initial density of 150 P. penetrans per 100 cm^3 soil
(C) = initial density of 300 P. penetrans per 100 cm^3 soil

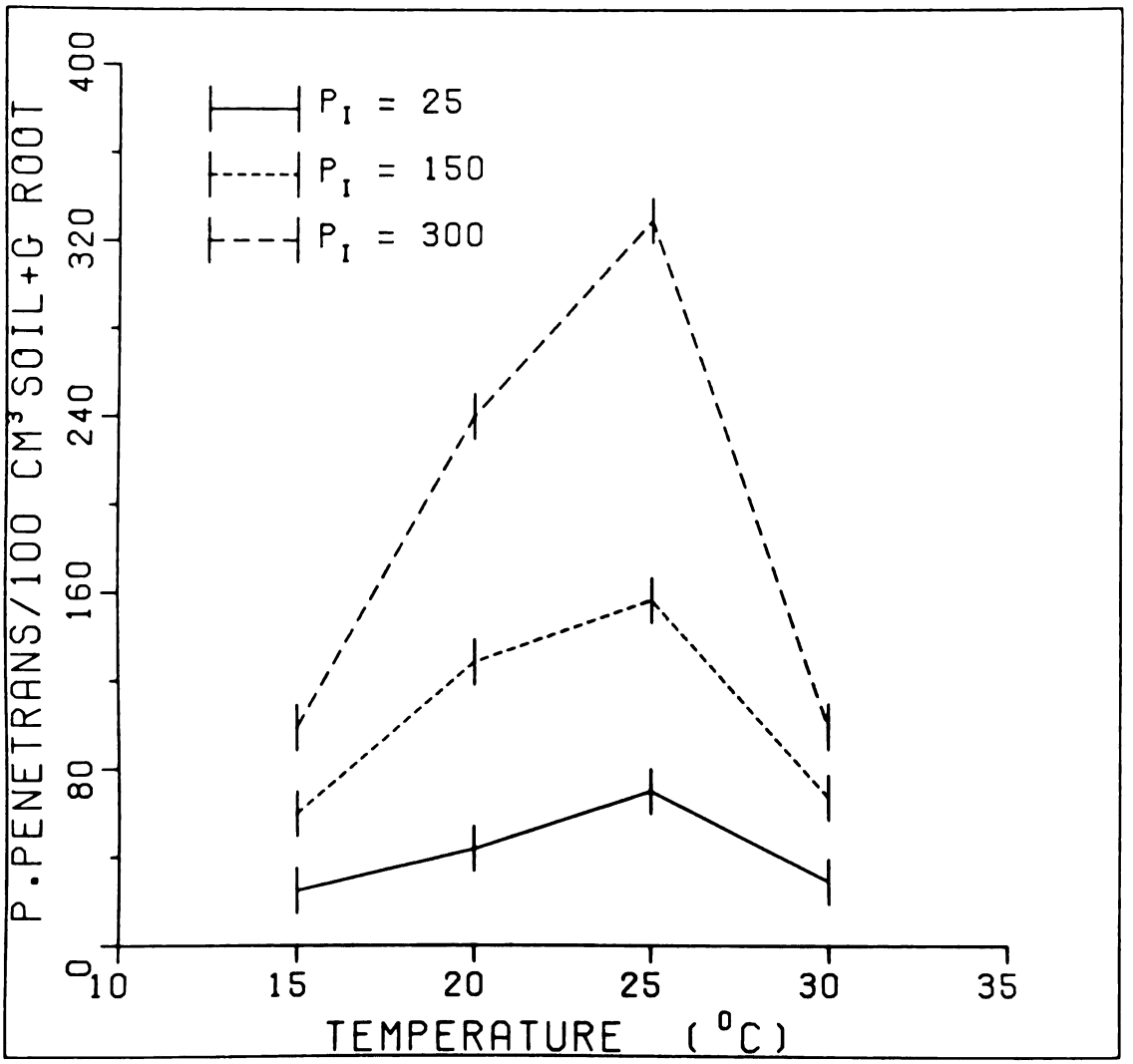


Figure 3.53. Influence of temperature on final total (root + soil) densities of P. penetrans associated with navy bean plants exposed to different initial population densities of P. penetrans.

Table 3.12 Influence of temperature on population cohort of P. penetrans associated with navy beans

Temp	Time	Life cycle stage (percent of population) F	M	2nd	3rd	4th
15	14	45.9	14.2	9.2	8.2	22.4
	35	51.5	16.5	10.3	7.2	14.4
	57	49.1	10.3	16.4	7.8	16.3
	92	44.2	12.2	3.9	5.5	34.2
20	14	41.7	14.4	18.2	6.1	17.6
	35	46.3	16.1	16.8	5.4	15.4
	57	44.5	15.1	19.4	10.5	10.4
	92	40.2	10.2	12.0	8.1	29.5
25	14	45.4	15.4	15.3	5.4	18.9
	35	39.3	20.8	17.3	9.2	13.3
	57	39.0	19.0	17.0	10.6	14.2
	92	45.8	10.7	4.3	6.3	32.9
30	14	33.3	16.7	25.6	7.7	16.7
	35	40.9	12.5	19.3	12.5	14.8
	57	32.7	10.2	24.5	16.3	16.2
	92	41.6	11.5	8.8	8.7	29.2

F = female

M = male

males was generally three times lower than that of females. At the end of the growth period the order of magnitude of the population cohort was females > fourth stage juveniles > males > third stage > second stage at 15 C. At 20 C the order of magnitude was females > fourth stage juveniles > second stage juveniles > males > third stage juveniles. At 25 C the order was females > fourth stage juveniles > males > third stage juveniles > second stage juveniles, and at 30 C the order was females > fourth stage juveniles > males > second stage juveniles > third stage juveniles (Table 3.12).

Plant height, root weight, shoot dry weight and dry bean yield were significantly (P = 0.05) influenced by interactions of temperature and P. penetrans (Tables A12-A14). Plant heights increased with increase in temperature (Figure 3.54). There was no significant (P = 0.05) difference in plant height of noninfected plants and plants exposed to an initial density of 25 P. penetrans per 100 cm^3 soil at temperatures of 15 and 25 C respectively (Figure 3.54A). Plant height was significantly (P = 0.05) reduced by population densities of 150 and 300 P. penetrans per 100 cm^3 soil at temperatures of 15, 20 and 30 C respectively (Table A12).

Shoot dry weight was significantly (P = 0.05) reduced by all densities of P. penetrans at the four

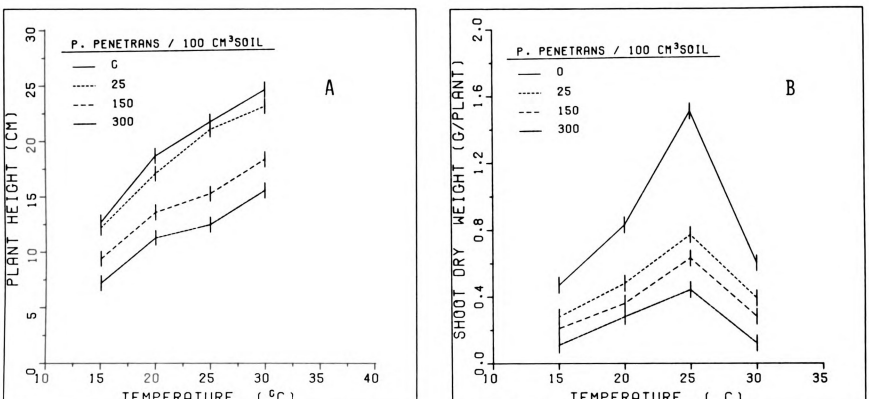


Figure 3.54. Effect of temperature on height (A) and shoot dry weight (B) of navy bean plants exposed to different initial densities of P. penetrans.

temperatures studied. For all temperatures dry weight increased with increase in temperature reaching maxima at 25 C and then decreasing (Figure 3.54B; Table A14).

There was no significant (P = 0.05) difference in root weight of noninfected plants and plants exposed to an initial density of 25 P. penetrans per 100 cm^3 soil at all four temperatures (Figure 3.55; Table A13). Root weight was significantly (P = 0.05) reduced by higher densities of 150 and 300 P. penetrans per 100 cm^3 soil at all four temperatures (Figure 3.55). Root weight increased with increase in temperature reaching maxima at 25 C and then decreasing with further increase in temperature (Figure 3.55).

Dry bean yields were significantly reduced by the highest density of 300 P. penetrans per 100 cm^3 soil at 15 C. At 20 and 25 C yields were reduced by all population densities while at 30 C yields were reduced by 150 and 300 P. penetrans per 100 cm^3 soil (Figure 3.56; Table A15). Dry bean yields increased with temperature in noninfected and infected plants reaching maxima at 25 C and then decreased with further increase in temperature (Figure 3.56).

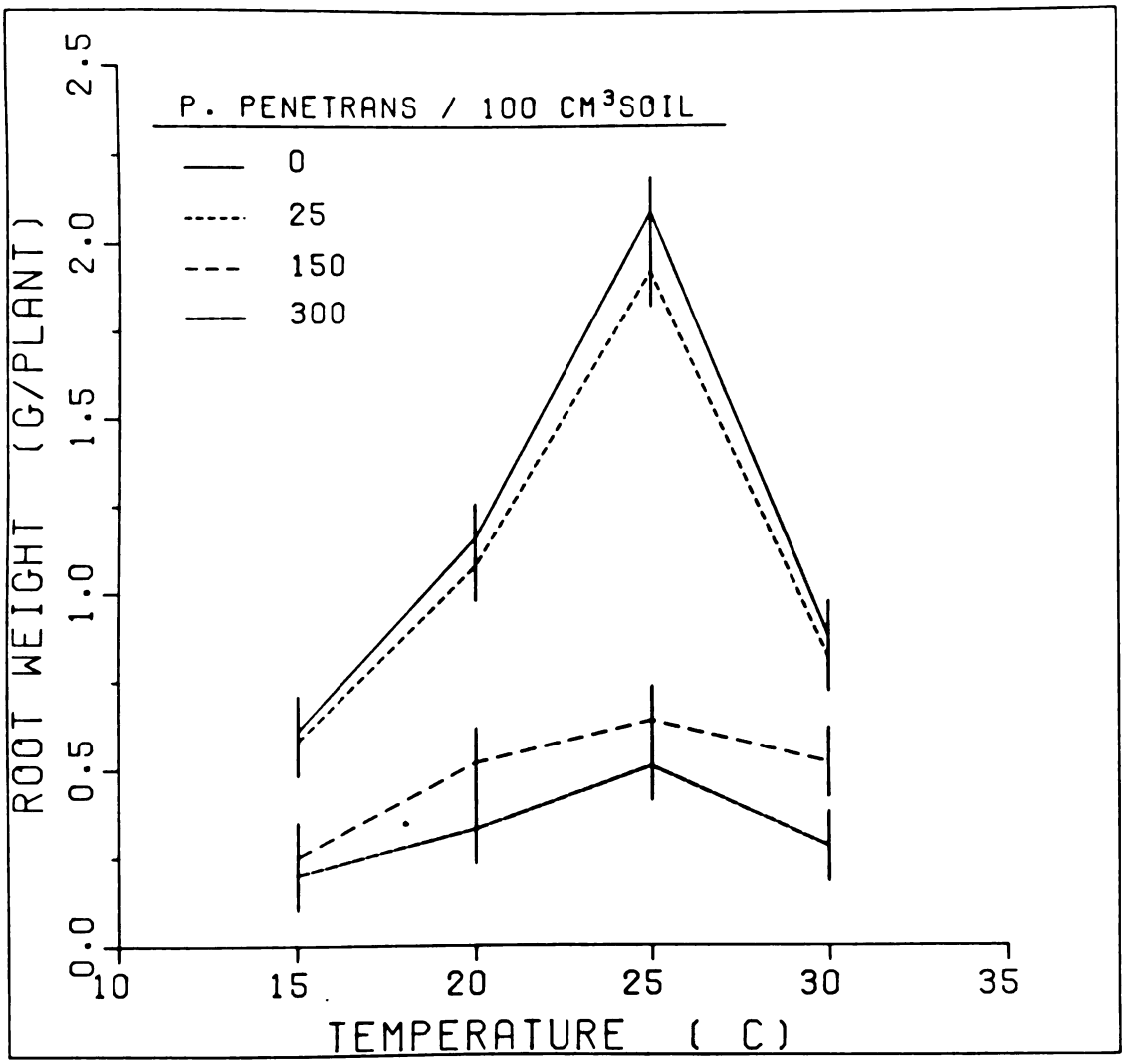


Figure 3.55. Effect of temperature on root weight of navy bean plants exposed to different initial densities of P. penetrans

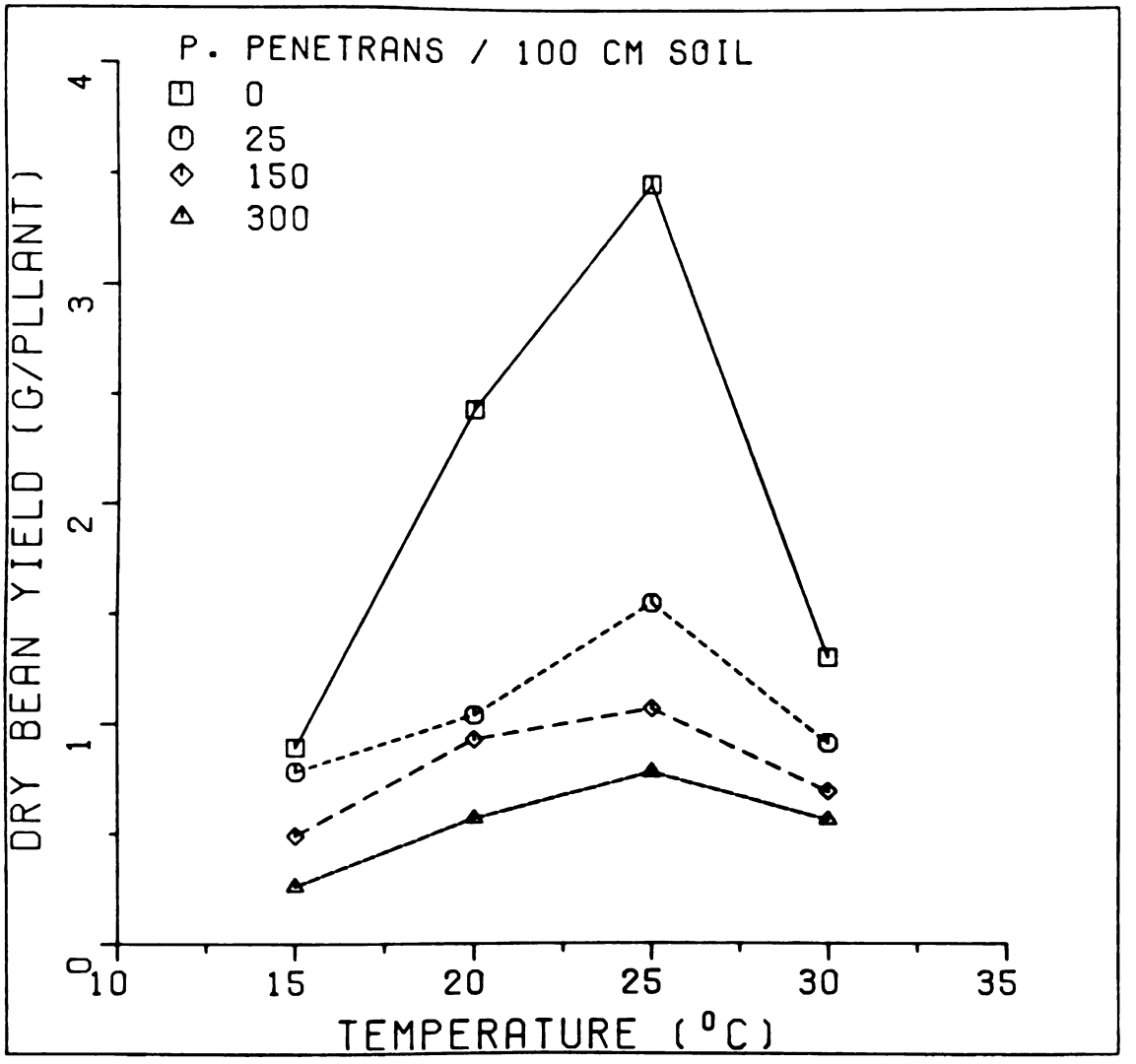


Figure 3.56. Effect of temperature on yield of navy bean plants exposed to different initial densities of P. penetrans

3.4.1.3.2 Interactions of temperature and *P. penetrans* associated with navy beans over the growth period

Total population densities of *P. penetrans* steadily increased from day 12 to day 91 of the growth period at temperatures of 15, 20 and 25 C respectively (Figure 3.57; Table A16). At 30 C total population densities increased reaching maxima at day 35 of the growth period. Soil population densities of *P. penetrans* decreased initially as nematodes entered roots and later increased as nematodes migrated from decaying roots into the soil at the end of the growth period (Tables A17-A18).

Shoot dry weight was significantly reduced by *P. penetrans* at harvest at all temperatures (Figure 3.58; Table A19). Dry weight increased over the growth period reaching maxima at 57 days of growth and then decreased (Figure 3.59) after this period.

Root area of noninfected and infected plants increased over the growth period reaching maxima at 57 days of growth (Figure 3.60; Table A20). *P. penetrans* decreased root area at temperatures of 15, 20 and 25 C respectively (Figure 3.60; Table A20).

Root weight, plant height, shoot fresh weight, root length and leaf area were significantly ($P = 0.05$)

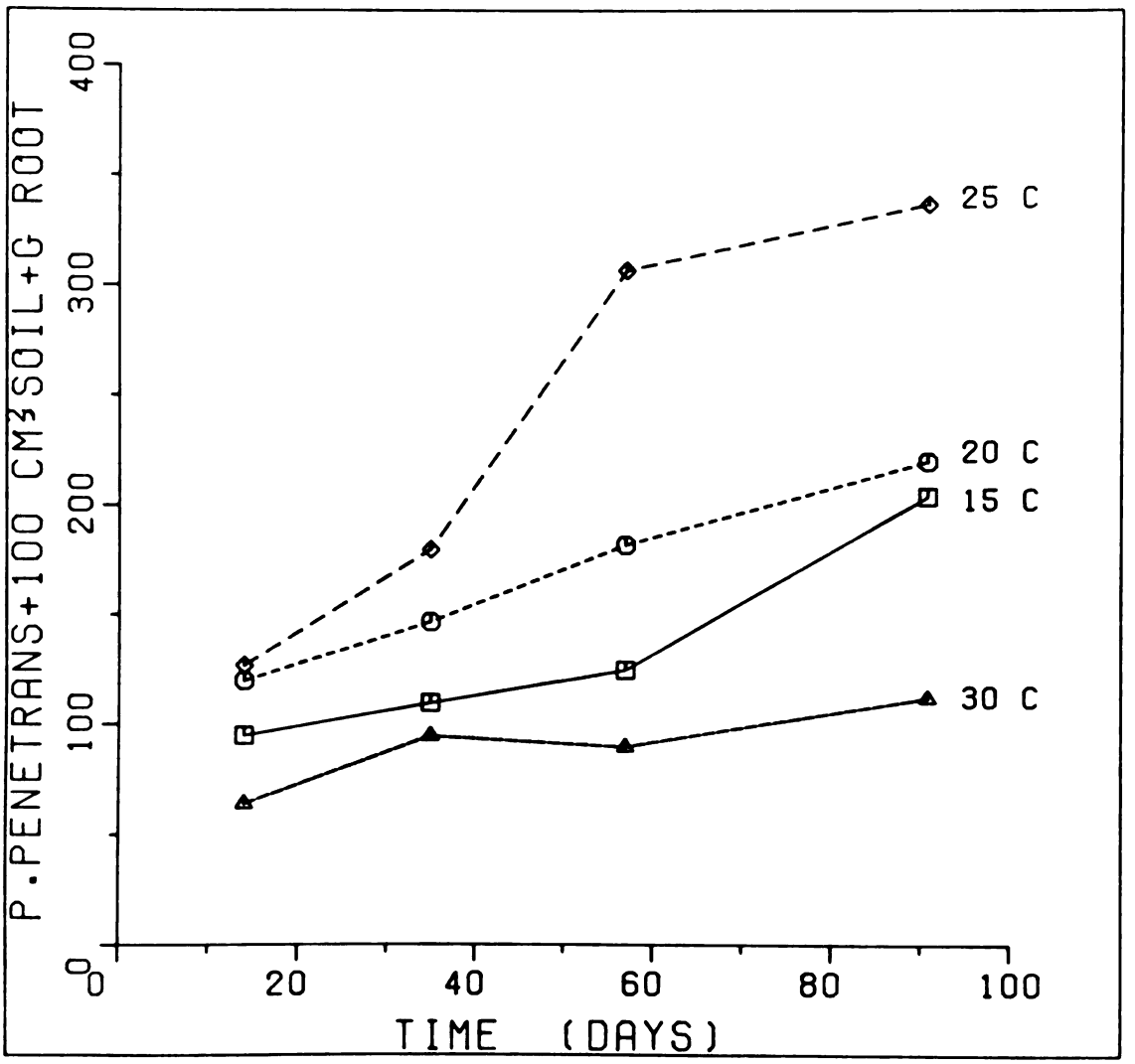


Figure 3.57. Influence of temperature on population dynamics of P. penetrans over the growth period of navy beans.

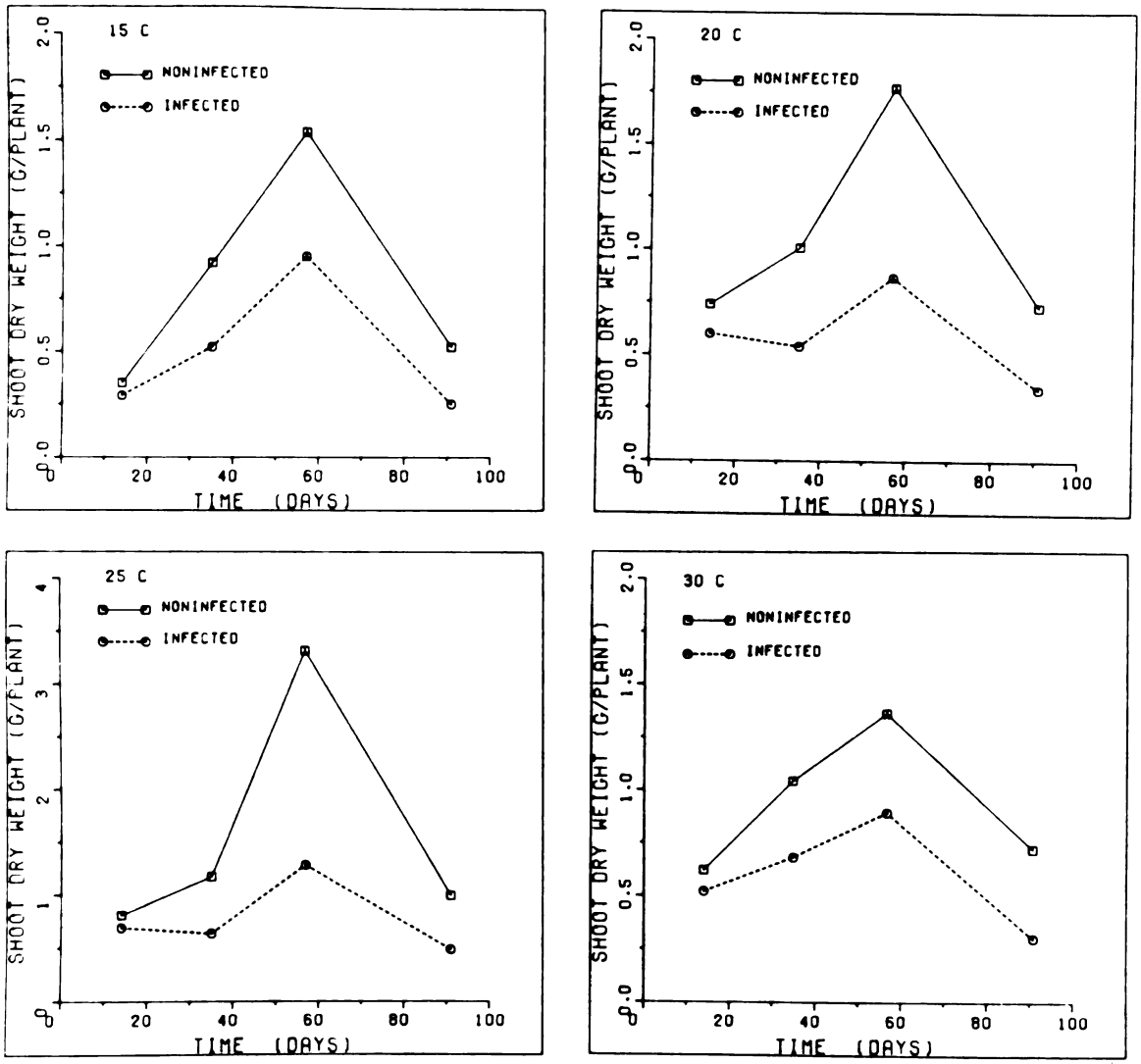


Figure 3.58. Effect of P. penetrans on shoot dry weight of navy beans over the growth period at four temperatures.

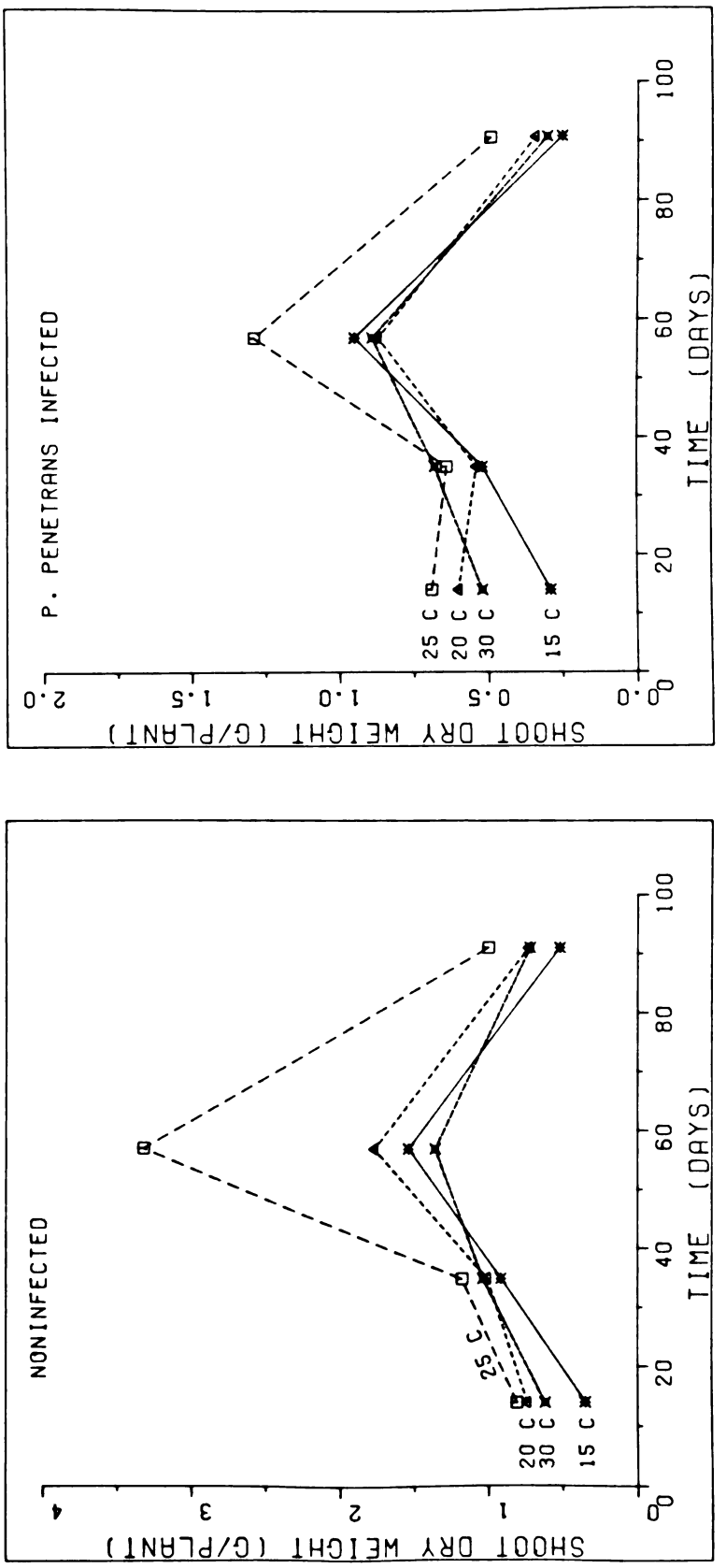


Figure 3.59. Effect of temperature on shoot dry weight of noninfected and P. penetrans infected navy bean plants over the growth period.

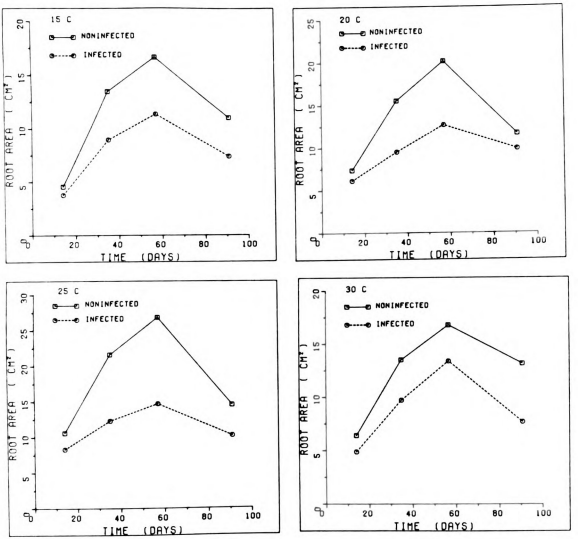


FIgure 3.60. Effect of P. penetrans on root area of navy bean plants over the growth period at four temperatures.

reduced by P. penetrans at 57 days of growth (Tables A21-A25).

Dry bean yield was significantly (P = 0.05) reduced by P. penetrans at all temperatures (Figure 3.61). Dry bean yield of noninfected plants increased with increase in temperature reaching maxima at 25 C. Dry bean yield was significantly (P = 0.05) lower at 30 C compared to yields at 20 and 25 C (Figure 3.61).

3.4.1.4 Discussion

The importance of the influence of temperature on growth, reproduction and infection of nematodes has been noted and several reports on effects of temperature on growth and development of nematodes and effects on plant growth and yield have been documented (Chapman, 1957; Patterson et al. 1967; Mamiya, 1971; Radewald et al. 1971; Wallace, 1973; Dunn, 1973; Miller and Rich, 1974; Acosta and Malek, 1979; Malek, 1980).

The results of studies on effects of temperature on P. penetrans and effect on growth of navy beans indicated that temperature significantly influenced P. penetrans effect on navy beans. Lower population densities associated with navy beans at 15 C indicated lower development and reproduction at this temperature. This suggests that 15 C is below the threshold temperature for development and

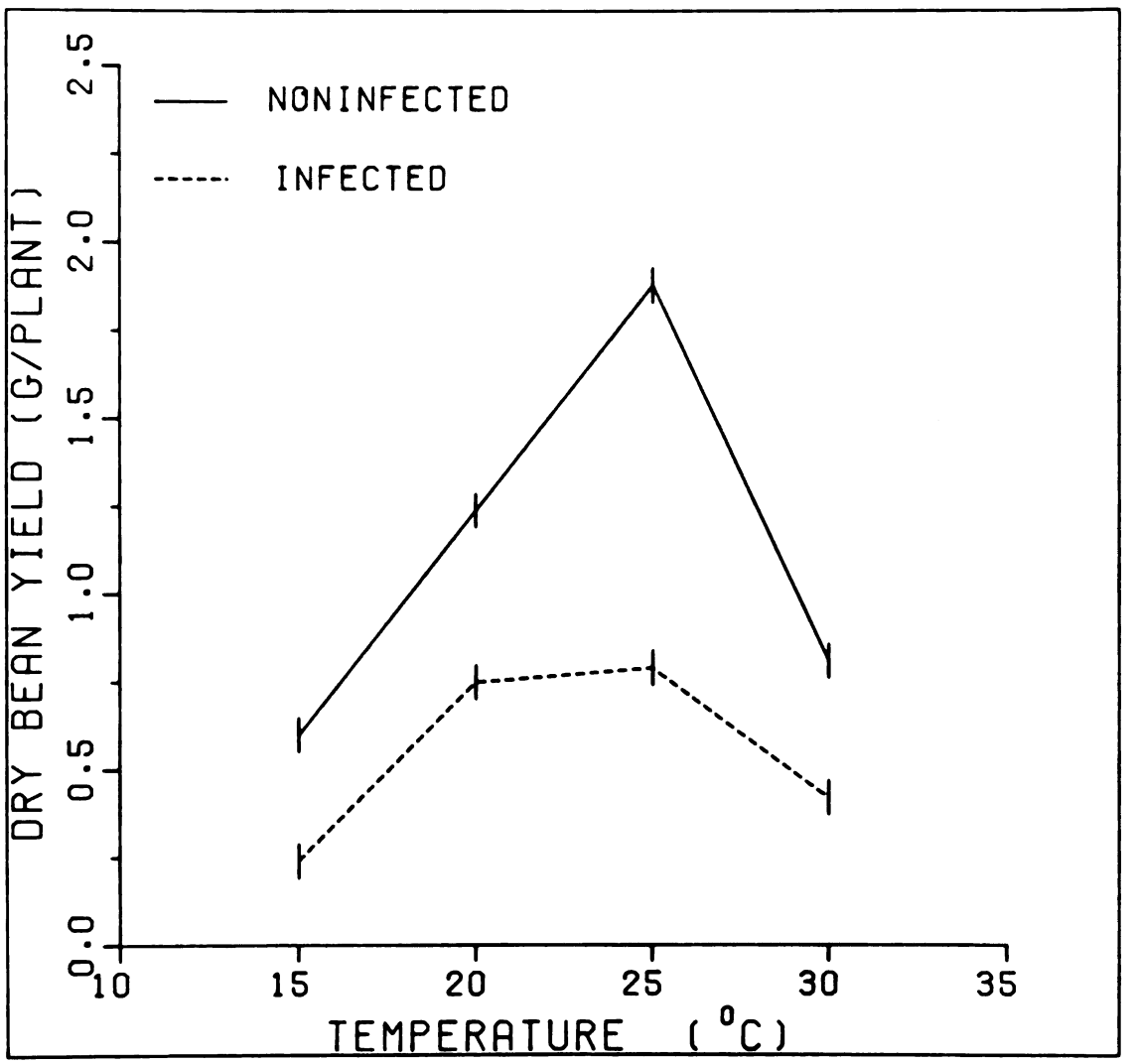


Figure 3.61. Influence of temperature on yield of noninfected and P. penetrans infected navy beans.
Vertical bars represent 95 % confidence intervals.

reproduction of P. penetrans associated with navy beans. Higher population densities were observed at 20 and 25 C compared to densities at other temperatures. The highest population densities were observed at 25 C and this indicates that this temperature is optimum for development and reproduction of P. penetrans on navy beans. Acosta and Malek (1979) observed similar responses of maximum densities of Pratylenchus penetrans and P. vulnus associated with soybeans. Decreases in population densities of P. penetrans at 30 C were observed and similar responses were observed by Mamiya (1971), who observed reduced oviposition at temperatures of 30 C compared to oviposition at 20-24C.

Population densities of P. penetrans increased with time at all temperatures. The fluctuations in densities observed in previous studies were not evident, and this is related to the choice of sampling date. Limitations in space in temperature control chambers dictated the number of pots which could be utilized in this study and consequently influenced the number of sampling periods. The four sampling intervals chosen appeared to correspond to maxima in population densities. In order to obtain detailed responses on population dynamics of P. penetrans associated with navy beans it is necessary to sample as often as

possible with a minimum of six sampling periods.

The higher densities associated with navy beans at a temperature of 25 C is related in part to the greater availability of food from larger root systems formed at this optimum growth temperature. Poor plant growth and smaller root systems with less food source could be responsible in part for the lower densities observed at 15 and 30 C respectively. The nature of the population cohort was also influenced by temperature. The proportion of second stage juveniles increased over the growth period indicating reproduction was taking place. Final population densities consisted generally of higher percentages of females and fourth stage juveniles compared to other stages. This could be related to the ability of these stages to withstand adverse effects of toxins from decaying roots to a greater extent than other younger stages and males.

The detrimental effect of high and low temperatures on physiological processes in plants contributed to decreases in bean yields. Metabolic processes which promote assimilation of carbohydrates for plant growth and transport of these products are temperature dependent (Leopold, 1964), and at low temperatures the enzyme and hormonal systems which initiate and maintain these processes may not function efficiently.

The influence of temperature on P. penetrans and effects on navy beans is important for the development of nematode control strategies in navy bean production. The recommended planting date for navy beans in Michigan is late May to early June. At this time in Michigan temperatures range from 15 to 18 C. At these temperatures population densities are maintained at low densities due to the lower reproductive potential and high mortality. The percentage of crop loss is dependent on the initial density of P. penetrans, therefore crop losses can be minimized in the presence of low initial densities of P. penetrans. The choice of an early planting date when densities are low can be considered as an effective control strategy. The choice of planting date is, however, influenced by other factors besides optimum temperature for low densities of P. penetrans as optimum temperatures for germination significantly influences yield.

3.4.2 Influence of Soil Moisture

Soil moisture is an important environmental parameter which influences the growth and development of plants, nematodes and other organisms. Soil moisture is highly dependent on soil type. Nematode activity occurs mainly in the thin film of water surrounding soil particles and through pore spaces, therefore, soil moisture and pore space which are influenced by soil type are critical for survival of nematodes. This study was designed to examine the interactions of soil type, soil moisture and P. penetrans associated with navy beans.

3.4.2.1 Development of soil moisture characteristic curves for three soil types

3.4.2.1.1 Method

In this experiment the volumetric percentage of moisture associated with four matrix potentials was determined in order to develop soil moisture characteristic curves for a sandy clay loam, a sandy loam and a clay loam respectively. Two replicates of 10 cm soil cores were prepared for each soil type. The soil cores were placed in a tray containing water and allowed to become saturated. The saturated soils were then subjected to pressures of 4, 30, 100 and 1500 centibars. The soils were weighed

prior to saturation with water. After moisture was removed from the soils at the respective pressures soils were reweighed. Soil cores were then oven dried at 105 C and reweighed. The percentage moisture associated with each pressure was calculated for each soil type (3.1.9). Soil moisture characteristic curves for each soil type were developed by plotting percent soil moisture versus matrix potential in negative centibars where soil matrix potential corresponded to pressures of 4, 30, 100 and 1500 centibars.

3.4.2.2 Interactions of soil type, soil moisture and P. penetrans associated with navy beans

3.4.2.2.1 Method

The experiment consisted of a three factorial design of three replicates of two levels of P. penetrans (0 and 150 per 100 cm^3 soil) at six moisture levels corresponding to soil matrix potentials of 5, 10, 50, 100, 500 and 1000 negative centibars, in three soil types including a sandy clay loam, a sandy loam and a clay loam (Table 3.13). Fifty-four 1 liter wax lined polythene cups were filled with 1000 cm^3 of each soil type. Soils were adjusted to the desired matrix potentials (Table 3.13C) by weighing soils in cups and adding calculated

Table 3.13A Volumetric soil moisture content as related to matrix potential

Matrix potential (-centibars)	Volumetric percent moisture		
	Clay loam	Sandy clay loam	Sandy loam
0	58.99	53.33	36.06
4	50.83	35.66	30.35
30	48.48	30.72	24.18
100	45.11	28.53	19.34
1500	40.10	26.82	13.53

Table 3.13B Mechanical composition of soils

	Clay loam	Sandy clay loam	Sandy loam
% clay	36.52	22.52	18.88
% silt	32.36	11.08	13.44
% sand	31.12	66.40	67.68

Table 3.13C Percent soil moisture associated with different matrix potentials

Matrix potential (-centibars)	Volumetric percent moisture		
	Clay loam	Sandy clay loam	Sandy loam
5	48	33	25
10	47	31	25
50	44	27	21
100	45	28	19
500	39	26	15
1000	38	25	14

quantities of water required to adjust soil water content to the desired matrix potentials. The soil in these cups was sterilized initially and served as noninfested P. penetrans soil.

Fifty-four similar polythene cups were filled with sterilized soil from each soil type to give 18 cups of each soil type (three replicates for each treatment). A suspension containing a calculated density of P. penetrans was prepared by extracting P. penetrans from navy bean roots propagated in culture boxes in the greenhouse. Calculated aliquants of this suspension of nematodes were pipeted in to the soil in these cups to give initial densities of 150 P. penetrans per 100 cm^3 soil. Soils were adjusted to the desired moisture potentials by weighing and adding calculated quantities of water (Table 3.13C).

Two navy bean seeds cv Sanilac were planted in the soil in each cup. Plants were thinned out leaving one seedling in the soil in each cup. Soils were maintained at the desired moisture potentials by weighing to an accuracy of 1.0 g, and adding appropriate quantities of water. Plant height, shoot dry weight, root area, root length and weight were recorded after 92 days of growth. Dry bean yield was determined at the end of the period. Soil and root samples were taken for nematode

analyses (3.1.1.2 and 3.1.2.2) and P. penetrans densities were determined (3.1.3-3.1.4).

3.4.2.3 Effect of interactions of soil type, soil moisture and initial population densities of P. penetrans on growth and yield of navy beans and on population densities of P. penetrans

3.4.2.3.1 Method

The experiment consisted of a 3x3x4 factorial design of three replicates of three soil types at three moisture levels with four initial population densities of P. penetrans. The soil types included a sandy clay loam, a clay loam and a sandy loam. The soil moisture levels corresponded to matrix potentials of 5, 50 and 1000 negative centibars respectively. Initial densities of P. penetrans included 0, 25, 150 and 300 P. penetrans per 100 cm^3 soil.

Three hundred and twenty-four wax-lined polythene cups were filled with 1000 cm^3 of the appropriate soil type to obtain the desired number of replicates. A suspension of P. penetrans was prepared by extracting nematodes from navy bean roots propagated in culture boxes in the greenhouse. The desired densities (25, 150 and 300 P. penetrans per 100 cm^3 soil) were added to the soil by

transferring aliquants of this suspension to the soil in appropriate cups. One hundred and eight wax lined polythene cups were filled with steam sterilized appropriate soil types to obtain the desired number of replicates. These soils served as controls containing a density of 0 P. penetrans per 100 cm^3 soil. Soils were adjusted to the desired moisture levels and maintained at these levels by weighing and adding water as required (Table 3.13). Two bean seeds were planted in the soil in each cup. Plants were thinned out leaving one seedling in the soil in each cup. Plant height, leaf area, shoot dry weight and root weight were recorded at four intervals during the growth period of 94 days. Dry bean yield was determined after this period. Soil and root samples were taken for nematode analyses (3.1.1.2 and 3.1.2.2) and P. penetrans densities were determined (3.1.3-3.1.4).

3.4.2.4 Results

3.4.2.4.1 Development of soil moisture characteristic curves for three soil types

The soil moisture characteristic curves developed for the three soil types indicated that the percent soil moisture increased in the order of sandy loam > sandy clay loam > clay loam. High moisture content was

associated with the clay loam even at a matrix potential of -1000 centibars (Figure 3.62).

3.4.2.4.2 Interactions of soil type, soil moisture and P. penetrans associated with navy beans

Final root population densities of P. penetrans were significantly influenced by interactions of soil type and soil moisture (Figure 3.63; Tables A26-1-A26-5). Population densities were lowest in the clay loam and highest in the sandy loam (Figure 3.63). Densities of P. penetrans were lowest at a matrix potential of -1000 centibars (Figure 3.63A, C). Population densities were highest at a matrix potential of -50 centibars in all soil types (Figure 3.63A, C).

Soil population densities of P. penetrans were also low at a matrix potential of -1000 centibars increasing with increase in soil moisture at a matrix potential of -50 centibars and then decreasing at high soil moisture levels corresponding to -5 centibars (Figure 3.64B, C). Final densities of P. penetrans in soil were influenced by interactions of soil type and soil moisture (Figure 3.64; Tables A27-1-A27-5). Population densities were significantly (P = 0.05) lower in the clay loam compared to densities in the other soil types (Figure 3.64A, B;

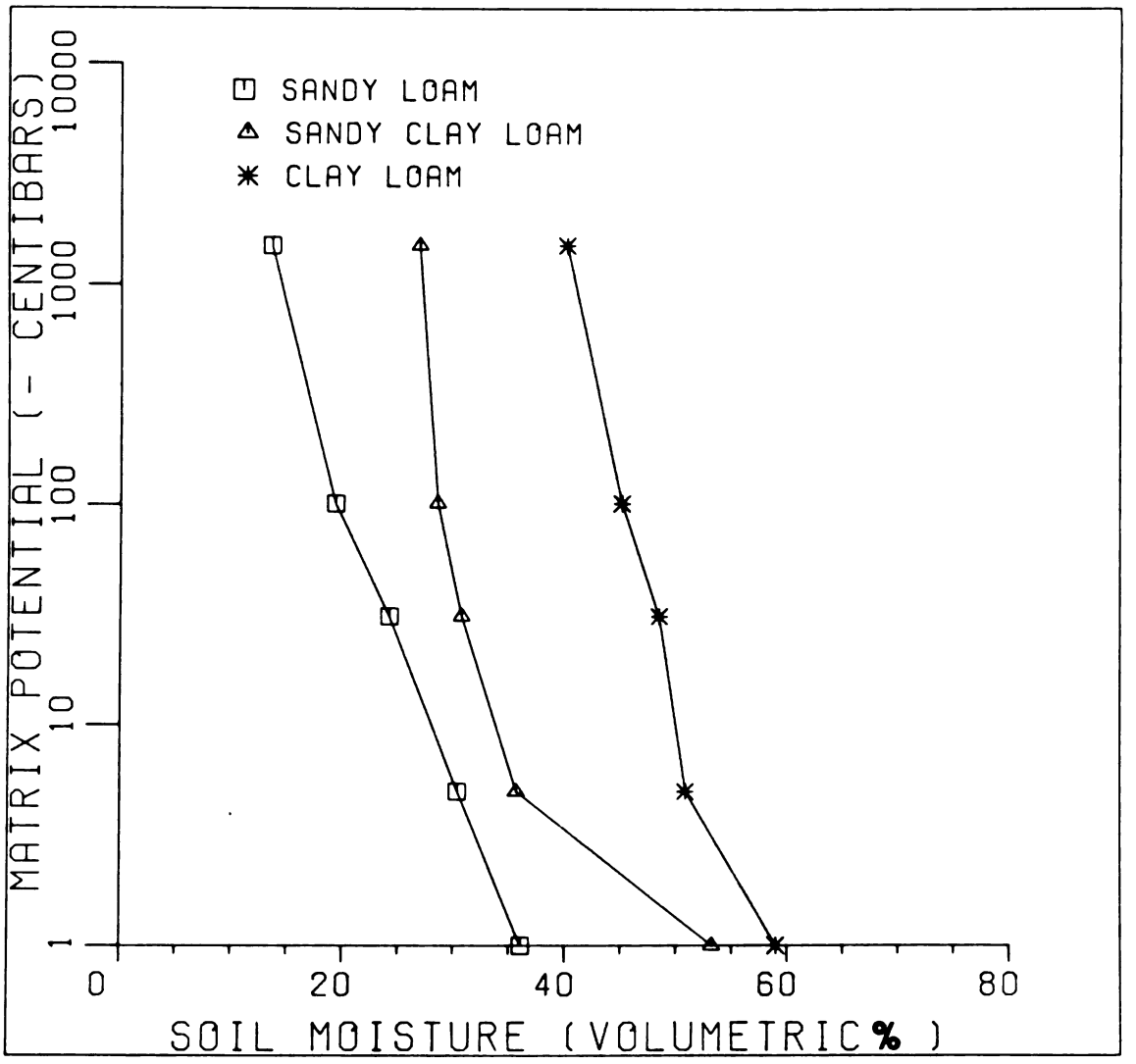


Figure 3.62. Volumetric soil moisture content associated with three soil types at different matrix potentials.

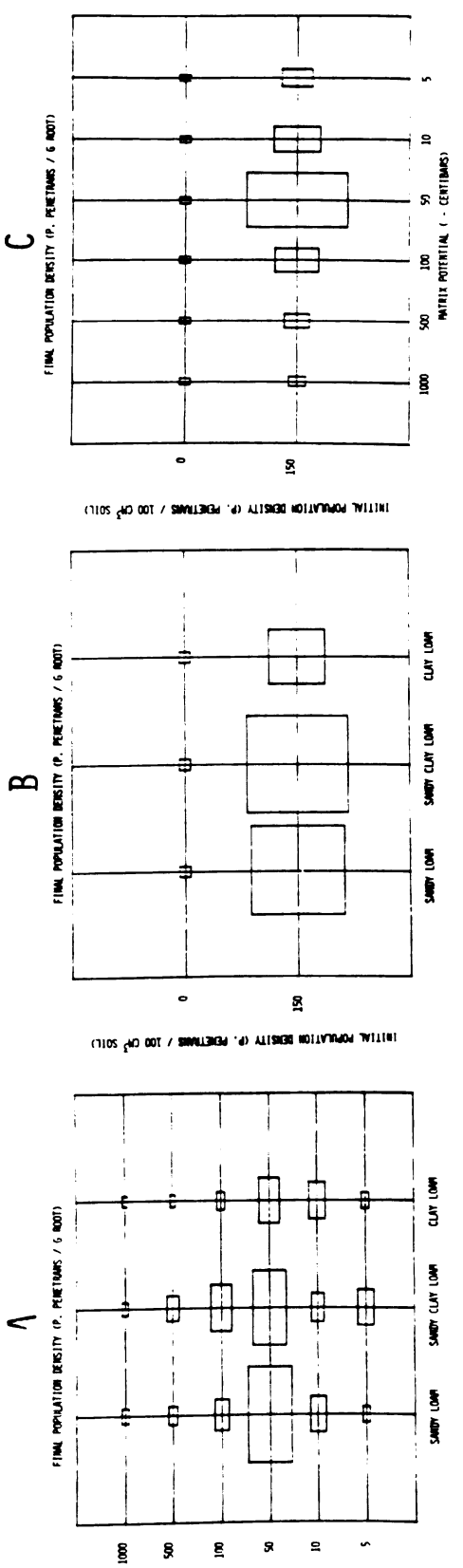


Figure 3.63. Influence of interactions of soil type and soil moisture (A), soil type and initial density of P. penetrans (B) and soil moisture and initial density of P. penetrans (C) on final root population densities of P. penetrans.

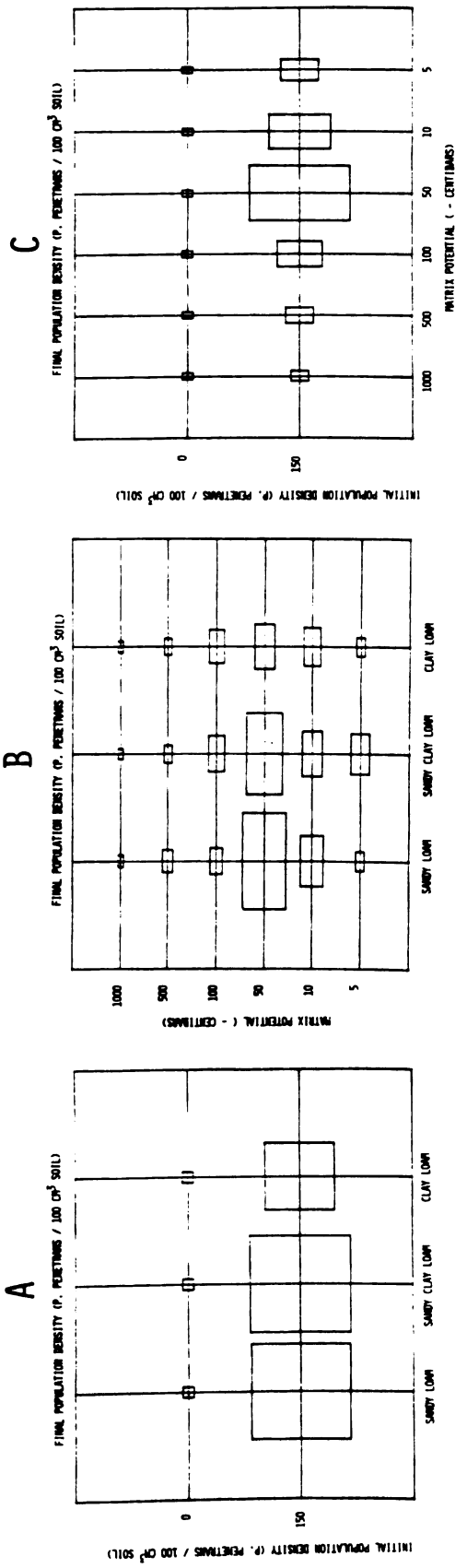


FIgure 3.64. Influence of soil type and initial density of P. penetrans (A), soil type and soil moisture (B), and soil moisture and initial density of P. penetrans (C), on final soil population densities of P. penetrans.

Table A27-1).

Total population densities in soil and roots associated with navy beans were lowest in the clay loam soil, and highest in the sandy loam (Figure 3.65). For all soils P. penetrans densities were lowest at the highest moisture level and highest at the moisture level corresponding to a matrix potential of -50 centibars (Figure 3.65; Table A28).

Length of navy bean roots were significantly influenced by interactions of soil type and soil moisture and interactions of soil moisture and P. penetrans (Figure 3.66; Tables A29-1-A29-4). Lengths of navy bean roots were greatest at a soil moisture level corresponding to a matrix potential of -50 centibars (Figure 3.66). Root length was significantly reduced by P. penetrans at a moisture level corresponding to a matrix potential of -5 centibars in all three soil types (Figure 3.66). Root lengths were lower in P. penetrans infected plants compared to noninfected plants in all three soil types (Figure 3.66).

Shoot dry weight was significantly influenced by interactions of soil type and soil moisture (Figure 3.67; Tables A30-1-A30-5). Shoot dry weights were significantly decreased by P. penetrans at all soil moisture levels (Figure 3.67A, B; Table A30-1). Averaged over soil

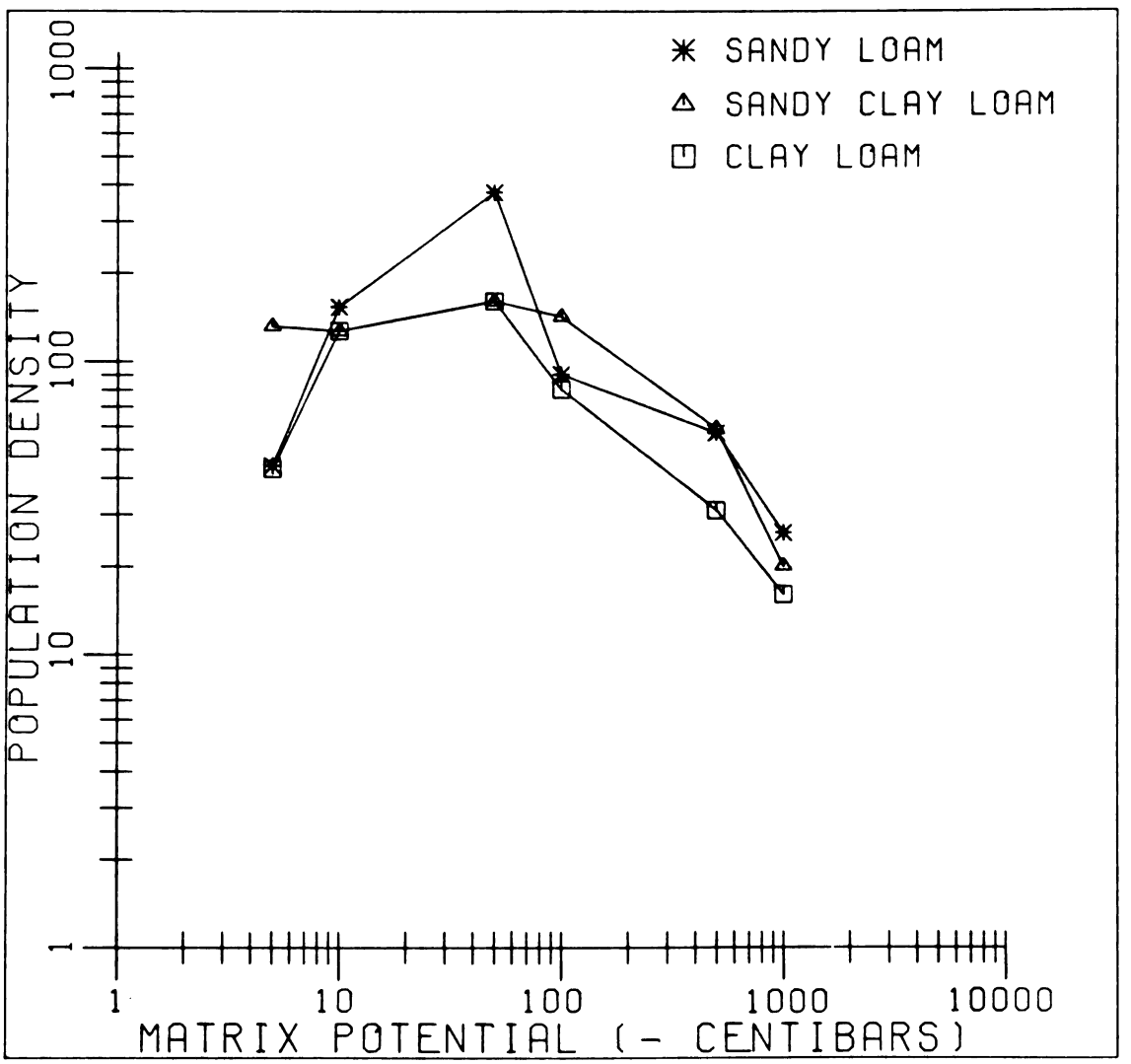


Figure 3.65. Influence of soil moisture on total population densities (root + soil) of P. penetrans associated with navy beans in three soil types.

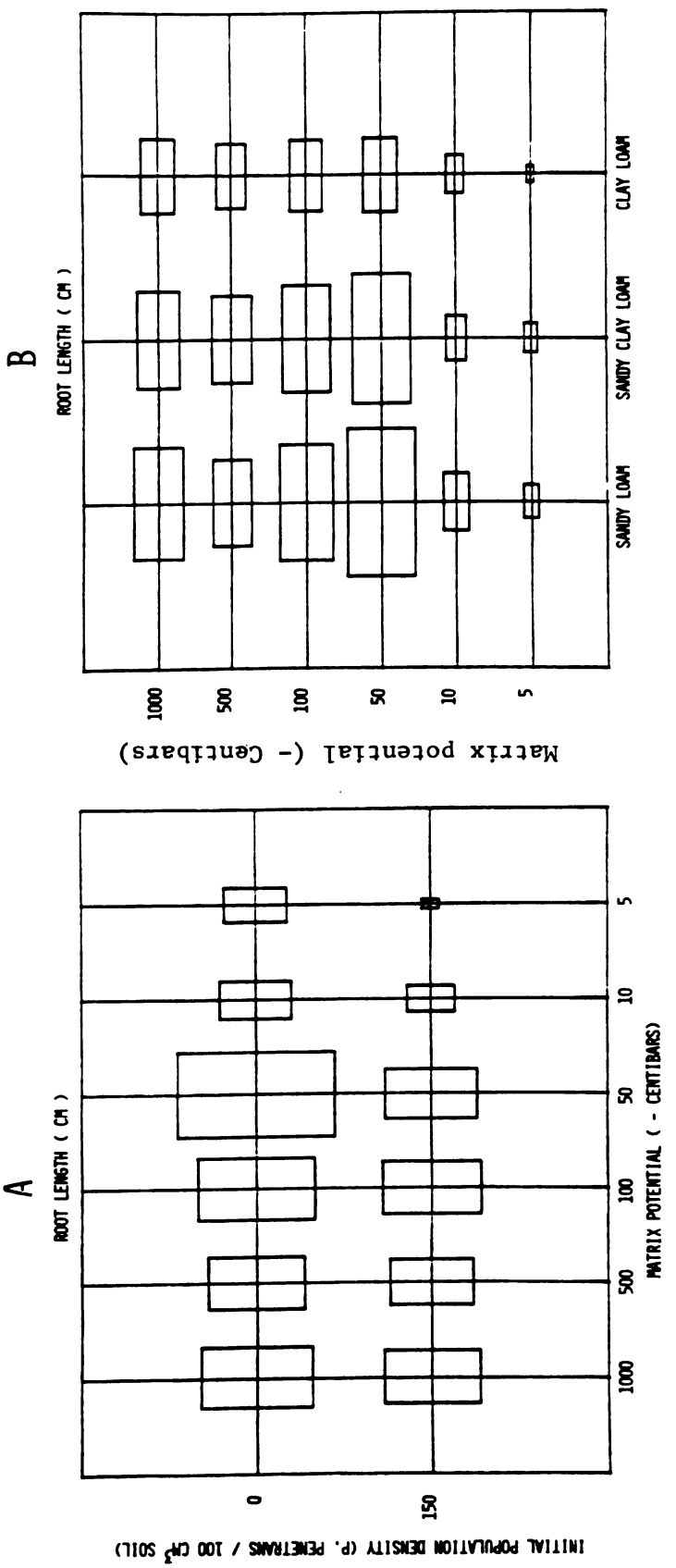


FIgure 3.66. Influence of interactions of soil moisture and initial density of P. penetrans (A), and soil type and soil moisture (B) on root length of navy bean plants.

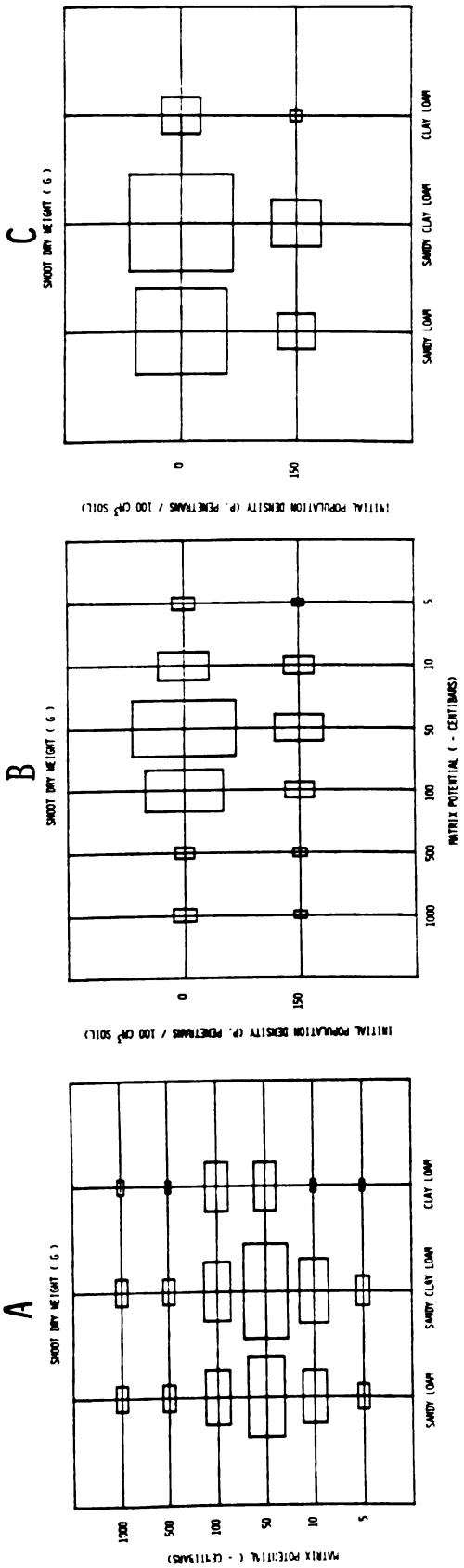


FIgure 3.67. Influence of interactions of soil type and soil moisture (A), soil moisture and initial density of P. penetrans (B) and soil type and initial density of P. penetrans (C) on shoot dry weight of navy beans.

moisture levels, dry weight was significantly (P = 0.05) reduced by P. penetrans in all soil types (Figure 3.67A, C). Shoot dry weight was lowest in the clay loam soil in noninfected and P. penetrans infected plants (Figure 3.67A, C).

Plant heights were influenced by interactions of soil type, soil moisture and P. penetrans (Figure 3.68; Tables A31-1-A31-5). Plant height was reduced by P. penetrans in all soil types (Figure 3.68B, C). Plant heights were lower at high moisture levels and increased at moisture levels corresponding to a matrix potential of -50 centibars (Figure 3.68A, C).

Root areas of plants were influenced by interactions of soil type and P. penetrans (Figure 3.69; Tables A32-1-A32-5). P. penetrans decreased root area at all soil moisture levels (Figure 3.69A). Root area was lowest in the clay loam in P. penetrans infected plants.

Yield of dry beans were influenced by interactions of soil type, soil moisture and P. penetrans (Figure 3.70; Table A33-1-A33-5). P. penetrans reduced bean yields in all three soil types at each moisture level studied (Figure 3.70). Highest yields were obtained at the soil moisture level corresponding to a soil matrix potential of -50 centibars (Figure 3.70-3.71). Lowest yields were obtained at high soil moisture levels corresponding

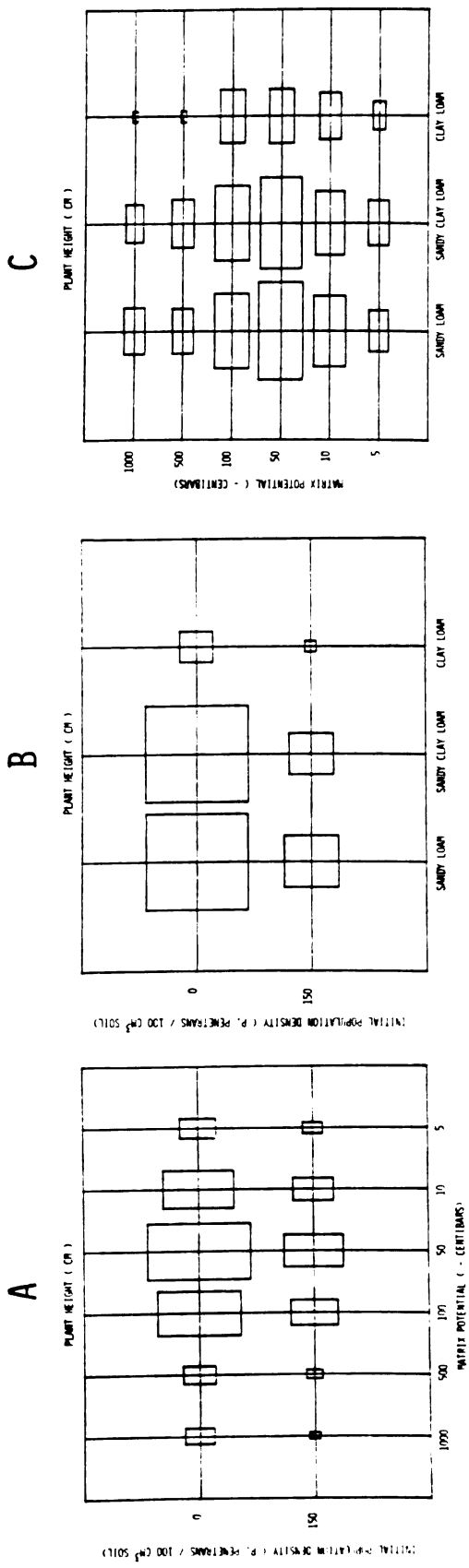


Figure 3.68. Influence of interactions of soil moisture and initial density of P. penetrans (A), soil type and initial density of P. penetrans (B), and soil moisture and soil type (C) on heights of navy bean plants.

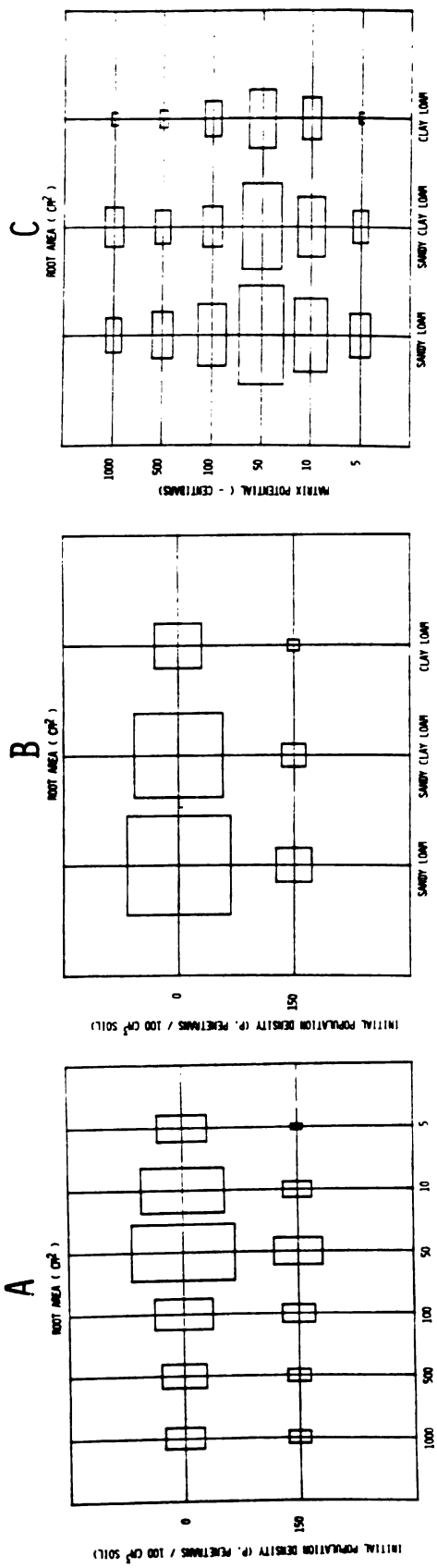


Figure 3.69. Influence of interactions of soil moisture and initial density of P. penetrans (A), soil type and initial density of P. penetrans (B) and soil moisture and soil type (C) on root area of navy bean plants.

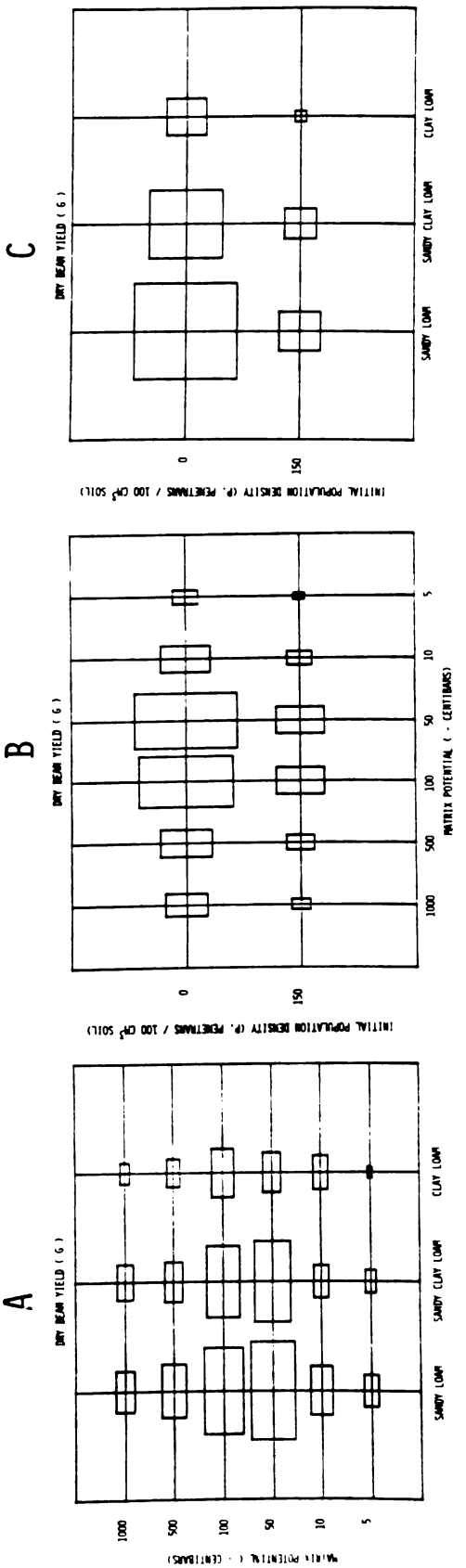


Figure 3.70. Influence of interactions of soil moisture and soil type (A), soil moisture and initial density of P. penetrans (B) and soil type and initial density of P. penetrans (C) on yield of navy beans.

Figure 3.71. Influence of soil moisture expressed as matrix potential on yield of noninfected and P. penetrans infected navy beans grown in three soil types.

Equations for the relationships between navy bean yield and matrix potential.
Y = navy bean yield; X = matrix potential
NI = noninfected; I = P. penetrans infected

Sandy loam

NI: $Y = -1.3430390178 + 3.94734232927\ X - 1.03799212599\ X^2$ $(R^2 = 0.93)$

I : $Y = -0.497700825489 + 1.89670676671\ X - 0.510629921261\ X^2$ $(R^2 = 0.82)$

Sandy clay loam

NI: $Y = -1.56876476974 + 3.78813577679\ X - 0.999015748033\ X^2$ $(R^2 = 0.84)$

I : $Y = -0.391307829268 + 1.5361323444\ X - 0.388188976379\ X^2$ $(R^2 = 0.94)$

Clay loam

NI: $Y = -0.612844452488 + 2.01878376449\ X - 0.532283464568\ X^2$ $(R^2 = 0.91)$

I : $Y = -0.245989441013 + 1.09555877425\ X - 0.287992125985\ X^2$ $(R^2 = 0.80)$

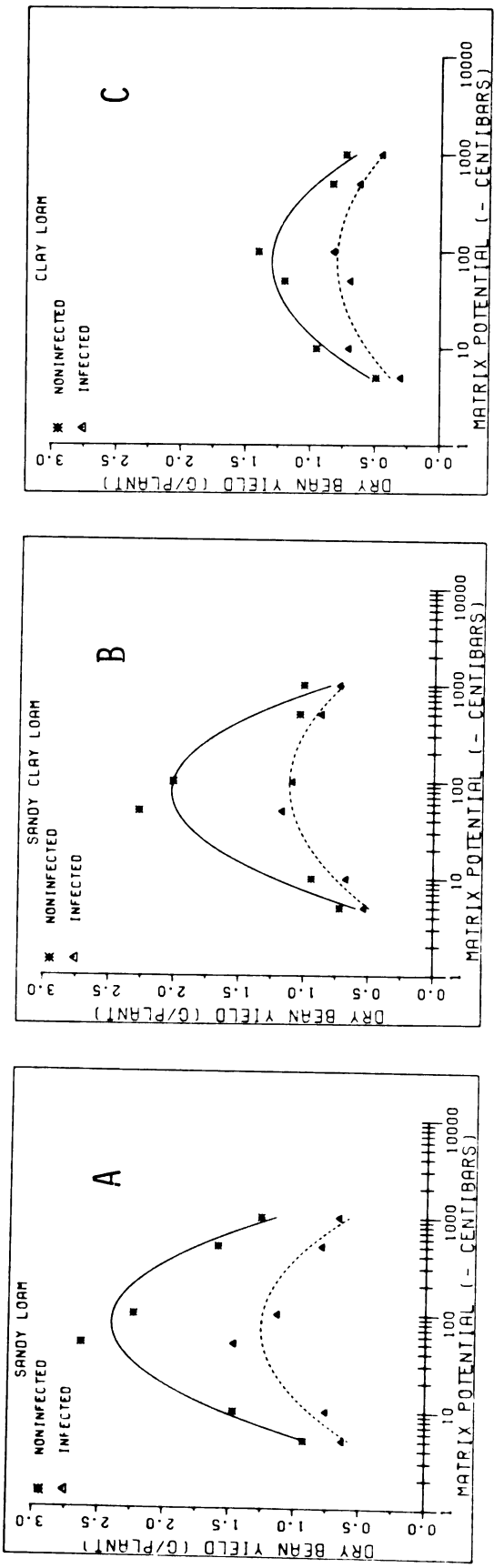

A
SANDY LOAM
NONINFECTED
INFECTED
DRY BEAN YIELD (G/PLANT)
MATRIX POTENTIAL (- CENTIBARS)
B
SANDY CLAY LOAM
C
CLAY LOAM

Figure 3.71.

to a matrix potential of -5 centibars (Figure 3.70A,B). The relationships between dry bean yield and matrix potential were expressed as second degree polynomials (Figure 3.71) and the curves for these reationships adequately describe the relationships.

In the sandy loam soil yields from noninfested plants were significantly higher than yields from noninfested plants in the sandy clay loam and clay loam respectively (Figure 3.71). The equation for yield of noninfested plants in the sandy loam soil is:

$$Y = -1.3430390178 + 3.94734232927\ X - 1.03799212599\ X^2 \qquad (R^2 = 0.93)$$

where Y = dry bean yield and X = matrix potential while the equation for yield from P.penetrans infected plants from the sandy loam soil is:

$$Y = -0.497700825489 + 1.89670676671\ X - 0.510629921261\ X^2 \qquad (R^2 = 0.82)$$

The differences in the terms in these two equations indicate the decrease in yield in P.penetrans infected plants.

In the sandy clay loam soil the equation relating yield to matrix potential for noninfected plants is:

$$Y = -1.56876476974 + 3.78813577679\ X - 0.999015748033\ X^2 \qquad (R^2 = 0.84)$$

while for P. penetrans infected plants the equation is:

$$Y = - 0.391307829268 + 1.5361323444\ X - 0.388188976379\ X^2 \qquad (R^2 = 0.94)$$

Reduction in yield is indicated in the equation for yield in P. penetrans infected plants compared to the equation for yield in noninfected plants.

For noninfected plants from the clay loam soil the equation for the relationship between yield and matrix potential is:

$$Y = - 0.612844452488 + 2.01878376449\ X - 0.532283464568\ X \qquad (R^2 = 0.91)$$

while the equation for yield from P. penetrans infected plants is:

$$Y = - 0245989441013 + 1.09555877425\ X - 0.287992125985\ X^2 \qquad (R^2 = 0.80)$$

The decrease in yield in P.penetrans infected plants is evident in the last equation and the decrease in yields in this type compared to yields from plants in the sandy loam and sandy caly loam respectively is also significant.

3.4.2.4.3 Effect of interactions of soil type, soil moisture and intial population densities of P. penetrans on growth and yield of navy beans and on population densities of P. penetrans

Root population densities increased with increase in degree days up to 1407 DD 10 C and then decreased (Table A34-1). Densities were influenced by interactions of soil type, soil moisture and initial density of P. penetrans at 1056 DD 10 C (Figure 3.72; Tables A34-2-A34-5). Root densities were lowest at matrix potentials of -1000 and -5 centibars respectively (Figure 3.72A, C).

Soil densities of P. penetrans were lowest at 1407 DD 10 C and highest at the end of the growth period. Densities were influenced by interactions of soil type, soil moisture and initial density of P. penetrans at 1056 DD 10 C (Tables A35-1-A35-2).

Final total densities at 1407 DD 10 C were lower in the clay loam at all moisture levels (Figure 3.73; Table A36-1). At 1056 DD 10 C final total densities in roots and soil were significantly influenced by interactions of soil type, soil moisture and initial density (Tables A36-2-A36-5).

Root weight was not influenced by three-way interactions of soil type, soil moisture and initial density

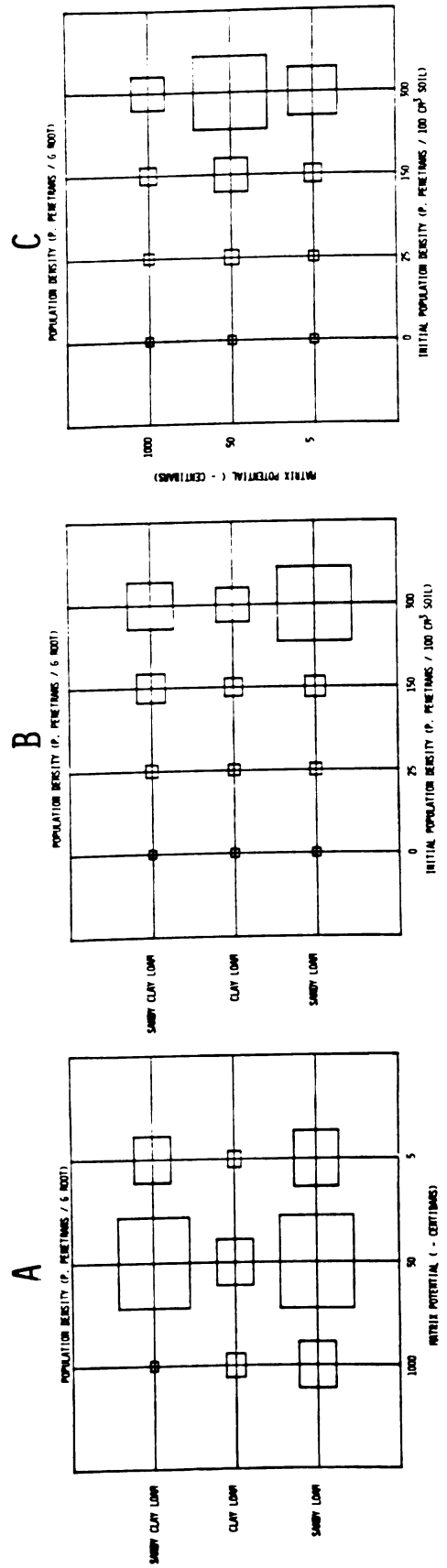


Figure 3.72. Influence of interactions of soil moisture and soil type (A), soil type and initial density of P. penetrans (B), and soil moisture and initial density of P. penetrans (C) on root population densities of P. penetrans at 1056 DD 10 C.

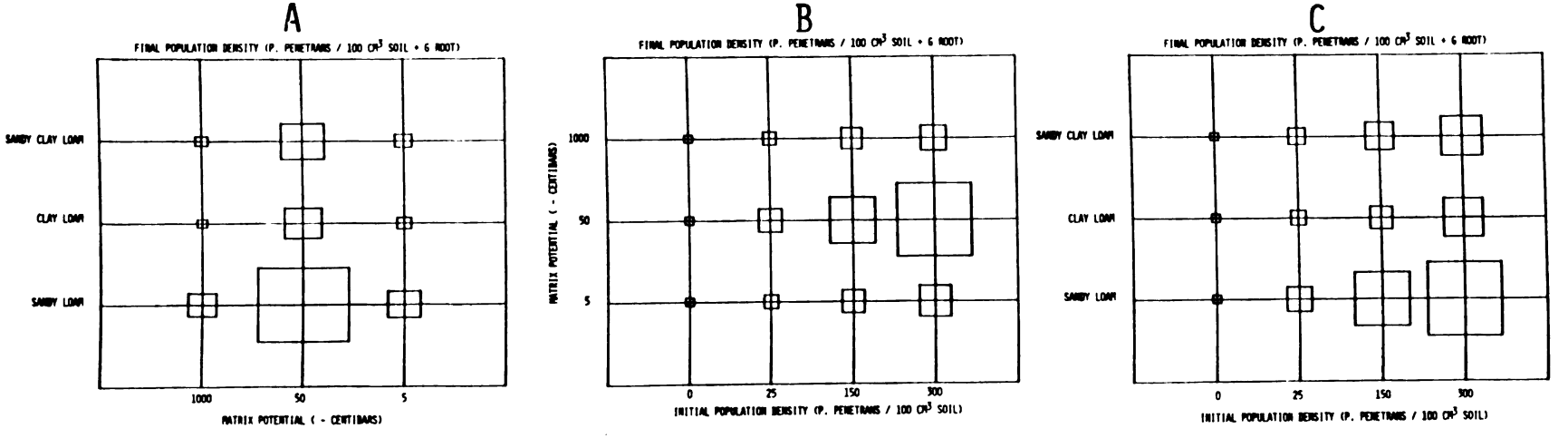


FIgure 3.73. Influence of interactions of soil type and soil moisture (A), soil moisture and initial density of P. penetrans (B) and soil type and initial density of P. penetrans (C) on final total densities (root + soil) of P. penetrans associated with navy beans.

of P. penetrans at any sampling period during growth (Table A37-1). However root weight was influenced by interactions of soil type and soil moisture as well as interactions of soil type and initial density (Table A37-2). There was also a significant difference in root weight of plants grown in the sandy clay loam soil and in the clay loam soil at matrix potentials of -5 and -1000 centibars respectively (Figure 3.74; Tables A37-1-A37-8) at 1746 DD 10 C.

At 1056 DD 10 C there was no significant difference (P = 0.05) in shoot dry weight of P. penetrans infected and noninfected plants in the three soil types at an initial density of 25 P. penetrans per 100 cm^3 soil (Figure 3.75; Tables A38-1-A38-8). Dry weight was not influenced by interactions of soil type, soil moisture and initial density at any sampling period during growth (Tables A38-2-A38-8). Dry weight was significantly reduced at high and low soil moisture levels (Figure 3.75A, B).

There were no significant interaction (P = 0.05) of soil type, soil moisture and initial density on height of bean plants (Tables A39-1-A39-5). At 285 DD 10 C plant height was influenced by interactions of soil type and soil moisture, soil type and initial density of P. penetrans and initial density of P. penetrans and soil

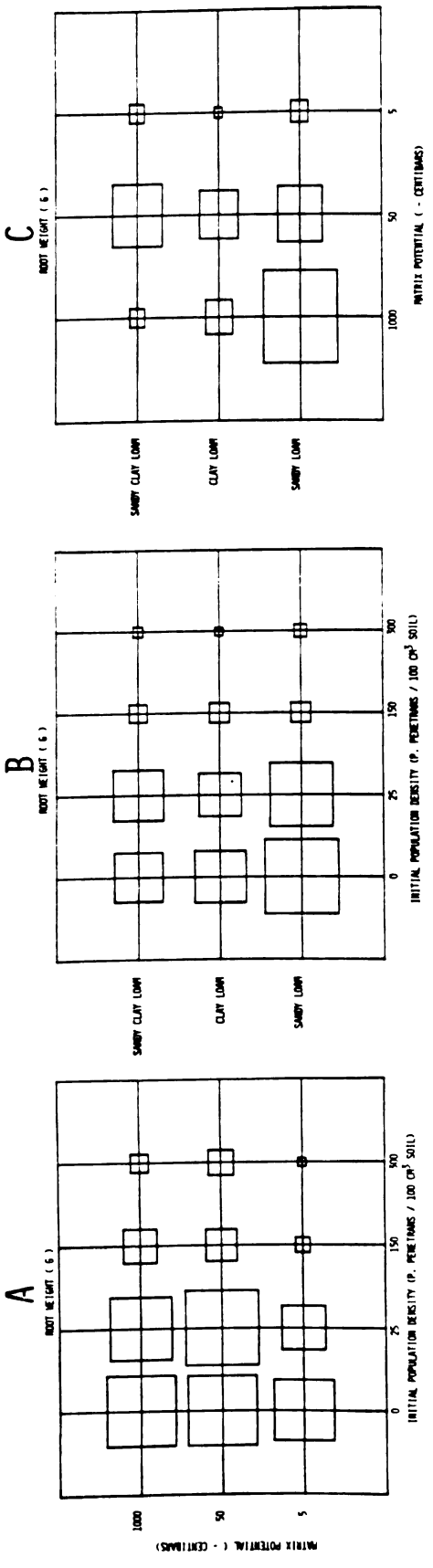


FIgure 3.74. Influence of interactions of soil moisture and initial density of P. penetrans (A), initial density of P. penetrans and soil type (B) and soil moisture and soil type (C) on root weight of navy bean plants at 1746 DD 10 C.

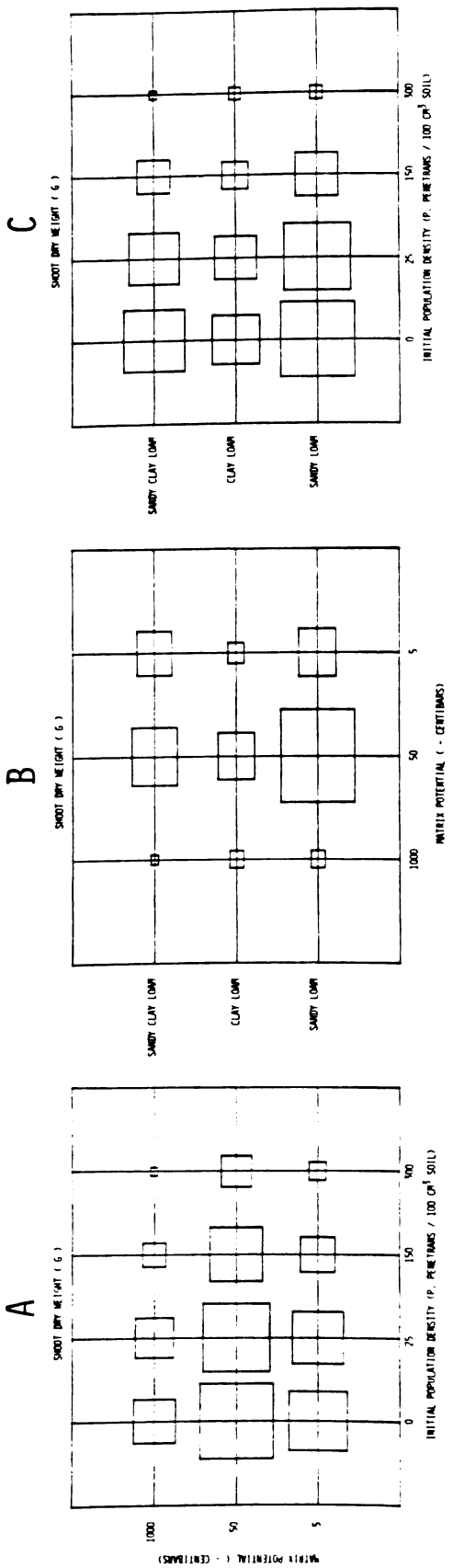


Figure 3.75. Influence of interactions of soil moisture and initial density of P. penetrans (A), soil type and soil moisture (B) and soil type and initial density of P. penetrans (C) on shoot dry weight of navy bean plants at 1056 DD 10 C.

moisture (Table A39-2). Plant height increased with increase in degree days over the growth period (Table A39-1). Plants were highest at a matrix potential of -50 centibars (Table A39-1). Plant heights were significantly (P = 0.05) reduced by densities of 150 and 300 P. penetrans per 100 cm^3 soil (Table A39-1).

High and low soil moisture levels corresponding to matrix potential of -5 and -1000 centibars respectively reduced yield of dry beans in all soil types (Figure 3.76; Table A40-1). Interactions of soil type and soil moisture, soil type and initial density of P. penetrans, and soil moisture and initial density of P. penetrans, respectively significantly (P = 0.05) influenced dry bean yields (Figure 3.76; Tables A40-2-A40-5). Navy bean yields were significantly reduced by population densities of 150 and 300 P. penetrans per 100 cm^3 soil respectively. Yields were lowest in the clay loam soil and highest in the sandy loam (Figure 3.76A, C). Highest yields were obtained at a matrix potential of -50 centibars (Figure 3.76B).

3.4.3 Discussion

Soil moisture characteristic curves for the three soils indicated that percent volumetric moisture content of soils increased with increase in matrix potential. The

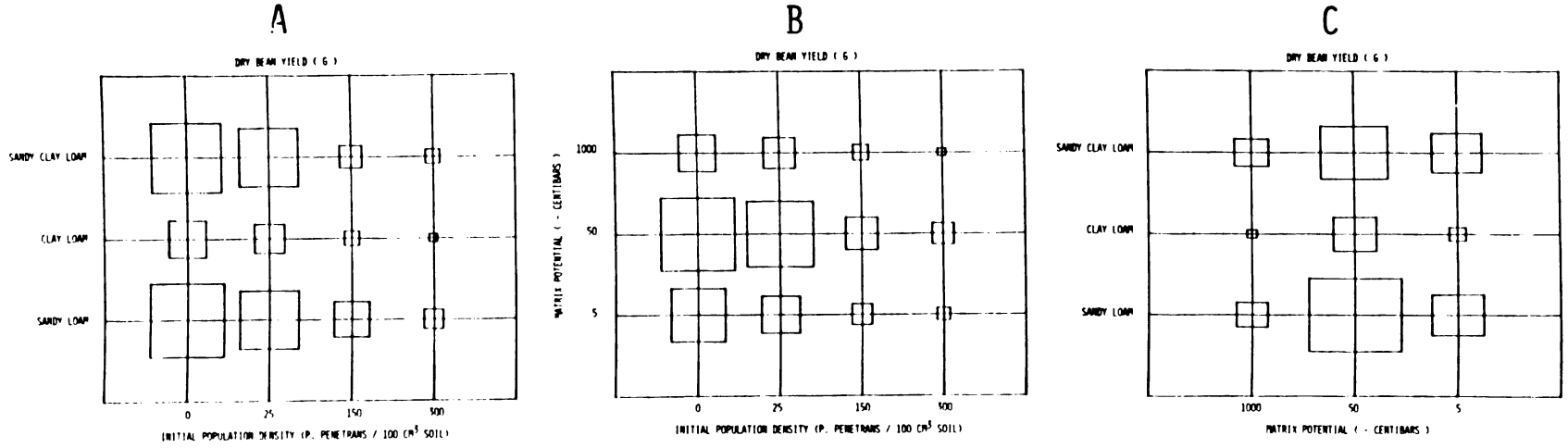


Figure 3.76. Influence of interactions of soil type and initial density of P. penetrans (A), soil moisture and initial density of P. penetrans (B) and soil type and soil moisture (C) on yield of navy beans.

soil moisture characteristic curve obtained for the sandy loam is as expected for this soil type (Baver, 1956). For the clay loam, however, the soil moisture characteristic curve is slightly different from that expected and percent soil moisture associated with low matrix potentials was somewhat higher than expected (Baver, 1956). The high moisture content could be due to inadequate removal of water at high pressures to the thickness of the soil cores used in experimental procedures. Adjustments were made in calculation of soil moisture content for the clay loam soil in determining soil moisture levels for other experiments.

The higher population densities associated with the sandy loam soil is in agreement with reports on nematode movement in sandy soils (Oostenbrink, 1966; Wallace, 1973; Norton, 1978). Nematodes live and move in the thin film of water surrounding soil particles and this movement is facilitated in coarser textured soils with large pore spaces than in fine textured soils with small pore spaces. Although soil moisture content is generally lower in sandy soils nematode survival is generally higher in these soils at adequate moisture levels. The higher population densities in sandy soils are also related to optimum temperatures which are attained in these drier soils in contrast to lower temperatures in

wetter cold clay soils.

The optimum soil moisture level for survival and reproduction of P. penetrans was at a matrix potential of -50 centibars. This matrix potential corresponded to volumetric soil moisture contents of 21, 27 and 44 percent in the sandy loam, sandy clay loam and clay loam respectively. In general population densities of P. penetrans increased with decrease in matrix potential reaching highest densities at -50 centibars and then decreasing at lower soil moisture levels. In the sandy loam and clay loam the rate of decrease in population densities of P. penetrans was greater than in the sandy clay loam soil. This is related to the ability of sandy clay loam soils to maintain optimum soil moisture levels because of drainage.

In the clay loam soil moisture content remained high even at high and low matrix potentials and reduction in densities of P. penetrans could be related to lack of oxygen which is expected under high soil moisture conditions. Kable and Mai (1968) observed similar decreases in population densities at high and low moisture levels. Townshend and Webber (1971) observed greater survival of P. penetrans at low moisture levels compared to survival at high moisture levels.

At low moisture levels plant roots were stimulated

to penetrate deeper into the soil matrix to obtain moisture, hence the increase in root length at high matrix potentials. Plant growth as indicated by shoot dry weight was greatest at a moisture content corresponding to -50 centibars. Plant growth was generally poor at high and low matrix potentials in both noninfected and P. penetrans infected navy bean plants. This is related to the lack of oxygen in wet soils and the inability of plants to maintain their water balance due to transpiration requirements in dry soils. The relationship between availability of soil moisture and expression of damage by P. penetrans on tobacco has been observed by Townshend and Marks (1976), who reported increased growth at high moisture regimes in contrast to growth at low moisture regimes. Tobacco plants infected with P. penetrans required less moisture compared to moisture requirements for noninfested plants and this is expected due to the higher growth rate of noninfested plants and greater transpiration requirements.

The higher cation exchange capacity of clay soils and higher associated organic matter content should enhance growth of plants at adequate soil moisture levels (Lyon et al. 1958). However the beneficial effects of cation exchange capacity and organic matter associated with clay soils can be negated under adverse soil moisture conditions. The sandy loam soil is also an adequate soil

type for plant growth under optimum moisture conditions. However rapid drainage can occur in these soils and result in soil moisture deficiencies. Nematode movement is enhanced in sandy loam due to the suitable size of pore spaces.

In the sandy clay loam and sandy loam soils it was evident that at a soil moisture level corresponding to -50 centibars an initial population density of 25 P. penetrans per 100 cm^3 soil could be tolerated on navy beans without significant losses in dry bean yields. In the clay loam however yield could be reduced by this initial population density at a moisture level of -50 centibars.

The need for adequate management of soil moisture in dry bean production is evident. Soil moisture influences temperature and to a large extent the functioning of plant disease and pest systems. The use of appropriate irrigation scheduling in bean production can overcome problems of moisture stress, while adequate drainage can alleviate problems associated with excess soil moisture. Use of an early planting date can also reduce problems of soil moisture stress. Temperatures are generally high at the time of flowering and moisture requirements are high at this period. If beans are planted early at adequate temperatures for germination, the physiological process of flowering can

be attained before moisture stress conditions begin. Assimilates can be transferred to the reproductive sink in the absence of moisture stress and thereby increase the probability of high yields. Therefore the choice of planting date is critical for avoiding moisture stress problems during some growth phases of navy beans.

3.5 Interactions of P. penetrans and Mycorrhizae

Endomycorrhizae are commonly found in bean production systems, and the need to examine the significance of this component of the P. penetrans-navy bean system is important. The following studies were designed to examine the effects of Glomus fasciculatus on growth and yield of navy beans and to examine interactions of this mycorrhizal fungus and P. penetrans and the effect on growth and yield of navy beans.

3.5.1 Effect of initial population densities of Glomus fasciculatus on growth and yield of navy beans

3.5.1.1 Method

The experiment consisted of a randomized design of four replicates of six treatments including population densities of 0, 10, 50, 100, 500 and 1000 spores of Glomus fasciculatus. Forty-eight 3.72 cm clay pots were filled with 3000 cm^3 of sandy clay loam soil containing the desired densities which were obtained by mixing steam sterilized soil with soil containing spores of G. fasciculatus.

Three navy bean seeds were planted in the soil in each pot. After germination plants were thinned out leaving one seedling in the soil in each pot. Plants

were watered daily and maintained at a temperature of 85 ± 10 C in the greenhouse. Shoot fresh weight, leaf area, plant height, root weight, root area and root length were recorded after a period of 56 days of growth (517 DD 10 C). Shoot systems were oven dried and shoot dry weight was recorded. After a period of 96 days dry bean yields were taken from the remaining 24 plants and dry bean yields were recorded. Vesicular-arbuscular root infection was determined (3.1.6) and spore density of Glomus fasciculatus was determined (3.1.5).

3.5.2 Interactions of P. penetrans and G. fasciculatus and effect on growth and yield of navy beans

3.5.2.1 Method

The experiment consisted of a randomized design of four replicates of four treatments including initial population densities of (1) 300 P. penetrans per 100 cm^3 soil (2) 1000 spores of G. fasciculatus per 100 cm^3 soil (3) 300 P. penetrans per 100 cm^3 soil plus 1000 spores of G. fasciculatus per 100 cm^3 soil and (4) 0 P. penetrans per 100 cm^3 soil plus 0 G. fasciculatus per 100 cm^3 soil.

One hundred and twelve 3.72 cm clay pots were filled with 3000 cm^3 soil containing desired densities of P. penetrans and G. fasciculatus, which were obtained by

mixing steam sterilized sandy clay loam soil with P. penetrans infested soil and soil containing spores of G. fasciculatus respectively.

Three navy bean seeds were planted in the soil in each pot. After germination plants were thinned leaving one seedling in the soil in each pot. Plants were watered daily and maintained at 85 ± 10 C in the greenhouse. Growth parameters of plant height, leaf area, shoot fresh weight, root weight, root area and root length were recorded at 14 day intervals over the growth period of 98 days. Shoot systems were oven dried at 30 ± 5 C and shoot dry weight was recorded. Leaf area ratios were calculated (3.1.8). Soil and root samples were taken for nematode analyses (3.1.1.2 and 3.1.2.2) and P. penetrans densities were determined (3.1.3-3.1.4). Vesicular-arbuscular root infection was determined (3.1.6). Soil samples were analyses to determine spore densities of G. fasciculatus (3.1.5).

3.5.3 Results

3.5.3.1 Effect of initial population densities of Glomus fasciculatus on growth and yield of navy beans

Glomus fasciculatus germinated and colonized navy bean roots (Figure 3.77; Tables A41-A42). Colonization

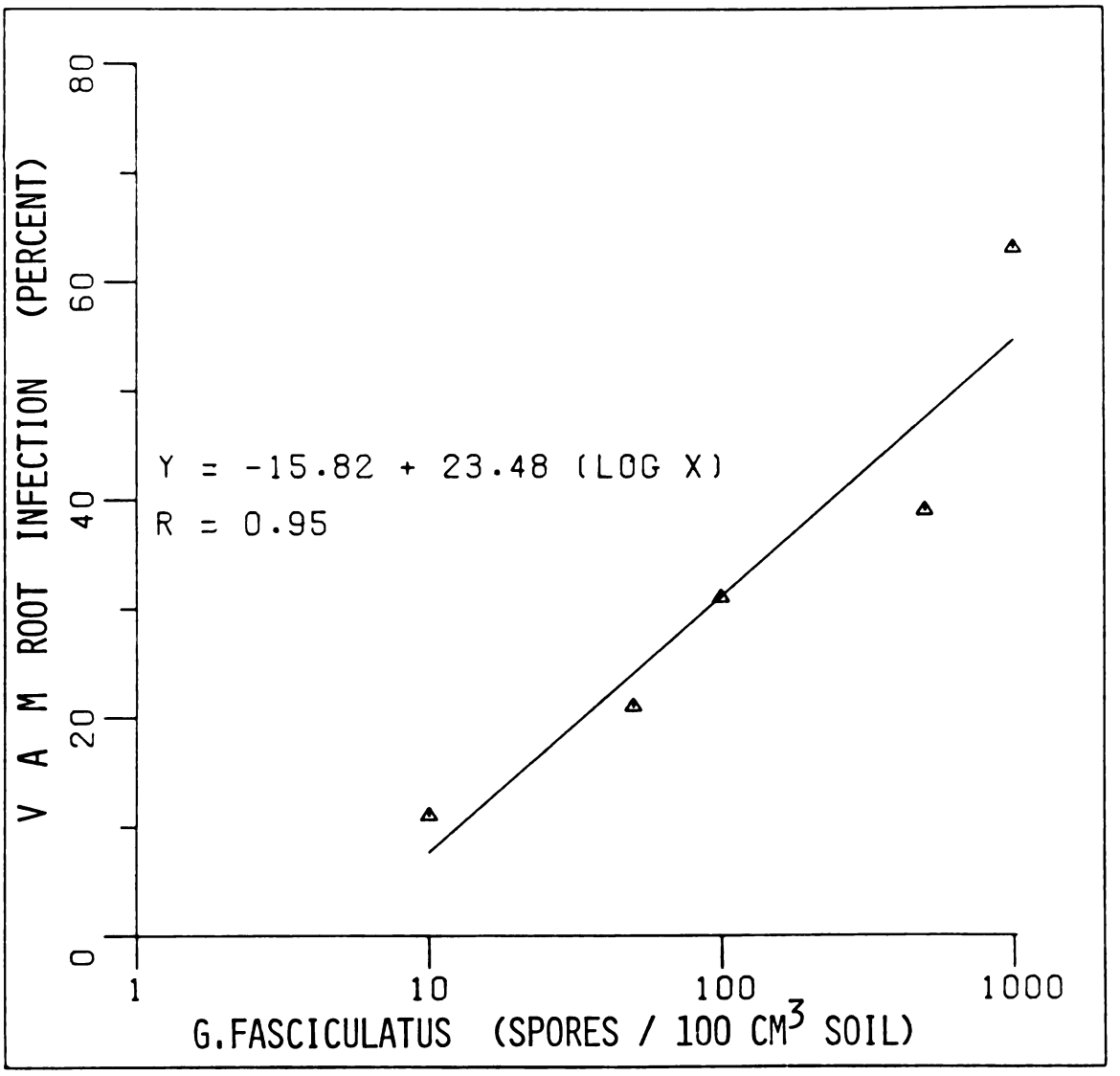


Figure 3.77. Relationship between percent vesicular-arbuscular mycorrhizal root infection of navy beans and log of initial spore density G. fasciculatus

levels at 517 DD 10 C ranged from 11% in plants exposed to an initial density of 10 spores of G. fasciculatus per 100 cm^3 soil to 63% in plants exposed to an initial density of 1000 spores of G. fasciculatus (Table A42). The relationship between vesicular-arbuscular root infection and initial spore density of G. fasciculatus was expressed as a linear function and the relatively high degree of correlation (R = 0.95) and confidence intervals indicate that the linear relationship is appropriate. The equation for the relationship is:

$$Y = 15.82 + 23.48 \text{ (log } X) \quad (R = 0.95)$$

where Y = percent vesicular-arbuscular root infection and X = log initial density of spores of G. fasciculatus, and the equation expresses the increase in root colonization by G. fasciculatus with increase in initial spore density.

Final spore densities were greater than initial spore densities of 10, 50 and 100, but lower than the initial densities of 500 and 1000 (Table A42).

Shoot fresh weight, shoot dry weight, leaf area, plant height, root area and root weight were significantly increased by initial spore densities of 100, 500 and 1000 G. fasciculatus per 100 cm^3 soil (Tables A41-A42).

Linear regression functions were developed to express the relationship between plant growth parameters

and log of initial spore density of G. fasciculatus (Figures 3.78-3.80). These linear regression functions adequately espressed the relationship except for the relationship between log initial spore density and root area (Figure 3.79A). The wide confidence intervals associated with this function indicated a low degree of significance. The equations for the linear functions indicated the increase in shoot dry weight, leaf area, plant height , root weight and root area with increase in initial spore density of G. fasciculatus (Figures 3.78-3.80). Dry bean yield increased with increase in initial spore density of G. fasciculatus and the relationship between these two variables is adequately described by the linear function expressed by the equation:

$$Y = 2.15 + 0.396 \text{ (Log X)} \quad (R = 0.96)$$

where Y = dry bean yield and X = log initial spore density of G. fasciculatus (Figure 3.81).

3.5.3.2 Interactions of P. penetrans and G. fasciculatus and effect on growth and yield of navy beans

Vesicular-arbuscular root colonization increased with increase in degree days (Figure 3.82; Table A43) and the relationship between vesicular-arbuscular root infection and degree days was expressed by second degree polynomials for plants infected with G. fasciculatus and

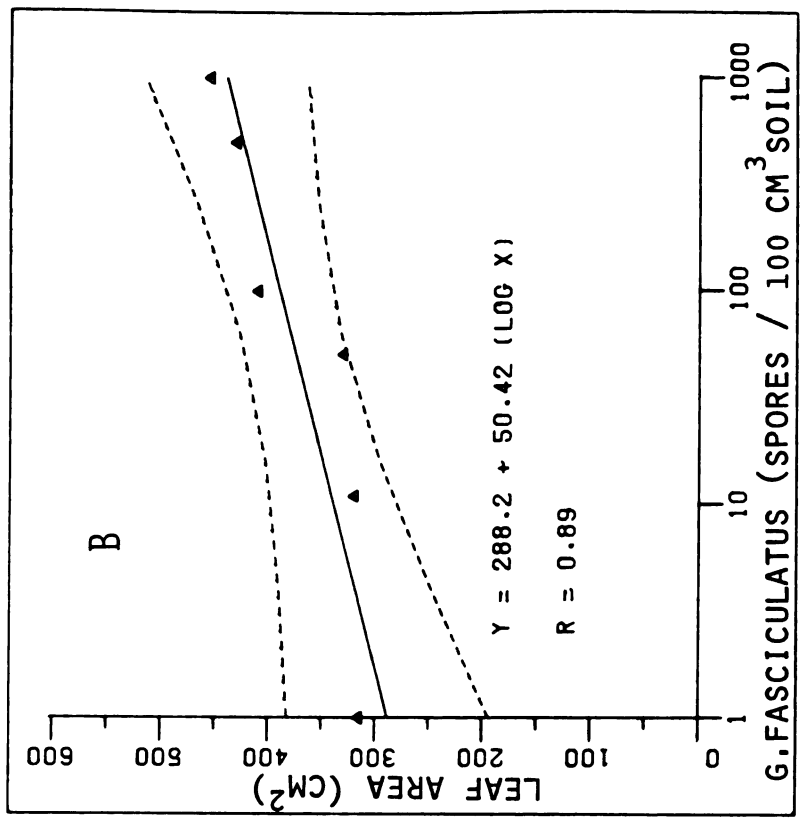


Figure 3.78. Effect of G. fasciculatus on shoot dry weight (A) and leaf area (B) of navy bean plants.

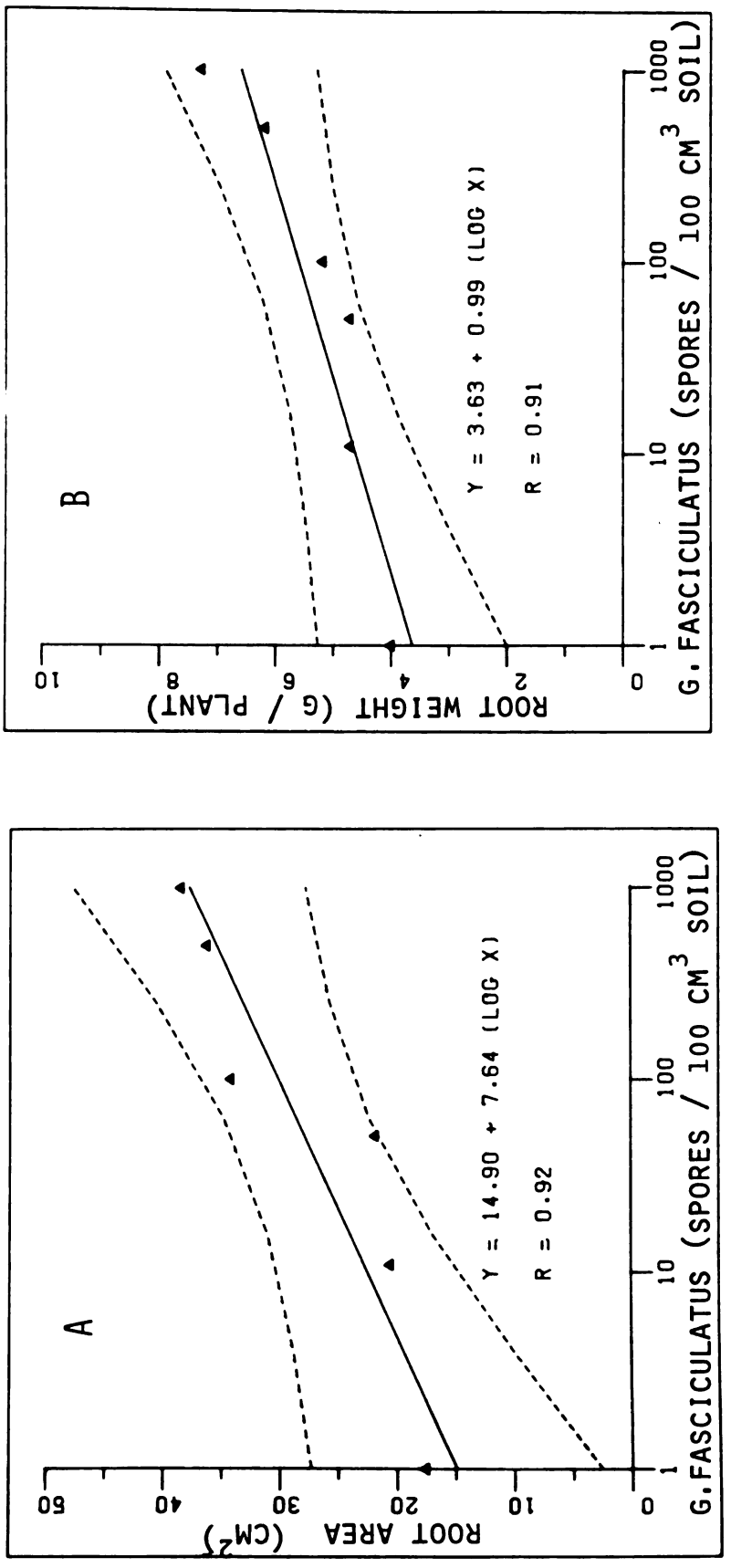


Figure 3.79. Effect of G. fasciculatus on root area (A) and root weight (B) of navy bean plants.

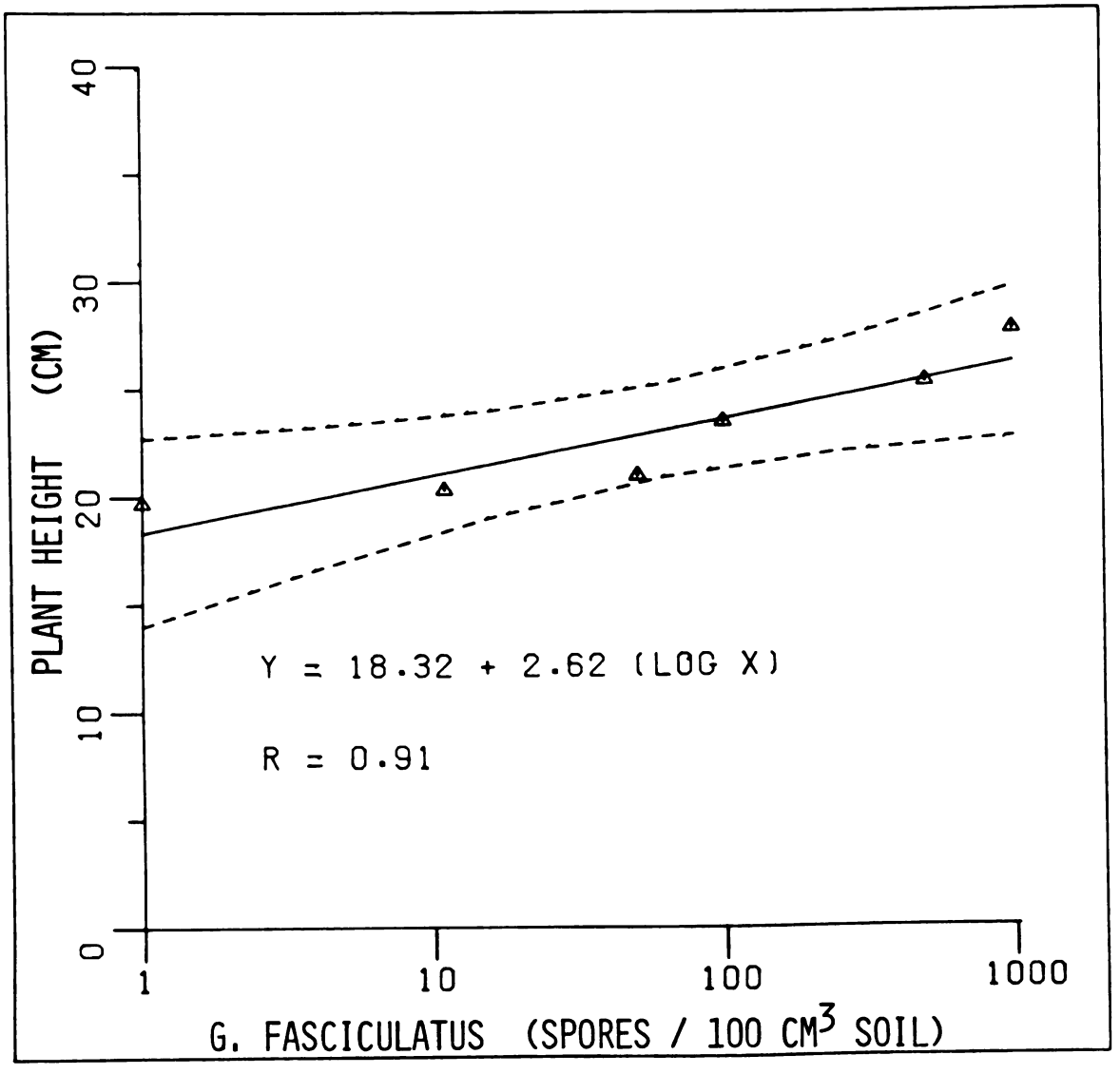


Figure 3.80. Effect of G. fasciculatus on height of navy bean plants.

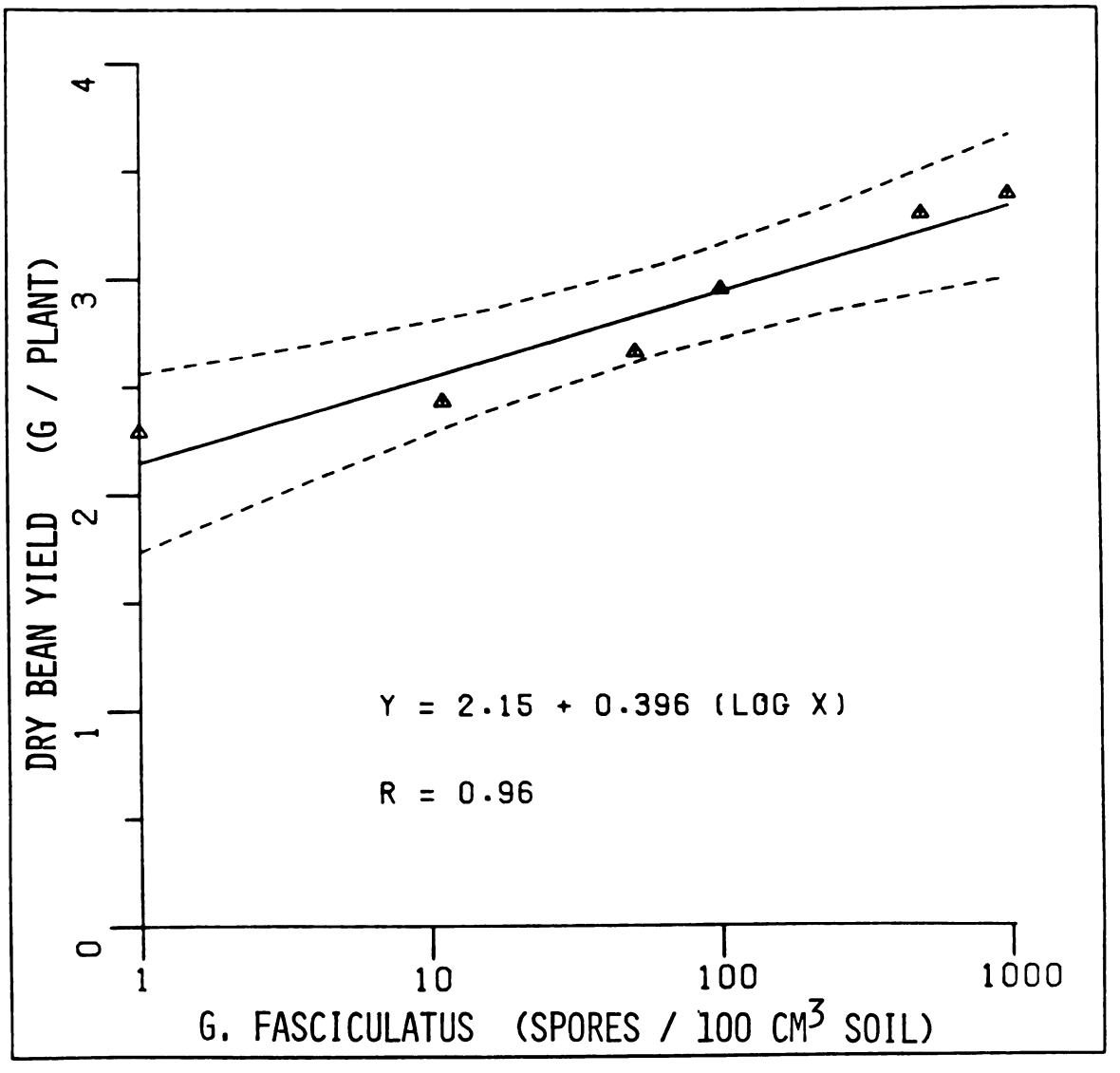


Figure 3.81. Effect of G. fasciculatus on yield of navy beans.

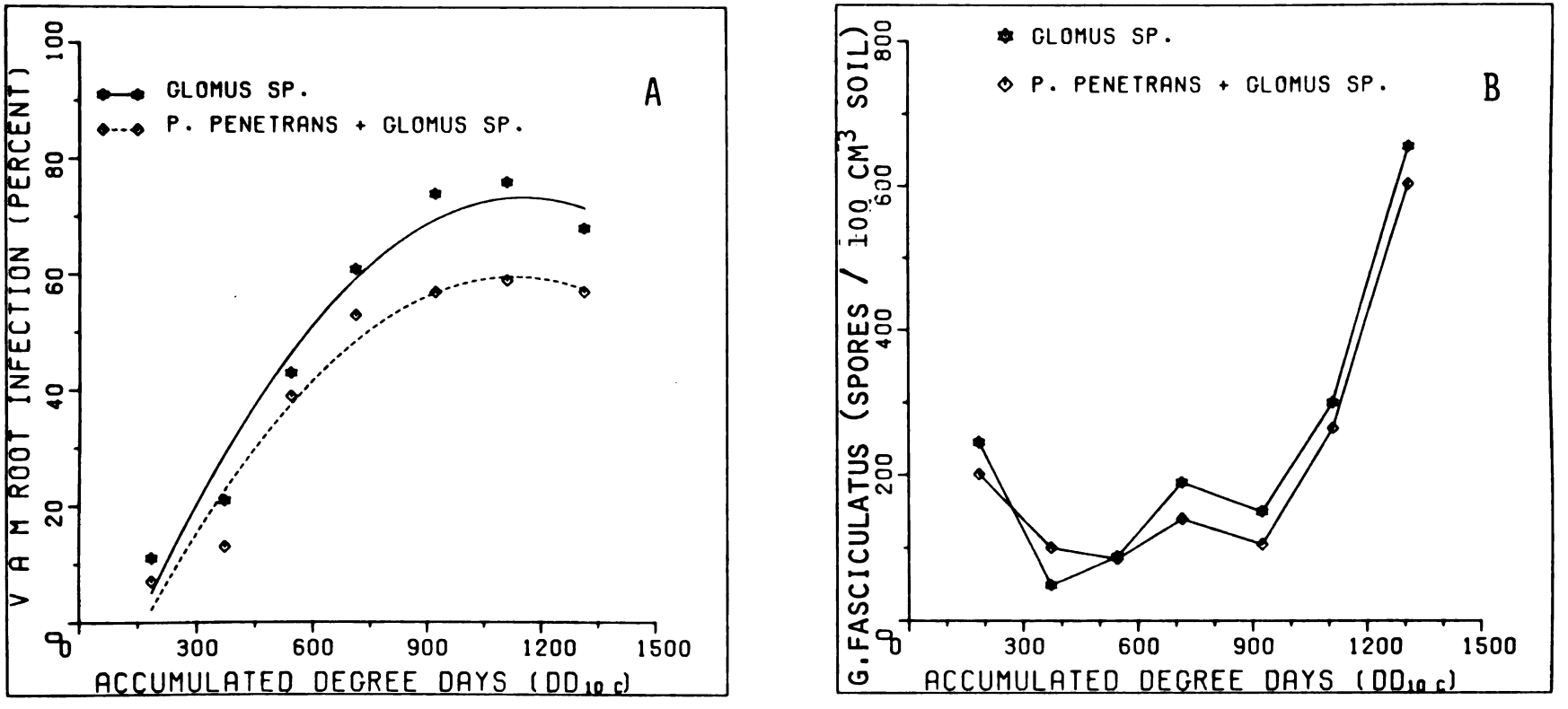


Figure 3.82. Influence of G. fasciculatus and G. fasciculatus plus P. penetrans on development of vesicular-arbuscular mycorrhizal infection in navy bean roots (A) and on spore densities of G. fasciculatus (B) over the growth period.

G. fasciculatus plus P. penetrans (Figure 3.82). Vesicular-arbuscular root infection was reduced in plants infected with both P. penetrans and G. fasciculatus compared to plants colonized with only G. fasciculatus (Figure 3.82A). The equation for the relationship between vesicular-arbuscular root infection and degree days in plants exposed to only G. fasciculatus is:

$$Y = -23.5352315148 + 0.167913586149\ X - 0.00007271347219\ X^2 \quad (R^2 = 0.96)$$

and for plants infected with both G. fasciculatus and P. penetrans the equation for the relationship is:

$$Y = -22.5500367928 + 0.145471967184\ X - 0.0000643638763\ X^2 \quad (R^2 = 0.95)$$

the high degree of correlation indicated by the R^2 value indicates that the relationship is adequately described by the second degree polynomial function.

Mycorrhizal spore density associated with soil initially infested with only G. fasciculatus was significantly ($P = 0.05$) higher compared to densities associated with soil infested with both G. fasciculatus and P. penetrans (Figure 3.82B; Table A44). Spore densities fluctuated throughout the growth period, and final spore densities were higher than initial spore densities of G. fasciculatus (Figure 3.82B).

Population densities of P. penetrans were higher

in plants infected with only P. penetrans at the beginning of the growth period. After 56 days (715 DD 10 C) population densities were higher in plants infected with both P. penetrans and G. fasciculatus (Figure 3.83B). Two maxima in population densities were observed at 343 and 603 DD 10 C respectively. Densities reached a maximum at 603 and remained relatively constant at these densities until 965 DD 10 C in plants infected with only P. penetrans. A similar trend was observed in plants infected with both P. penetrans and G. fasciculatus except for a slight increase in densities between 603 and 965 DD 10 C (Figure 3.83A). Total densities in roots plus soil followed a similar trend except for a leveling off of densities in the presence of both P. penetrans and G. fasciculatus (Figure 3.83).

Growth parameters of shoot fresh weight, shoot dry weight, leaf area, plant height, root weight, root area and root length were significantly (P = 0.05) increased by colonization with G. fasciculatus (Tables A45-A51). Dry weight of plants infected with both P. penetrans and G. fasciculatus were significantly higher (P = 0.05) compared to plants colonized with only G. fasciculatus after 14 days of growth (185 DD 10 C) (Table A46). There were no significant (P = 0.05) differences in dry weight and leaf area in plants infected with

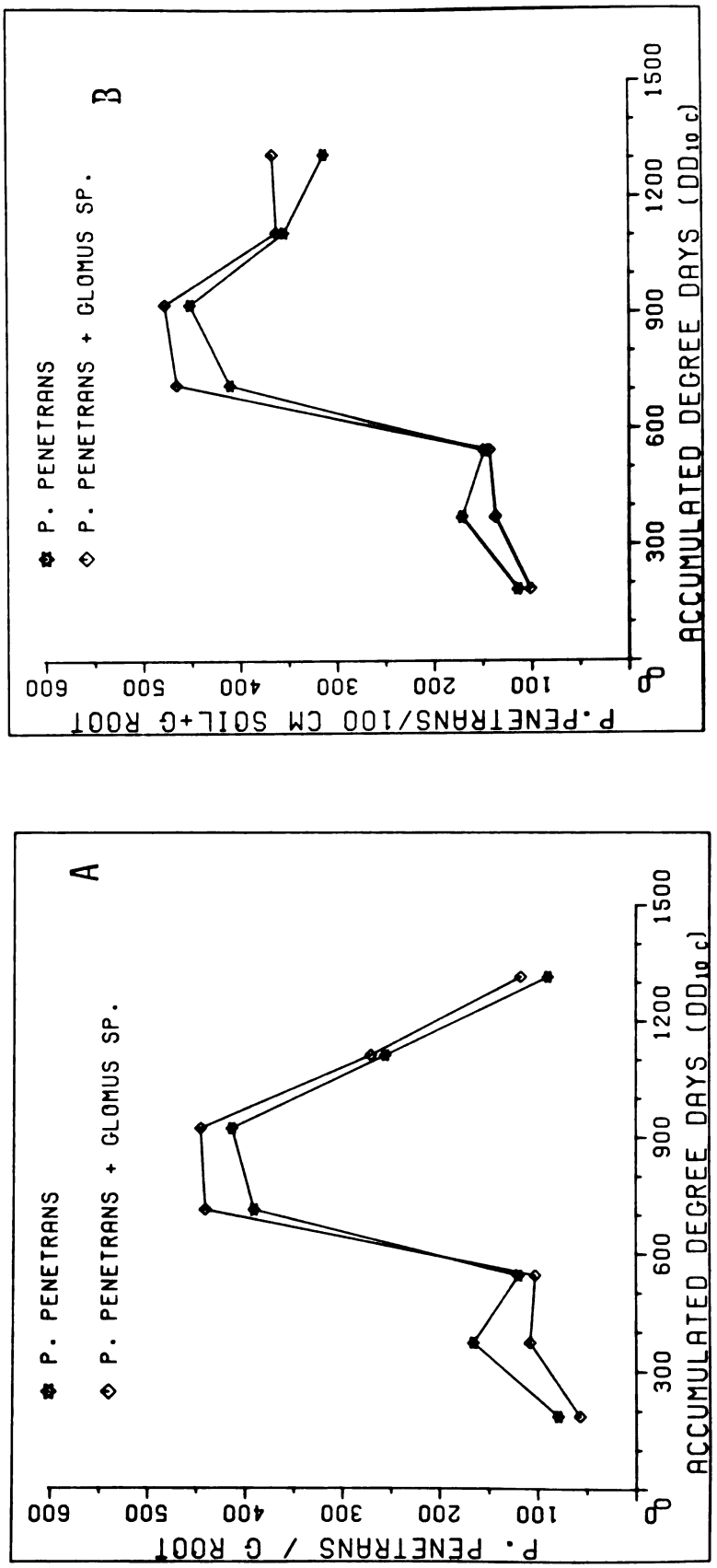


Figure 3.83. Population dynamics of P. penetrans associated with navy beans exposed P. penetrans and P. penetrans plus G. fasciculatus respectively.

G. fasciculatus plus P. penetrans, compared to controls after 14 days of growth (185 DD 10 C) (Tables A46-A47). P. penetrans significantly (P = 0.05) decreased all growth parameters (Tables A45-A51). Root area was lowest in plants infected with P. penetrans and highest in plants colonized with G. fasciculatus. Root area increased throughout the growth period reaching maxima at 715 DD 10 C and then decreased after this period (Figure 3.84). The relationship between root area and degree days was expressed as second degree polynomial functions (Figure 3.85). For control plants the equation for the relationship is:

$$Y = -3.40464028328 + 0.0552470297167\ X - 0.000037776936613\ X^2 \quad (R^2 = 0.90)$$

The increase in root area in plants infected with G. fasciculatus was evident from the equation for the relationship between the two variables:

$$Y = -6.60066024855 + 0.0974171382959\ X - 0.00006676630977\ X^2 \quad (R^2 = 0.87)$$

and the decrease in root area in plants infected with P. penetrans is observed in the equation for the relationship between the two variables:

$$Y = -1.760739383 + 0.0386747170543\ X - 0.0002693062666\ X^2 \quad (R^2 = 0.92)$$

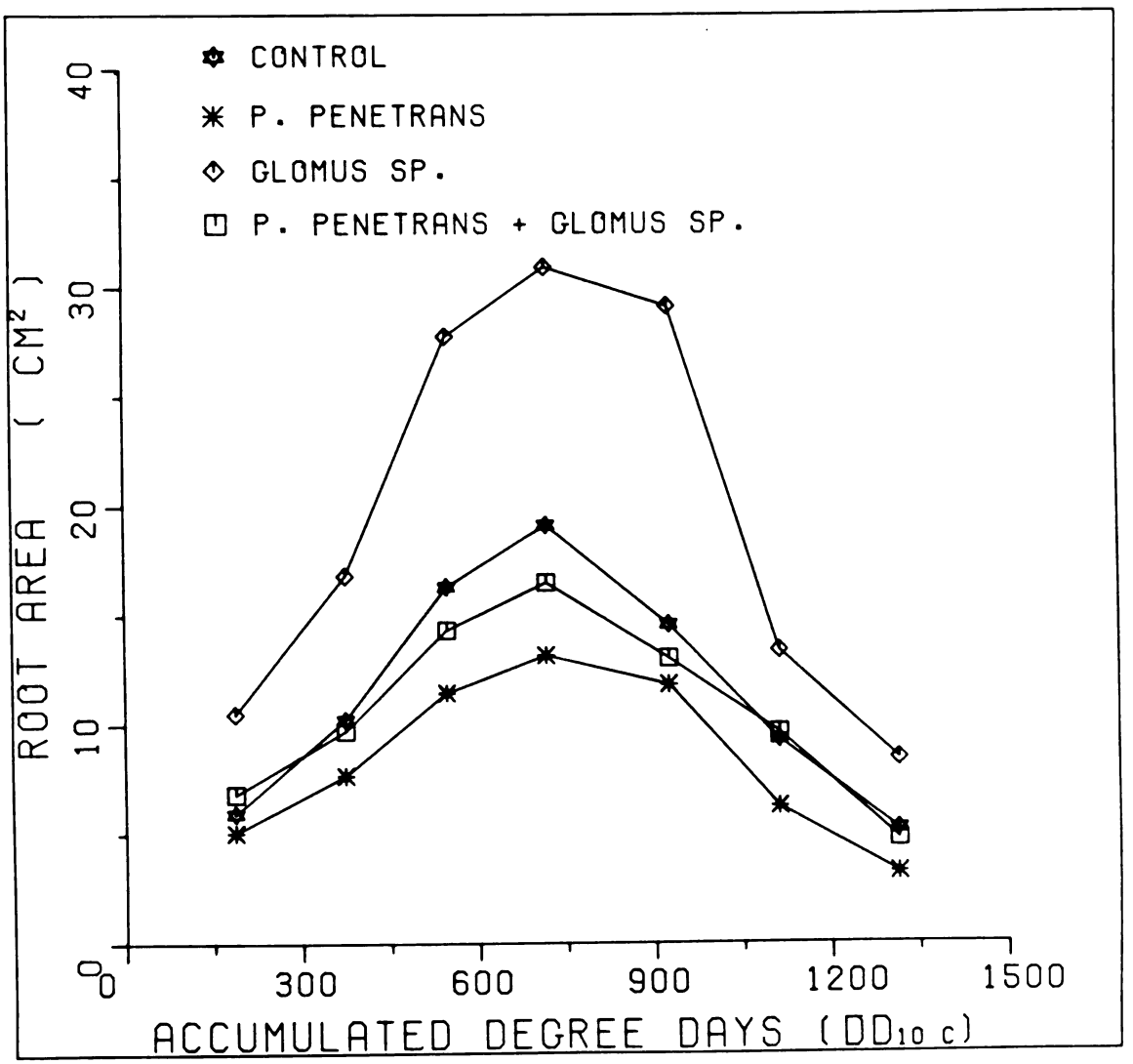


FIgure 3.84. Influence of P. penetrans , G. fasciculatus and P. penetrans plus G. fasciculatus on root area of navy bean plants over the growth period.

Figure 3.85. Relationship between root area and degree days of noninfected plants and navy bean plants infected with P. penetrans (A), G. fasciculatus (B) and P. penetrans plus G. fasciculatus

Equations for the relationships between root area and accumulated degree days at base 10 C
Y = root area, X = accumulated degree days base 10 C.

Control (noninfected)

$$y = -3.40464028328 + 0.0552470297167\ X - 0.00003776936613\ X^2 \quad (R^2 = 0.91)$$

P. penetrans

$$Y = -1.760739383 + 0.0386747170543\ X - 0.00002693062666\ X \quad (R^2 = 0.92)$$

Glomus fasciculatus

$$Y = -6.60066024855 + 0.0974171382959\ X - 0.00006676630977\ X^2 \quad (R^2 = 0.87)$$

P. penetrans + G. fasciculatus

$$Y = -0.773505254102 + 0.0433471733572\ X - 0.000029999118087\ X^2 \quad (R^2 = 0.94)$$

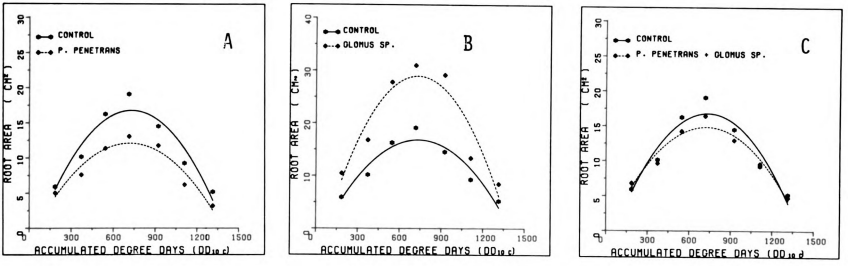

CONTROL
P. PENETRANS
A
ROOT AREA (CM²)
ACCUMULATED DEGREE DAYS (DD 18 C)
CONTROL
GLOMUS SP.
B
ROOT AREA (CM²)
ACCUMULATED DEGREE DAYS (DD 18 C)
CONTROL
P. PENETRANS + GLOMUS SP.
C
ROOT AREA (CM²)
ACCUMULATED DEGREE DAYS (DD 18 C)

Figure 3.85.

Leaf area ratios of plants fluctuated throughout the growth period (Figure 3.86) and were highest in plants infected with P. penetrans and lowest in plants colonized with G. fasciculatus.

Dry bean yield was significantly (P = 0.05) increased in plants colonized with G. fasciculatus (Figure 3.87). There was no significant (P = 0.05) difference in yield of dry beans from control plants compared to plants infected with both G. fasciculatus and P. penetrans.

3.5.4 Discussion

Beneficial associations between G. fasciculatus and navy beans resulted in increased growth and yield in mycorrhizal bean plants. Spore densities above 50 G. fasciculatus per 100 cm^3 soil significantly increased growth and yield of navy beans. The adverse effects of P. penetrans on growth and yield of dry beans can be minimized by the presence of mycorrhizal associations between navy beans and G. fasciculatus.

The mode of action and the function of the fungus in interactions with P. penetrans and navy beans is unclear. Population densities of P. penetrans were not significantly (P = 0.05) different in plants infected with P. penetrans compared to densities in plants infected with both P. penetrans and G. fasciculatus, therefore the mode of action

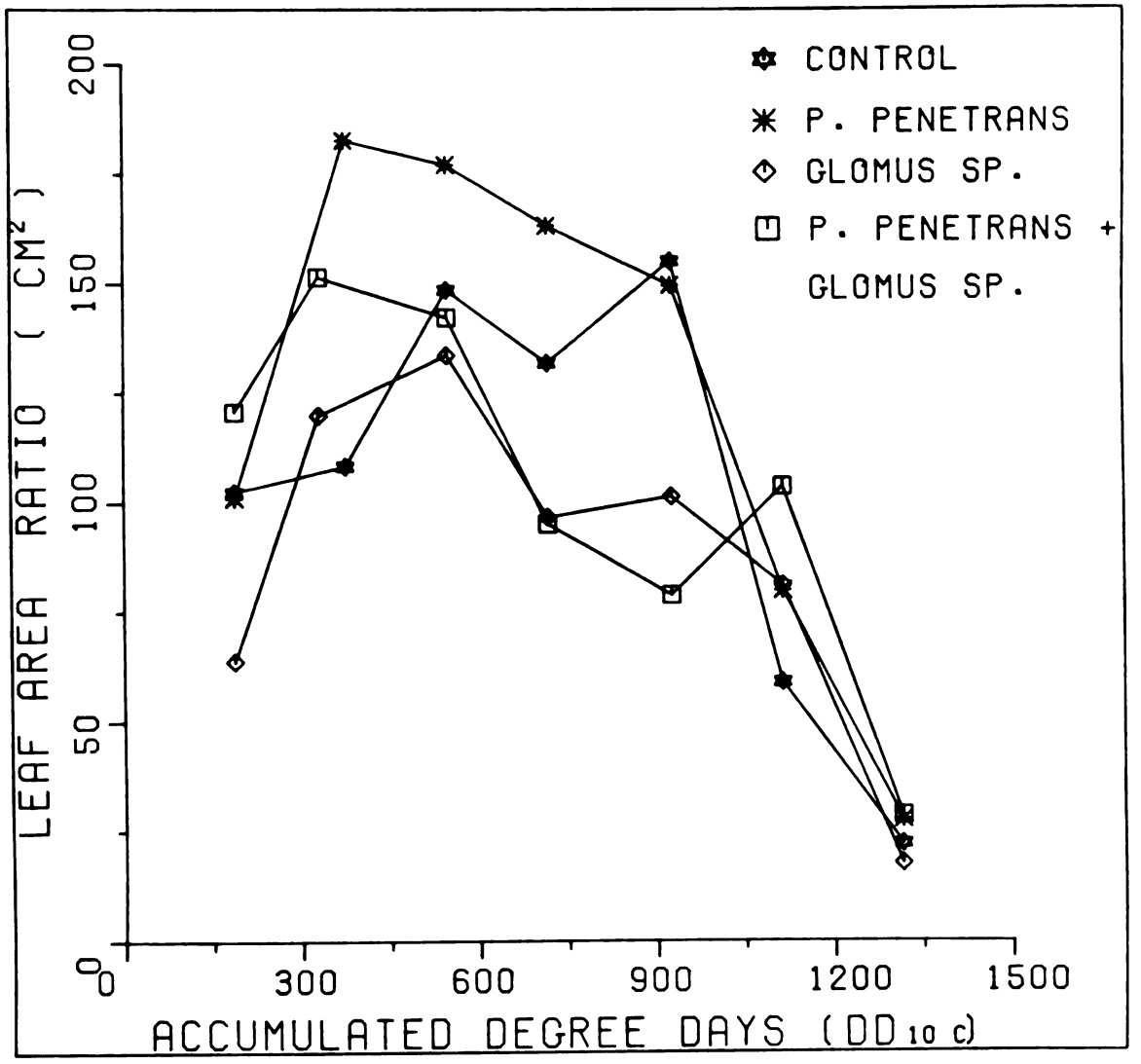


Figure 3.86. Influence of P. penetrans, G. fasciculatus and P. penetrans plus G. fasciculatus on leaf area ratio of navy bean plants over the growth period.

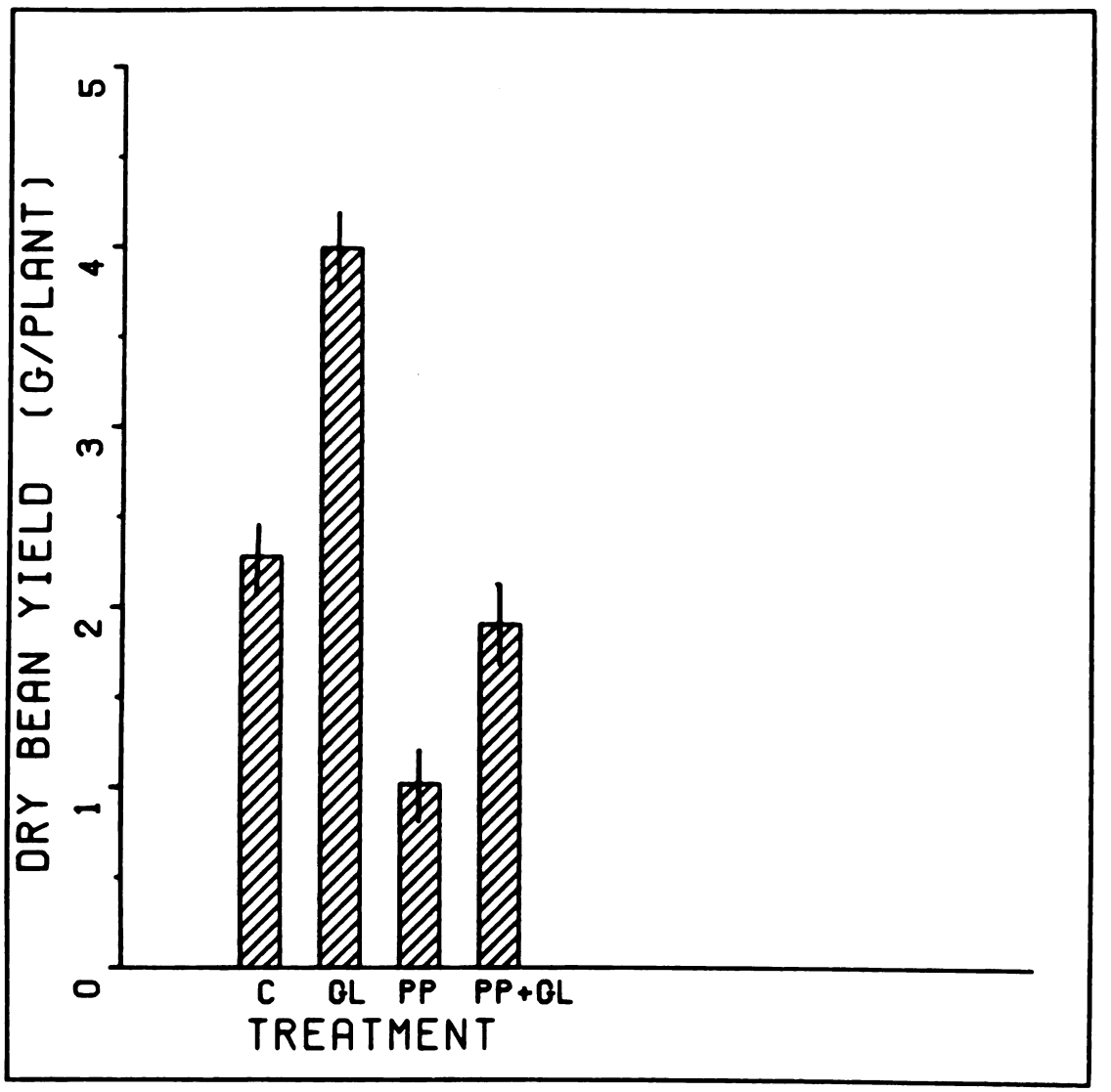


Figure 3.87. Influence of P. penetrans, G. fasciculatus and P. penetrans plus G. fasciculatus on yield of navy beans.

of the fungus was not related to reduction of population densities. Reports indicate that interactions of nematodes and mycorrhizal fungi are complex (Fox and Spasoff, 1972; Baltruschat, 1973; Schenck and Kinlock, 1974; Schenck et al. 1975). In some reports increases in nematode population densities were observed and this could be related to the increased food source provided by the larger healthier root system produced by the beneficial symbiotic association of the plant and mycorrhizal fungus. Decreases in population densities in the presence of mycorrhizal associations suggest an antagonistic interaction between fungi and nematodes.

Reports on increased growth of plants in the presence of mycorrhizal fungi, contribute the increased growth to increased nutrient availability. It has been hypothesized that the fungus transfers the nutrients to the plant through a symbiotic relationship (Gray and Gerdemann, 1967; Rhodes, 1976). The exact mechanism by which phosphorus is transferred is unknown however, Tinker (1975) proposed that bulk flow and cyclosis are involved in the translocation of phosphorus from the fungi to the plant. The beneficial effects of mycorrhizae are influenced by soil fertility and is promoted in soils of low fertility in contrast to soils of high fertility (Tinker, 1975).

The presence of certain species of mycorrhizae in navy bean production systems can be considered as a beneficial phenomenon, and maintenance of optimum densities of beneficial mycorrhizal fungi should be incorporated into management strategies in navy bean production. The influence of pesticides on mycorrhizal associations should be considered in development of nematode control strategies. Various reports indicate that pesticides influence mycorrhizal populations and associations (Nesheim and Linn, 1969; Kleinschmidt and Gerdemann, 1972; Bird et al. 1974; Backman and Clark, 1977; Bailey and Safir, 1977).

The integration of mycorrhizal fungi as a nematode control strategy in management of navy bean production systems is dependent on the species of mycorrhizal fungus. The nature of the indigenous species must be determined and the effect of introducing other species should be evaluated before recommended strategies can be developed. Where the beneficial mycorrhizal species is not indigenous it can be introduced by first propagating plants in soil infested with the species in the greenhouse and transferring these plants to the field (Khan , 1972; 1975). In the field population densities of mycorrhizal fungi can be increased by effective crop rotation with plants inoculated with the desired beneficial mycorrhizal species.

3.6 Rotation Crops - Kidney Beans

3.6.1 Susceptibility and control of P.penetrans associated with five dry bean varities

3.6.1.1 Method

Five dry bean varieties were planted in a randomized block design of five replicates of plots treated with aldicarb (Temik 15G) for control of P. penetrans and five replicates of plots containing initial densities of 116-134 P. penetrans per 100 cm^3 soil. Each plot consisted of four rows 6.1 m in length and 0.9 m apart. Aldicarb was applied in 0.2 m bands at the time of planting on June 5, 1979 (207 DD 10 C). The dry bean cultivars used were Sanilac, Seafarer and Tuscola navy beans, and Montcalm kidney and Charlevoix kidney beans. Soil and root samples were taken for nematode analysis at six intervals during the growing period. Population densities of P. penetrans were determined (3.1.1.1 and 3.1.3.2; 3.1.3-3.1.4). The two center rows of each plot were harvested on October 25, 1979 (1281 DD 10 C), and dry bean yield was recorded.

3.6.2 Results

3.6.2.1 Susceptibility and control of P.penetrans associated with five dry bean varieties

Population densities of P.penetrans fluctuated throughout the season, and two maxima in densities were

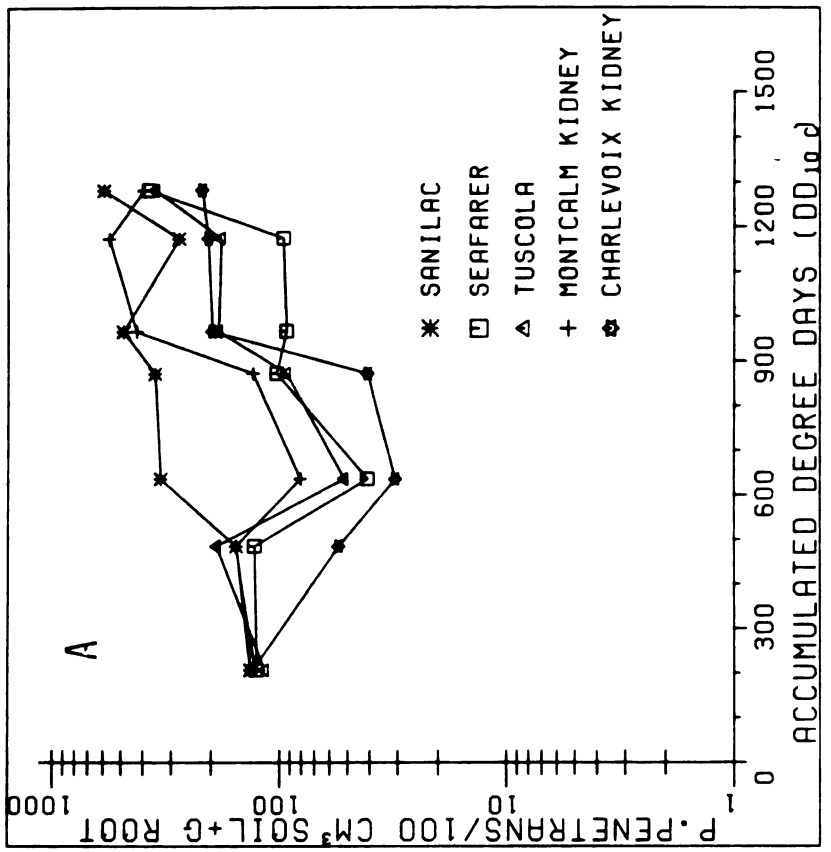
associated with Sanilac navy beans and Montcalm kidney beans (Figure 3.88). Lowest densities were associated with Charlevoix kidney beans and Seafarer navy beans (Figure 3.88; Table A52). Densities associated with Montcalm Kidney beans decreased towards the end of the season in contrast to an observed increase in densities associated with other varieties at similar growth periods (Table A52).

Aldicarb (2.0 lb per acre) was effective in reducing population densities of P. penetrans associated with all five varieties (Figure 3.88B; Table A52). Aldicarb was effective in maintaining population densities of P. penetrans at low densities throughout the season (Table A52).

Yield of dry beans were significantly (P = 0.05) higher in plots with low densities of P. penetrans obtained through treatment with aldicarb compared to yields from plots with high densities of P. penetrans in the absence of nematode control inputs (Table A52).

3.6.3 Discussion

Sanilac, Seafarer and Tuscola varieties were highly susceptible to P. penetrans. Seafarer appears to be less susceptible than Sanilac variety. Montcalm Kidney beans were highly susceptible to P. penetrans and maintained high densities of P. penetrans. This indicates that rotation



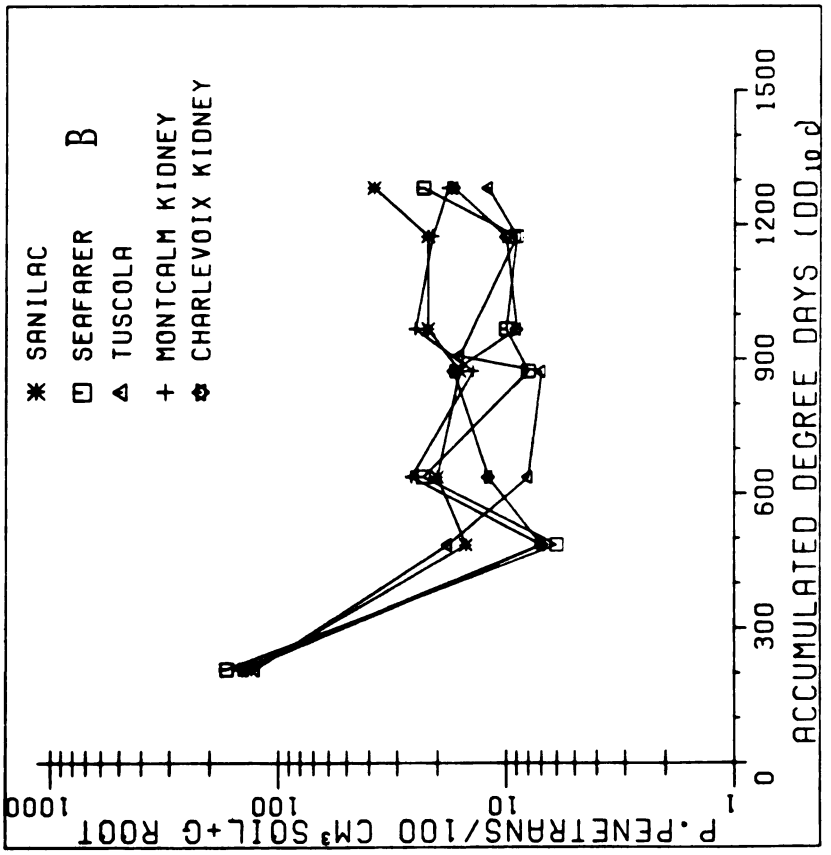


Figure 3.88. Population dynamics of P. penetrans (A) and control of P. penetrans with an input of aldicarb for control of P. penetrans associated with five dry bean varities.

of navy beans with Montcalm kidney beans could lead to increased densities of P. penetrans and greater reduction in yields in susceptible navy bean varieties. Lower population densities of P. penetrans were maintained on Charlevoix kidney and this variety is a more suitable choice for rotation in a nematode control program for navy beans.

3.7 Comparison of Population Dynamics of P. penetrans Associated with Navy Beans Over Two Growing Seasons

Because of changes in environmental conditions over periods of time, variations in seasonal patterns of population dynamics may occur from year to year. This study was designed to compare population dynamics of P. penetrans associated with navy beans in 1978 and 1979 navy bean growing seasons in Michigan.

3.7.1 Population dynamics and control of P. penetrans associated with navy beans in 1978

3.7.1.1 Method

Six replicates of navy beans cv Sanilac were planted in a randomized block design on a sandy clay loam soil at Michigan State University Montcalm experimental farm. Six replicates of seven nematicide

treatments were included for evaluation for nematode control. Each plot consisted of four rows 6.1 m in length and 0.9 m apart. Three fumigant nematicide treatments of Di (2-chloroisopropyl) ether (Nemamort 8E) were applied in-row 19 days prior to planting. The nonfumigant nematicides were applied (in-row) at the time of planting on June 21, 1978 (171 DD 10 C). Soil samples for nematode analysis were taken prior to the application of soil fumigants and at the time of planting. Soil and root samples from treatments were taken at six intervals during the growing season (3.1.1.1 and 3.1.3.2; 3.1.3-3.1.4). The center two rows of each plot were harvested on October 20, 1978 (1301 DD 10 C) and the yield of navy beans recorded.

3.7.2 Population dynamics and control of *P. penetrans* associated with navy beans in 1979

3.7.2.1 Method

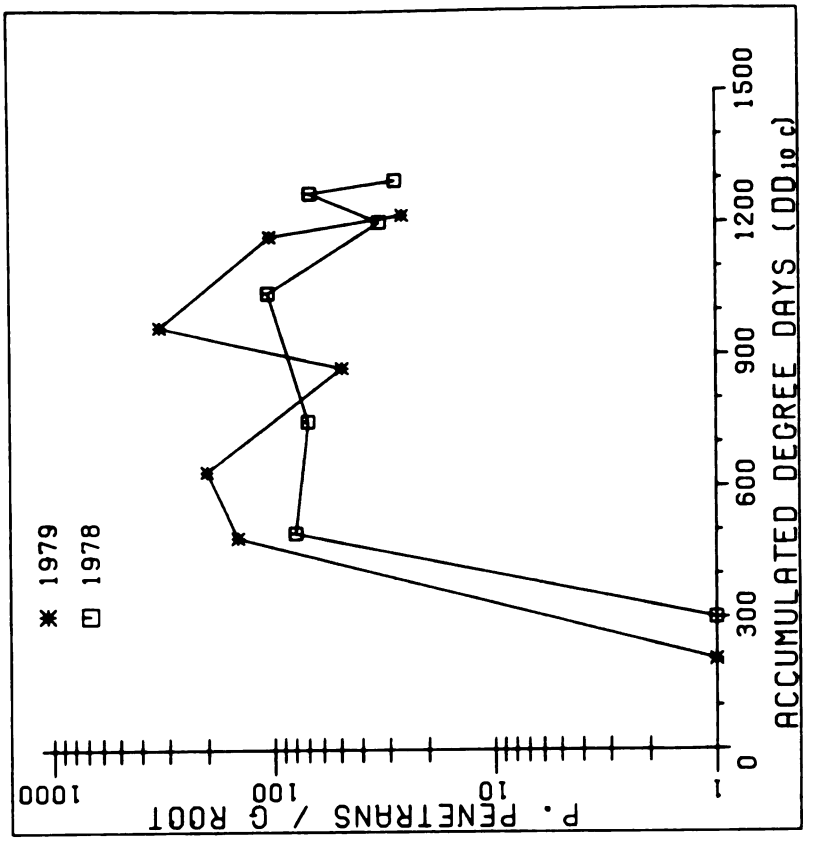
Five replicates of navy beans cv Sanilac were planted in a randomized block design in a sandy clay loam soil at Michigan State University Montcalm experimental farm. The average initial density was 116 *P. penetrans* per 100 cm^3 soil. Five replicates of seven nematicide treatments were also included for evaluation for nematode

control. Each plot consisted of four rows 6.1 m in length and 0.9 m apart. All nematicide treatments were applied in 0.2 m bands at the time of planting on June 5, 1979 (207 DD 10 C). A foliar oxamyl (Vydate L) spray was applied three weeks after planting (392 DD 10 C). Soil and root samples were taken for nematode analysis (3.1.1.1 and 3.1.3.2; 3.1.3-3.1.4) at six intervals during the growing season. The two center rows were harvested on September 21, 1979 (1221 DD 10 C).

3.7.3 Results

3.7.3.1 Population dynamics and control of *P. penetrans* associated with navy beans in 1978

Three maxima in soil and root population densities of *P. penetrans* were observed during the growth period (Figure 3.89). Root densities were highest at 1044 DD 10 C and decreased towards the end of the season (Figure 3.89B). The highest percentage of the population cohort consisted of females at all sampling periods (Table 3.14). The percentage of males were three times lower than that of females but was higher than that of other life cycle stages. The percentage of fourth stage juveniles increased and was higher at the end of the season than at the initial growth period at 300 DD 10 C (Table 3.14).



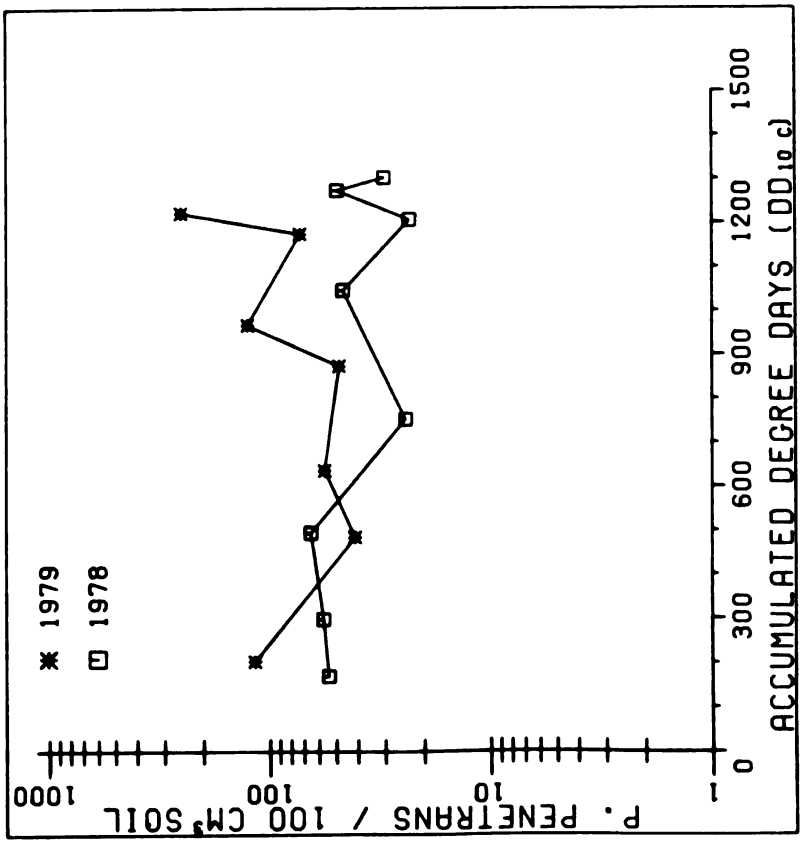


Figure 3.89. Population dynamics of P. penetrans associated with navy beans in 1978 and 1979.

Table 3.14 Dynamics of the population cohort of *P. penetrans* associated with navy beans in 1978.

DD 10 C	Population cohort (percent population)				
	F	M	2nd	3rd	4th
300	60.6	18.0	6.6	6.5	8.2
495	48.0	17.6	15.5	6.8	12.1
700	59.1	20.4	8.6	3.3	8.5
1044	56.3	16.6	11.9	5.6	8.6
1205	50.9	17.5	7.0	5.3	19.3
1272	45.7	17.2	19.8	7.8	9.5
1301	44.6	17.9	7.1	5.4	25.0

F = female

M = male

Population densities were reduced by all nematicide treatments (Table A53). Soil and root densities of P. penetrans remained relatively low throughout the growing season in plots treated for nematode control (Table A53). Navy bean yields were significantly (P = 0.05) increased in plots treated with aldicarb for nematode control. Yields were significantly (P = 0.05) reduced in plots treated with Di (2-chloroisopropyl) ether (Nemamort 8E) at 36 lb per acre (Table A53).

3.7.3.2 Population dynamics and control of P. penetrans associated with navy beans in 1979

Two maxima in root population densities were observed (Figure 3.89; Table A54). Root densities of P. penetrans increased reaching an initial maximum at 636 DD 10 C and then decreased until 872 DD 10 C. Another maximum in population densities was attained at 966 DD 10 C (Figure 3.89; Table A54). Soil population densities of P. penetrans fluctuated throughout the season decreasing rapidly during the early part of the season as nematodes entered the roots and later increasing towards the end of the season as nematodes migrated from decaying roots (Figure 3.89).

Population densities of P. penetrans were decreased with an input of aldicarb for nematode control (Table A54).

Aldicarb at 0.5 lb per acre did not significantly (P = 0.05) reduce population densities throughout the season (Table A54). Root population densities were significantly (P = 0.05) decreased by treatments of oxamyl at 1.0 lb per acre and oxymal at 1.0 lb per acre plus a foliar oxamyl spray (Table A54).

Comparison of population densities in untreated plots over 1978 and 1979 navy bean growing seasons indicated some differences in the population dynamics of P. penetrans over the two different growing seasons. Three maxima in soil population densities were observed in 1978 in contrast to two maxima in soil densities in 1979 (Figure 3.89). While soil densities of P. penetrans decreased at the end of the growing season in 1978, densities increased at this time in 1979. Soil and root population densities were higher in 1979 compared to densities in 1978 (Figure 3.89). Three maxima in root population densities were evident in 1978 and 1979 (Figure 3.89). In 1978 P. penetrans densities decreased after the maximum at 1044 DD 10 C, while in 1979 densities increased after the first maximum at 636 DD 10 C reaching another peak at 966 DD 10 C (Figure 3.89). The growing season was shorter in 1979 compared to 1978.

In 1979 dry bean yields were significantly higher in plots treated with aldicarb at rates above 0.5 lb per

acre (Table A54). Yields were also higher in plots treated with oxamyl at 1.0 lb per acre plus a foliar oxamyl spray at 1.0 lb per acre.

3.7.4 Discussion

Population densities of P. penetrans fluctuated throughout the growing season on navy beans. Soil densities generally decreased early in the season as nematodes entered roots and then remained relatively low throughout the season. P. penetrans is an endoparasite and the low soil densities are expected. Soil densities increased towards the end of the season as nematodes migrated from decaying roots.

Control of P. penetrans was obtained with inputs of aldicarb, at rates above 0.5 lb per acre. Oxamyl was also effective in controlling P. penetrans. While Di (2-chloroisopropyl) ether offered some degree of control phytotoxicity was evident as indicated by the lower yields obtained with the application of this input. Phenamiphos was also effective in controlling P. penetrans but use of this input also resulted in some degree of phytotoxicity.

The need for development of more cultural and biological methods for control of P. penetrans associated with navy beans is evident. Research on biological control of P. penetrans is limited and should increase in the

future (Ramaro, 1972; Saka, 1975). The choice of varieties tolerant to P. penetrans should be examined in conjunction with the economics of production of chosen varieties.

4.0 GENERAL DISCUSSION

4.1 An Overview of the Research Findings

Research findings indicated that Pratylenchus penetrans was found in 68% of Michigan bean fields. This nematode species was pathogenic to navy beans and significant decreases in yields of navy bean resulted in the presence of P. penetrans at densities above 25 per 100 cm^3 soil. Varieties which were tolerant to P. penetrans were identified. Temperature, soil type and soil moisture significantly influenced the pathogenic relationship between P. penetrans and navy beans. Mycorrhizal associations with navy beans also influenced the development of the root-lesion disease on navy beans. Kidney beans were also susceptible to P. penetrans. Population dynamics of P. penetrans varied over two navy bean growing seasons.

4.2 A Conceptual Model of the P. penetrans-navy Bean system based on Research Findings

A model of the P. penetrans navy bean system was developed, based on research findings (Figure 4.1). In this research study the interacting components of mycorrhizae and other crops grown in rotation with navy beans were examined. The approach to this study however, indicated a

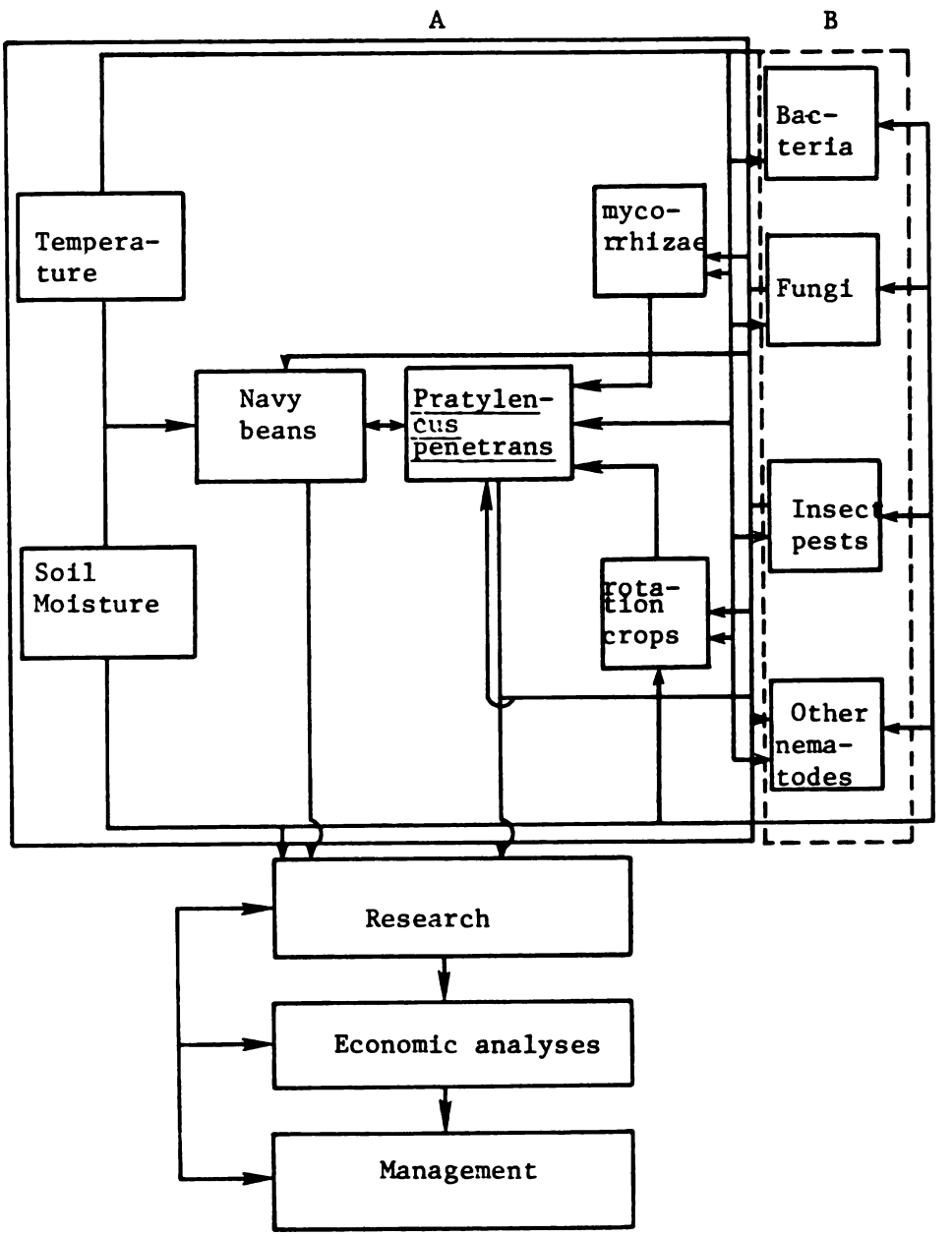


Figure 4.1. Components of the P. penetrans - navy bean ecosystem.
Components studied are enclosed in bold lines (A). Other interacting components are enclosed in dotted lines (B).

number of other interacting components. The model indicates that navy bean production is influenced by P. penetrans. The relationship between this crop and pest is influenced by environmental factors of temperature and moisture (Figure 4.1). Interacting components of mycorrhizae and other crops grown in rotation with navy beans also influence the pathogenic relationship between P. penetrans and navy beans.

The development of effective management strategies requires detailed examination of the research findings, and economic analyses of control strategies. The research findings indicated that population densities of P. penetrans were lowest at low temperatures. This indicates that planting dates should be considered as a control option if possible. Low temperatures are generally associated with early planting dates, and choice of early planting dates which are suitable for adequate germination of beans could reduce the yield loss of navy beans, as percentage yield loss is proportional to the initial P. penetrans density. Control of soil moisture is another management input which was identified. The detrimental effects of P. penetrans are emphasized under soil moisture stress or in the presence of excess soil moisture.

The incorporation of bean varieties which are tolerant to P. penetrans should be included in control programs.

5.0 SUMMARY AND CONCLUSIONS

Pratylenchus penetrans occurs in an aggregated type distribution in the field. This therefore requires that analyses of data involve suitable transformations which assist in normalizing data. The log transformation is recommended or log plus a constant when data contain zero values.

Pratylenchus spp. were present in bean fields in Michigan and high densities were associated with sandy soils and Kidney bean varieties. Tylenchorhynchus spp. were also associated with dry beans, and future research on the effect of this species on navy beans is necessary. The predominant Pratylenchus spp. was P. penetrans and this species is generally considered the most economically important species in this genus.

Pathogenicity studies indicated that this species was detrimental to growth and yield of navy beans. The response to infection by this species varied depending on the bean variety. Studies indicated that varieties of Sanilac, Seafarer and Tuscola navy beans and Montcalm Kidney beans were highly susceptible to P. penetrans, while Saginaw, Gratiot and Kentwood navy bean varieties were tolerant to P. penetrans.

The pathogenic relationship between P. penetrans and navy beans was influenced by temperature. Growth and yield of navy beans were reduced at temperatures of 15 and 30 C respectively. Optimum growth and yield were obtained at a temperature of 25 C. Population densities of P. penetrans were also influenced by temperature. Densities were highest at 25 C indicating maximum reproduction and survival at this temperature. Densities were lower at 15 and 30 C respectively, indicating lower reproduction or higher mortality.

Interactions of soil type and soil moisture influenced the development of the root-lesion disease on navy beans. Optimum growth and development of P. penetrans was obtained at a soil matrix potential of -50 centibars. Population densities of P. penetrans were higher in the sandy loam and this is expected as movement and activity of nematodes are promoted in sandy soils due to the presence of large pore spaces and more favorable temperatures. Growth and yield of beans were generally poor in the clay loam and this was due to the large volume of water retained by this soil type with its numerous small pore spaces and great water holding capacity due to slow drainage. Growth and development of beans were decreased at high and low moisture levels corresponding to matrix potentials of -5 and -1000 centibars. Population densities of P. penetrans were

decreased at these two moisture levels. The importance of adequate management of soil moisture in bean production was demonstrated.

The detrimental effects of P. penetrans on navy beans were minimized in the presence of mycorrhizal associations of G. fasciculatus and navy beans. Growth and yield of navy beans were increased by mycorrhizal associations of G. fasciculatus and navy beans in the absence of P. penetrans. The exact mechanism of the interaction of G. fasciculatus and P. penetrans is unclear and further research in this area is necessary.

Considering aspects of control choice of rotation crops should be carefully examined. The maintenance of low densities of P. penetrans at low temperatures indicate that choice of planting dates corresponding to temperatures high enough to allow adequate germination but low enough to maintain low densities of P. penetrans is advisable. Choice of early planting dates is also recommended for preventing problems associated with moisture stress at mid-season.

While control of P. penetrans was obtained with a management input of aldicarb, the use of the input should be examined from economic feasibility studies. The use of all control inputs should theoretically be economically

analysed. However the use of economic thresholds as a decision criteria in control programs is not always feasible because of the difficulty associated with assigning monetary values to control inputs such as planting date, and crop rotation. The model indicates that continual updating of the research on this system is necessary to maintain control of P. penetrans.

The research findings contribute to the understanding of the P. penetrans-navy bean ecosystem. The studies on the behavior of this system and the effects of interacting components provide information for development of management strategies for control of P. penetrans in bean production. While the research study addressed effects of environmental parameters of temperature and moisture and interacting components of mycorrhizae and Kidney beans, more detailed studies on other components such as insect pests, bacteria, fungi, other nematodes and other crops grown in rotation with navy beans are necessary for a more comprehensive understanding of the pest-crop ecosystem, and for development of more effective management of P. penetrans in bean production systems. These data should be adequate for simulation of a model of the P. penetrans-navy bean system. It would be essential however to validate such a model under varying field conditions in bean production. This model could then be used for development of management strategies.

APPENDIX

6.0 APPENDIX A

Table A1: The effect of Pratylenchus penetrans on height of six dry bean varieties.

	Accumulated degree days ($DD_{50}F$)													
	368		488		642		987		1318		1668		1956	
	Initial population density (P. penetrans/100 cm^3 soil)													
	0	150	0	150	0	150	0	150	0	150	0	150	0	150
	Plant height (cm)													
Sanilac	5.2ab	4.1a	11.9bc	5.6a	16.1c	9.0a	21.2c	11.9a	23.9c	14.9a	24.1b	14.8a	24.4b	15.0a
Seafarer	6.0ab	4.1a	12.1bc	5.9a	15.5c	8.6a	21.4c	13.0ab	22.5bc	14.8a	22.5b	14.9a	22.60b	14.93a
Tuscola	6.9b	5.3ab	13.3bc	6.3a	19.0d	11.2b	28.3d	14.1b	29.4d	15.7a	29.3c	15.8a	29.5c	15.9a
Gratiot	4.9ab	4.8ab	11.17b	12.2bc	14.4c	15.3c	19.4c	19.2c	21.2b	20.7b	21.3b	21.2b	21.5b	21.6b
Saginaw	6.3b	6.2ab	11.4bc	10.7b	13.4bc	13.5bc	20.5c	20.0c	21.2b	20.8b	22.1b	21.9b	22.4b	22.3b
Kentwood	7.0b	7.1b	13.9c	13.2bc	20.3d	20.0d	28.9d	28.3d	30.0d	29.7d	30.3c	30.0c	30.8c	30.7c

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A2: The effect of Pratylenchus penetrans on root weight of six dry bean varieties.

	Accumulated degree days ($DD_{50}F$)													
	368		488		642		987		1318		1668		1956	
	Initial population density (P. penetrans/100 cm^3 soil)													
	0	150	0	150	0	150	0		0	150	0	150	0	150
	Root weight (g/plant)													
Sanilac	0.91a	0.85a	2.06b	0.98a	2.39bc	1.15a	3.8cd	1.84ab	4.59bc	2.25a	2.22b	1.04a	0.99bc	0.39a
Seafarer	0.93a	0.75a	2.13b	0.93a	2.45bc	1.27a	3.9cd	1.53a	4.67bc	2.13a	2.32b	1.05a	0.96b	0.37a
Tuscola	1.08a	1.04a	2.35b	1.13a	2.94c	1.28a	4.31de	2.22b	5.34cd	2.59a	2.79b	1.19a	1.61d	0.53a
Gratiot	0.87a	0.86a	2.18b	2.26b	2.26b	2.76bc	3.65c	3.46c	4.34b	4.13b	2.21b	2.06b	1.24c	1.08bc
Saginaw	0.90a	0.84a	2.05b	2.03b	2.44bc	2.64bc	3.78cd	3.76cd	4.14b	4.06b	2.41b	2.31b	1.14bc	0.99bc
Kentwood	1.53b	1.46b	2.63b	2.69b	3.43d	3.36d	4.79e	4.76e	6.07d	5.74d	2.70b	2.66b	1.76d	1.69d

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A3: The effect of Pratylenchus penetrans on leaf area of six dry bean varieties.

Bean Variety	Accumulated degree days ($DD_{50}F$)													
	368		488		642		987		1318		1668		1956	
	Initial population density (P. penetrans/100 cm^3 soil)													
	0	150	0	150	0	150	0	150	0	150	0	150	0	150
	Leaf area cm^2													
Sanilac	32.07abc	28.70ab	65.34abc	77.93bc	144.5d	79.01a	247.45bc	135.31a	382.23cd	214.72ab	204.38b	77.89a	67.13b	22.02a
Seafarer	34.22abc	29.82abc	65.19abc	40.67a	135.18d	71.86a	251.22bc	114.03a	364.97cd	170.48a	186.40b	58.52a	65.46b	18.99a
Tuscola	60.07e	47.23cde	65.64abc	44.86a	171.23ef	90.45ab	298.84bc	148.69a	355.31cd	217.75ab	189.20b	66.14a	64.35b	24.41a
Gratiot	25.45a	23.75a	48.22a	46.62a	152.21de	182.10f	225.74b	249.07bc	357.61cd	313.72bcd	138.53ab	127.89ab	64.91b	58.75b
Saginaw	44.17bcde	39.44abcd	60.25abc	58.23ab	116.72c	107.62bc	220.91b	212.43b	330.54cd	285.19bc	147.86ab	143.22ab	47.83ab	45.95ab
Kentwood	54.41de	52.76de	86.99c	78.53bc	165.46ef	173.34ef	290.25bc	316.13c	420.09d	392.29cd	222.77b	220.87b	116.67c	113.50c

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A4-1: Influence of initial population density of P. penetrans on root population dynamics of P. penetrans associated with navy beans.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
$DD_{10\ C}$	Population Density/P. penetrans/g root							
254	0a	2a	3a	5a	12a	33b	47c	59c
341	0a	2a	6a	9a	20b	39c	85d	99e
434	0a	3a	13ab	19ab	23b	53c	94d	132e
523	0a	5b	19ab	29bc	44c	113d	149e	169f
603	0a	8a	19a	19a	20a	83b	115c	123c
688	0a	18a	30a	34a	37a	137b	192c	215c
782	0a	8a	15a	49a	55a	160b	292c	309c
865	0a	17ab	38ab	58ab	80ab	117b	332c	333c
967	0a	9a	29a	45a	65a	154b	208b	218b
1094	0a	3a	14a	20a	45a	127b	168c	183c
1305	0a	2a	8a	12a	28a	114b	115b	143b

The row means followed by the same letter(s) are not significantly (P = 0.05) different according to the student Newman Keuls multiple range test.

Table A4-2: Influence of initial population density of P. penetrans on soil population dynamics of P. penetrans associated with navy beans.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
$DD_{10\ C}$	Final Population Density/100 cm^3 soil							
254	0a	2a	5a	5a	29a	38a	75b	140c
341	0a	3a	4a	5a	7a	10ab	13ab	19b
434	0a	1a	2ab	4ab	5ab	10bc	15c	30d
523	0a	2ab	4ab	6ab	7ab	9b	15c	17c
603	0a	4a	12ab	13ab	20bc	27bc	30bc	37c
688	0a	3ab	6a	8bc	9bc	14c	13c	24d
782	0a	3a	7a	12ab	19bc	20bc	23bc	25c
865	0a	2a	3a	7a	10b	12b	15b	18b
967	0a	7ab	12ab	22bc	25bcd	27bcd	39cd	43d
1094	0a	17ab	25abc	48bcd	60cd	77d	117e	139e
1305	0a	20b	18b	24b	49c	63d	103e	104e

The row means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.
DD 10 C = accumulated degree days at base 10 C

Table A4-3: Influence of initial population densities of P. penetrans on total (root + soil) population dynamics of P. penetrans associated with navy beans.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
DD_{10C}	Final Population Density/100 cm^3 soil + g root							
254	0	4	8	10	41	71	122	199
341	0	5	10	14	27	49	98	118
434	0	4	15	23	28	63	109	162
523	0	7	23	35	51	122	164	186
603	0	12	31	32	40	110	145	160
688	0	21	36	42	46	151	206	239
782	0	11	22	61	74	180	315	334
865	0	19	41	65	90	129	347	351
967	0	16	41	67	90	181	247	261
1094	0	16	39	68	105	204	285	322
1305	0	22	26	36	77	177	218	247

Row means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newmans Keuls multiple range test.
DD 10 C = accumulated degree days at base 10 C.

Table A-5: Effect of different initial densities of P. penetrans on weight of navy bean roots over the growth period.

	INITIAL POPULATION DENSITY P. PENETRANS/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
DD_{10C}	Root Weight (g/plant)							
254	1.03a	1.02a	0.99a	1.48b	0.99a	0.95a	0.87a	0.73a
341	1.73b	1.64ab	1.63ab	1.50ab	1.19ab	0.85ab	0.45ab	0.78a
434	2.56c	2.98cd	3.40d	2.94cd	1.97b	1.42a	1.21a	0.97a
523	3.67b	3.66b	4.06b	3.18b	2.46a	2.19a	1.88a	1.48a
603	3.98c	3.79c	3.78c	3.50c	2.83b	2.48ab	2.36ab	1.77a
688	4.35d	3.93cd	3.84bcd	3.67abcd	3.21abc	2.91ab	2.75ab	2.85a
782	4.21b	4.13b	3.86ab	3.76ab	3.28ab	3.07a	2.84a	2.92a
865	3.87d	3.48cd	3.29cd	3.10c	2.51b	2.26b	1.93ab	1.40a
967	2.41b	2.24b	2.01b	1.98b	1.50a	1.51a	1.18a	1.13a
1094	1.56b	1.50b	1.41b	1.26b	0.97ab	0.82a	0.75a	0.56a

Row means followed by the same letter(s) are not significantly (P = 0.05) different according to the student Newman Keuls multiple range test.

Table A6: Effect of different initial densities of P. penetrans on leaf area of navy beans over the growth period.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
DD_{10C}	Leaf Area/cm^2							
254	39.06c	45.16b	43.66b	33.97b	25.29a	23.77a	20.76a	17.63a
341	70.93c	72.48c	71.88c	69.96c	50.88b	40.72ab	40.66ab	31.89a
434	123.26e	122.14e	117.70de	112.50d	76.49b	63.72b	60.43b	48.47a
523	196.83a	195.27c	188.01c	181.28b	153.03c	118.87b	97.17c	83.92a
603	308.99f	307.40f	306.30f	270.86e	238.32d	203.40c	162.96b	124.57a
688	431.68g	408.85fg	400.67f	369.15e	296.61d	246.52c	212.79b	138.94a
782	308.76f	307.85f	303.25f	223.70e	190.24d	129.50c	112.22b	82.48a
865	189.62d	179.52d	176.24d	112.61c	107.56c	71.79b	50.21ab	35.20a
967	104.22c	103.14c	100.74c	75.63b	72.08b	39.13a	31.42a	24.08a
1094	53.79d	51.11d	49.23d	34.34c	25.22b	19.04ab	13.12a	9.73a

Row means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A7: Effect of different initial densities of P. penetrans on shoot fresh weight of navy beans over the growth period.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
DD_{10C}	Fresh Weight/g							
254	1.84b	1.77b	1.72ab	1.56ab	1.51ab	1.49ab	1.31ab	1.21a
341	2.27bc	2.48c	2.86d	2.23bc	2.04bc	1.89ab	1.76a	1.51a
434	3.83c	4.12c	4.26c	3.19b	2.94ab	2.53ab	2.26a	2.16a
523	6.53c	6.94c	7.27c	6.09c	4.93b	4.34ab	3.23a	3.08a
603	9.82d	11.42e	12.39e	9.37d	7.63c	6.24b	5.26ab	4.19a
688	14.89d	16.10d	15.97d	11.79c	9.03b	7.93b	6.73b	4.42a
782	12.39c	14.47c	13.38c	8.50b	8.30b	5.94a	5.12a	3.86a
865	7.77c	9.15d	8.98d	5.93b	5.44b	4.08a	3.38a	2.93a
967	5.39cd	5.75d	6.22d	4.50c	3.58b	3.01ab	2.42a	2.08a
1094	3.16c	4.53c	4.65c	3.10b	2.26ab	2.03a	1.50a	1.34a

Row means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.
DD 10 C = accumulated degree days at base 10 C

Table A8: Effect of different initial densities of P. penetrans on dry weight of navy bean shoot system over the growth period.

	INITIAL POPULATION DENSITY/100 cm^3 SOIL							
	0	5	10	20	40	80	160	320
DD_{10C}	Dry Weight/g							
254	0.77d	0.73cd	0.68bcd	0.66bcd	0.65abc	0.60ab	0.54ab	0.50a
341	1.20c	1.18c	1.08c	1.03c	0.85b	0.78ab	0.69ab	0.59a
434	1.96b	1.65b	1.58b	1.44b	1.00a	1.92a	0.82a	0.74a
523	2.47c	2.39c	2.28c	2.18c	1.73b	1.10a	1.01a	0.89a
603	4.23e	4.17e	4.07e	3.60d	2.49c	2.07b	1.31a	1.05a
688	5.64d	5.52d	5.51d	4.77c	3.72b	3.44b	2.49a	1.66a
782	4.04c	4.02c	3.99c	3.20b	2.81b	2.16a	1.48a	0.90a
865	2.55d	2.48d	2.19d	1.39c	1.26b	0.89ab	0.72ab	0.54a
967	1.41c	1.31c	1.29c	0.89b	0.80ab	0.68ab	0.46ab	0.36a
1094	0.99d	0.91d	0.90d	0.60c	0.46bc	0.35abc	0.25ab	0.12a

Row means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.
DD 10 C = accumulated degree days at base 10 C.

Table A9: Interactions of initial density of P. penetrans and temperature on final root densities of P. penetrans.

Initial density P. penetrans/ 100 cm³ soil	Temperature (C) 15	20	25	30
	Final Population Density (P. penetrans/g root)			
0	0a	0a	0a	0a
25	5b	7b	12c	5b
150	20d	35b	62f	20d
300	27de	79f	92f	29de

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A10: Interactions of initial density of P. penetrans and temperature on final soil population densities of P. penetrans

Initial density P. penetrans/ 100 cm³ soil	Temperature (C) 15	20	25	30
	Final Population Density (P. penetrans/100 cm^3 soil			
0	0	0	0	0
25	20b	37c	59cd	24b
150	40c	94ef	128fg	45cd
300	72de	162g	237i	70de

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A11: Interactions of initial density of P. penetrans and temperatures on final total population densities of P. penetrans.

Initial density P. penetrans/ 100 cm^3 soil	Temperature (C)			
	15	20	25	30
	P. penetrans/100 cm^3 + g root			
0	0a	0a	0a	0a
25	25b	44c	70d	29b
150	60d	129fg	157g	67de
300	99ef	240h	329h	99def

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A12: Effect of P. penetrans on height of navy bean plants at different temperatures.

P. penetrans/ 100 cm^3 soil	Temperature (C)			
	15	20	25	30
	Plant Height (cm)			
0	12.7c	18.7f	21.8g	24.7h
25	12.2c	17.1ef	21.1g	23.2gh
150	9.4b	13.6cd	15.3de	18.4f
300	7.2a	11.3bc	12.5c	15.6de

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A13: Effect of P. penetrans on weight of navy bean roots at different temperatures

P. penetrans/ 100 cm³ soil	Temperature (C)			
	15	20	25	30
	Root Weight (g)			
0	0.61ab	1.16c	2.09d	0.88bc
25	0.58cd	1.08c	1.92d	0.82bc
150	0.25a	0.52ab	0.64ab	0.52ab
300	0.20a	0.33a	0.51ab	0.28a

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A14: Effect of P. penetrans on dry weight of navy bean shoot system at four different temperatures.

P. penetrans/ 100 cm³ soil	Temperature (C)			
	15	20	25	30
	Shoot Dry Weight (g/plant)			
0	0.47cd	0.83f	1.51g	0.60de
25	0.28ab	0.48cd	0.77ef	0.39c
150	0.21a	0.36b	0.63de	0.28ab
300	0.11a	0.28ab	0.44cd	0.12a

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A15: Effect of P. penetrans on yield of navy beans at different temperatures.

P. penetrans/ 100 cm³ soil	Temperature (C)			
	15	20	25	30
	Navy Bean Yield (g/plant)			
0	0.89bc	2.43e	3.46f	1.30cd
25	0.78abc	1.04bc	1.55d	0.91bc
150	0.49ab	0.93bc	1.07bc	0.70ab
300	0.26a	0.57ab	0.78abc	0.56ab

Column means followed by the same letter(s) are not significantly (P = 0.05) different according to the student Newman Keuls multiple range test.

Table A16: Effect of temperature on total population densities (root & soil) of P. penetrans associated with navy beans over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Total population density (P. penetrans/ 100 cm^3 soil)							
14	0a	95a	0a	120c	0a	127c	0a	64b
35	0a	110b	0a	147c	0a	180c	0a	95b
57	0a	125c	0a	182d	0a	307e	0a	90b
91	0a	204c	0a	220c	0a	337d	0a	112b

Table A17 : Effect of temperature on root densities of P. penetrans associated with navy beans over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of Growth	0	150	0	150	0	150	0	150
	Root population density (P. penetrans/ 100 cm^3 soil)							
14	0	40b	0	72c	0	89c	0	52b
35	0a	80b	0a	135c	0a	174c	0a	87b
57	0a	109c	0a	167d	0a	289e	0a	75b
91	0a	72c	0	74c	0	110d	0	30b

Column means followed by the same letter are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A18: Effect of temperature on soil densities of P. penetrans associated with navy beans over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Soil population densities (P.penetrans / 100 cm^3 soil)							
14	0a	55c	0a	49c	0a	38c	0a	13b
35	0a	30c	0a	12b	0a	7b	0a	9b
57	0a	17b	0a	13b	0a	20b	0a	22b
91	0a	132c	0a	147c	0a	227d	0a	82b

Means followed by the same letter are not significantly (P = 0.05) different according to the Student Newman Keuls multiple range test.

Table A19: Influence of temperature and P. penetrans on shoot dry weight of navy beans over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	Shoot dry weight (g)							
	0	150	0	150	0	150	0	150
14	0.35a	0.29a	0.74b	0.60ab	0.81b	0.69b	0.62ab	0.52ab
35	0.92ab	0.52a	1.01c	0.54a	1.18d	0.64ab	1.04c	0.68ab
57	1.54a	0.95a	1.77a	0.87a	3.32b	1.29a	1.36a	0.89a
92	0.52b	0.25a	0.73c	0.36ab	1.00d	0.49b	0.72c	0.30a

Means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newmans Keuls multiple range test.

Table A20: Effect of temperature and P. penetrans on root area of navy beans.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Root area (cm^2)							
14	4.57a	3.78a	7.36abc	6.13ab	10.06c	8.30bc	6.4ab	4.87ab
35	13.5ab	9.00a	15.53b	9.5a	21.6c	12.27ab	13.53ab	9.70a
57	16.7bc	11.43a	20.17c	12.67ab	26.83d	14.67ab	16.77bc	13.37ab
91	11.03abc	7.41a	11.62bc	9.86ab	14.50c	10.19ab	13.15bc	7.68a

Means followed by the same letter(s) are not significantly different (P = 0.05) according to the Student Newman Keuls Multiple Range Test.

TableA21. Effect of temperature and P. penetrans on root weight of navy beans over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Root weight (g/Plant							
14	.54a	.46a	.69a	.56a	1.05b	.76a	.53a	.48a
35	1.06ab	.61a	1.37b	.71a	2.42c	1.09ab	1.43b	.69a
57	1.81abc	1.03a	2.22c	1.10a	3.27d	1.44ab	2.01bc	1.05a
91	.82ab	.36a	1.22bc	.42a	1.49c	.63a	.84ab	.45a

Means followed by the same letter(s) are not significantly different (P = 0.05) according to the Student Newman Keuls Multiple Range Test.

Table A22: Effect of temperature and P. penetrans on height of navy bean plants over the growth period.

	Temperature C							
	15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Plant Height (cm)							
14	6.0ab	4.7a	8.0bc	5.9ab	9.1c	6.1ab	10.0c	9.9c
35	11.0ab	7.9a	14.1bc	11.4b	15.1c	9.5a	16.7c	14.3bc
57	16.7bc	11.4a	18.4cd	12.9ab	21.7d	14.1ab	21.1d	16.0bc
91	17.3bc	13.8a	19.9cd	14.0a	22.7e	15.8ab	21.0de	16.6abc

Means followed by the same letter(s) are not significantly different (P = 0.05) according to the Student Newman Keuls Multiple Range Test.

Table A23: Effect of temperature and P. penetrans on shoot fresh weight of navy beans over the growth period.

	Temperature C							
	15		44		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
Day of growth	0	150	0	150	0	150	0	150
	Shoot Fresh Weight (g/Plant)							
14	0.85ab	0.78a	0.98ab	0.83ab	1.12c	0.88ab	0.92ab	0.86ab
35	1.79a	0.95ab	2.09b	1.79ab	3.17c	1.68ab	1.7ab	1.03ab
57	3.58b	1.41a	6.31c	2.95b	8.34d	3.59b	3.34b	1.69a
91	1.76c	0.90ab	2.22c	1.09b	3.44d	1.22b	1.79c	0.59a

Means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newman Keuls Multiple Range Test.

TableA24: Effect of temperature and P. penetrans on length of navy bean roots over the growth period.

Day of growth	Temperature C 15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
	0	150	0	150	0	150	0	150
	Root Length (cm)							
14	5.8a	5.4a	6.8ab	7.4ab	8.7b	7.1ab	6.7ab	6.2a
35	9.9b	6.3a	17.4d	12.0bc	22.4e	13.3c	11.7bc	6.4a
57	15.9ab	12.0a	34.0c	18.9b	37.4c	19.8b	19.6b	11.7a
91	9.3ab	5.7a	16.7d	12.1bc	21.8e	13.0bc	16.6c	9.0ab

Means followed by the same letter(s) are not significantly (P = 0.05) different according to the Student Newman Keuls Multiple Range Test.

TableA25: Effect of temperature and P. penetrans on leaf area of navy beans over the growth period.

Day of growth	Temperature C 15		20		25		30	
	Initial density (P. penetrans / 100 cm^3 soil)							
	0	150	0	150	0	150	0	150
	Leaf Area (cm^2)							
14	8.90a	7.31a	15.36b	12.58ab	17.92b	16.65b	16.62b	11.97ab
35	65.76ab	41.30a	104.22c	60.84ab	132.86d	73.78e	93.82c	61.89ab
57	98.57b	55.24a	141.27c	76.22ab	188.52d	90.98ab	89.52ab	65.96ab
91	12.97a	4.73a	24.23b	12.13a	28.29b	14.32a	9.17a	6.51a

Means followed by the same letter(s) are not significantly different (P = 0.05) according to the Student Newman Keuls Multiple Range Test.

Table A26-1: Effect of soil moisture on final root populations of Pratylenchus penetrans associated with navy beans

P. Penetrans/100cm^3 Soil	Matrix potential (- Centribars)					
	P_i	10000	500	100	50	10	5
	0	0	0	0	0	0	0
Sandy Loam	150	12	20	45	175	54	14
	0	0	0	0	0	0	0
Sandy Clay Loam	150	10	34	75	132	40	55
	0	0	0	0	0	0	0
Clay Loan	150	4	7	19	73	57	15

LSD (5% = 27)

TableA26-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig Level
	107	202426.74074			
A	1	58427.25926	58427.25926	110.10738	0.00000 ***
B	5	40192.40741	8038.48148	15.14869	0.00000 ***
C	2	4232.01852	2116.00926	3.98766	0.02278 *
AB	5	40192.40741	8038.48148	15.14869	0.00000 ***
AC	2	4232.01852	2116.00926	3.98766	0.02278 *
BC	10	8472.31481	847.23148	1.59663	0.12501
ABC	10	8472.31481	847.23148	1.59663	0.12501
ERROR	72	38206.00000	530.63889		

A = Initial population density B = matrix potential C= soil type

Table A26-3. Interactions of soil type and soil moisture on final root densities of P. penetrans associated with navy bean

Soil Type	Matrix potential (- Centibars)					
	1000	500	100	50	10	5
	Final population density (P. penetrans/g root					
Sandy loam	6	10	23	88	27	7
Sandy clay loam	5	17	38	66	20	28
Clay loam	2	4	10	37	28	8

LSD (5 %) = 19

Table A26-4. Interactions of soil type and initial density of P. penetrans

Soil type	Initial population density P_i/100cm^3 soil	
	0	150
	Final population density (P. penetrans/g root)	
Sandy loam	0	53
Sandy clay loam	0	58
Clay loam	0	29

LSD (5 %) = 11

Table A26-5. Interactions of soil moisture and initial density of P. penetrans

Matrix potential (-Centibars)	Initial population density of (P_i/100cm^3 soil)	
	0	150
	Final population density (P. penetrans/100cm^3 soil	
1000	0	9
500	0	20
100	0	46
50	0	127
10	0	50
5	0	28

LSD (5 %) = 16

Table A27-1: Effect of soil moisture and *P. penetrans* on final soil population densities of *Pratylenchus penetrans* associated with navy beans

P. penetrans/100cm^3 Soil		Matrix potential (- centibars)					
	P_i	1000	500	100	50	10	5
Sandy Loam	0	0	0	0	0	0	0
	150	14	37	45	202	100	30
Sandy Clay	0	0	0	0	0	0	0
Loam	150	10	25	67	166	87	77
Clay Loam	0	0	0	0	0	0	0
	150	13	24	62	87	72	28

LSD (5% = 31)

P = initial *P. penetrans*/100cm^3 Soil

Table A27-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	300065.21296			
A	1	108742.78704	108743.78704	154.72609	0.00000 ***
B	5	56520.04630	11304.00926	16.08391	0.00000 ***
C	2	3515.35185	1757.67593	2.50091	0.08911
AB	5	56520.04630	11304.00926	16.08391	0.00000 ***
AC	2	3515.35185	1757.67593	2.50091	0.08911
BC	10	10323.98148	1032.39815	1.46896	0.16895
ABC	10	10323.98148	1032.39815	1.46895	0.16895
ERROR	72	50602.66667	702.81481		

A = Initial population density of *P. penetrans*
B = Soil matrix potential
C = Soil type

Table A27-3. Interactions of soil type and initial density of *P. penetrans* on final soil densities of *P. penetrans* associated with navy bean

Soil Type	Initial density (*P. penetrans*/100cm^3 soil)	
	0	150
	Final population density (*P. penetrans*/100cm^3 soil	
Sandy loam	0	71
Sandy clay loam	0	72
Clay loam	0	48

TableA27-4. Interactions of soil type and soil moisture

Soil Type	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Final population density (*P. penetrans*/100cm^3 soil					
Sandy loam	7	19	23	101	50	15
Sandy clay loam	5	13	33	84	43	39
Clay loam	6	12	31	43	36	14
LSD (5 %) =						

TableA27-5. Interactions of soil moisture and intital density of *P. penetrans*

Matrix Potential (- centribars)	Initial population density (P_i/100cm^3 soil)	
	0	150
	Final population density (*P. penetrans*/100cm^3 soil	
1000	0	11
500	0	28
100	0	58
50	0	152
10	0	87
5	0	45

Table A28: Effect of soil moisture on final total (root + soil) densities of P. penetrans associated with navy beans.

P. penetrans/100cm^3 Soil		Matrix potential (- centribars)					
	P_t	1000	500	1000	50	10	5
Sandy Loam	0	0	0	0	0	0	0
	150	26	57	90	377	154	44
Sandy Clay	0	0	0	0	0	0	0
Loam	150	20	59	142	298	127	132
Clay Loam	0	0	0	0	0	0	0
	150	17	31	71	160	129	43

P_t = Initial P. penetrans density/100cm^3 Soil

Table A29-1: Effect of P. penetrans on length of navy bean roots grown at six different soil water potentials

		Matrix potential (- centibars)					
	P_i	1000	500	100	50	10	5
		Root Length (cm)					
Sandy Loam	0	19.1	16.00	18.7	25.8	13.8	13.0
Sandy Clay Loam	150	16.3	14.6	17.6	16.0	11.7	8.2
Clay	0	16.4	16.5	18.5	21.5	13.1	12.3
	150	16.2	14.4	15.9	16.9	10.2	8.2
	0	15.0	13.6	14.7	16.7	11.8	11.1
	150	13.6	13.4	13.3	12.0	10.3	7.1

(LSD 5%) = 1.8

P_i = initial P. penetrans density/100cm^3 Soil

Table A29-2: Analysis of Variance

Source Total	DF	SS	MS	F	Sig. Level
	107	1652.24852			
A	1	222.45370	222.45370	86.74225	0.00000 ***
B	5	852.43407	170.48681	66.47859	0.00000 ***
C	2	194.15907	97.07954	37.85461	0.00000 ***
AB	5	93.30296	18.66059	7.27640	0.00001 ***
AC	2	10.48130	5.24065	2.04351	0.13702
BC	10	66.83537	6.68354	2.60614	0.00926 **
ABC	10	27.93537	2.79354	1.08929	0.38192
ERROR	72	184.64667	2.56454		

A = initial P. penetrans density B = matrix potential C = soil type

Table A29-3. Interactions of soil moisture and initial density of P. penetrans on length of navy bean roots.

Matrix potential	Initial population density (P. penetrans/100cm^3 soil	
	0	150
(- Centibars)	Root Length (cm)	
1000	16.8	15.4
500	15.4	14.1
100	17.3	15.6
50	21.3	14.9
10	12.9	10.9
5	12.1	7.8
LSD (5 %) = 1.0		

Table A29-4. Interactions of soil type and soil moisture

Soil Type	Matrix potential (-centibars)					
	1000	500	1000	50	10	5
	Root Length (cm)					
Sandy loam	17.7	15.3	18.2	20.9	12.8	10.6
Sandy clay loam	16.3	15.5	17.2	19.2	11.7	10.3
Clay loam	14.3	13.5	14.1	14.4	11.1	9.2
LSD (5 %) = 1.4						

Table A30-1: Effect of P. penetrans on dry weight of navy bean plants grown at six different soil water potentials

		Matrix potential (- centibars)					
	P_i	1000	500	100	50	10	5
			Shoot dry weight (g)				
Sandy Loam	0	0.36	0.35	0.72	1.11	0.71	0.37
	150	0.24	0.27	0.42	0.53	0.40	0.22
Sandy Clay	0	0.35	0.32	0.85	1.27	0.78	0.41
Loam	150	0.27	0.29	0.38	0.68	0.56	0.27
Clay	0	0.22	0.18	0.76	0.63	0.16	0.15
	150	0.17	0.15	0.29	0.40	0.17	0.16

(LSD 5%) = 0.14
P_i = initial population density of P. penetrans/100cm^3 soil

Table A30-2: Analysis of Variance

Source Total	DF	SS	MS	F	Sig. Level
	107	9.14680			
A	1	1.21603	1.21603	69.80896	0.00000 ***
B	5	3.90992	0.78198	44.89147	0.00000 ***
C	2	1.21129	0.60564	34.76830	0.00000 ***
AB	5	0.74809	0.14962	8.58912	0.00000 ***
AC	2	0.09627	0.04813	2.76320	0.06979
BC	10	0.54076	0.05408	3.10432	0.00244 **
ABC	10	0.17024	0.01702	0.97732	0.47068
ERROR	72	1.25420	0.01742		

A - initial P. penetrans density B = matrix potential C = soil type

TableA30-3. Interactions of soil type and soil moisture on shoot dry weight of navy beans

Soil Type	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Shoot dry weight (g)					
Sandy loam	0.30	0.31	0.57	0.82	0.56	0.30
Sandy clay loam	0.32	0.30	0.62	0.97	0.67	0.34
Clay loam	0.20	0.17	0.53	0.52	0.17	0.16

LSD (5 %) = 0.10

TableA30-4. Interactions of soil moisture and initial density of P. penetrans

Matrix potential (- Centibars)	Initial population density (P_i 100/cm^3 soil)	
	0	150
	Shoot dry weight (g)	
1000	0.31	0.23
500	0.28	0.24
100	0.78	0.36
50	1.0	0.53
10	0.6	0.38
5	0.3	0.22

LSD (5 %) =

TableA30-5. Interactions of soil type and initial density of P. penetrans

	Initial population density (P_i 100/cm^3 soil)	
	0	150
	Shoot dry weight (g)	
Sandy loam	0.60	0.35
Sandy clay loam	0.66	0.41
Clay loam	0.35	0.22

LSD (5 %) = .06

Table A31-1: Effect of P. penetrans on height of navy bean plants grown at six different moisture levels.

		Matrix potential (- centibars)					
	P_i	1000	500	100	50	10	5
				Plant Height (cm)			
Sandy Loam	0	14.4	13.2	19.6	23.6	19.3	12.4
	150	11.5	12.3	14.8	17.3	13.7	12.1
Sandy Clay	0	12.7	15.0	19.7	23.7	18.2	13.7
Loam	150	10.8	11.5	14.7	15.5	12.8	11.8
Clay	0	8.4	8.5	15.6	14.8	12.7	11.9
	150	7.1	7.2	12.6	13.6	13.4	8.7

(LSD 5%) = 1.2
P_i = initial density of P. pentrans/100cm^3 soil

Table A31-2: Analysis of Variance

Source Total	DF	SS	MS	F	Sig. Level
	107	1724.94000			
A	1	261.95593	261.95593	209.72009	0.00000 ***
B	5	801.38556	160.27711	128.31674	0.00000 ***
C	2	379.69389	189.84694	151.99014	0.00000 ***
AB	5	45.33409	9.06681	7.25883	0.00001 ***
AC	2	35.65019	17.82509	14.27064	0.00001 ***
BC	10	49.86056	4.98606	3.99180	0.00023 ***
ABC	10	61.12648	6.11265	4.89374	0.00002 ***
ERROR	72	89.93333	1.24907		

A = initial P. penetrans density B = matrix potential C = soil type

Table A31-3. Interactions of initial density and soil moisture on height of navy bean plants

Initial density *P. penetrans*/100cm^3 soil	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Plant height cm/g root					
0	11.9	12.3	18.2	20.7	16.8	12.7
150	9.8	10.4	14.1	15.5	13.3	10.9
LSD (5 %) = 0.8						

Table A31-4. Interactions of soil type and initial density of *P. penetrans*

Soil Type	Initial population density (P_i/100cm^3 soil)	
	0	150
	Plant height (cm)	
Sandy loam	17.1	13.6
Sandy clay loam	17.2	12.9
Clay loam	12.0	10.4
LSD (5 %) = 0.5		

Table A31-5. Interactions of soil moisture and soil type

Soil Type	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Plant height (cm)					
Sandy loam	12.9	12.8	17.2	20.4	16.5	12.2
Sandy clay loam	11.8	13.3	17.2	19.6	15.5	12.8
Clay loam	7.8	7.9	14.0	14.2	13.0	10.3
LSD (5 %) = 1.0						

Table A32-1: Effect of P. penetrans on root area of navy bean plants grown at six different water potentials

		Soil Water potential (- Centibars)					
	P_i	1000	500	100	50	10	5
			Root area (cm^2)				
Sandy Loam	0	5.56	6.34	6.88	10.08	8.65	6.57
	150	3.35	4.02	5.22	6.22	4.72	3.43
Sandy Clay	0	5.12	5.33	6.17	9.67	8.04	5.8
Loam	150	4.56	3.60	3.61	5.33	3.92	2.95
Clay	0	3.53	3.58	4.99	7.32	6.28	3.92
	150	2.94	3.42	4.13	4.53	3.52	2.32

LSD (5%) = 0.74
P_i - initial P. penetrans density/$100cm^3$ soil

Table A32-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	410.20931			
A	1	147.84588	147.84588	351.27465	0.00000 ***
B	5	129.14776	25.82955	61.36976	0.00000 ***
C	2	54.75177	27.37589	65.04378	0.00000 ***
AB	5	27.92629	5.58526	13.27030	0.00000 ***
AC	2	10.54544	5.27272	12.52773	0.00002 ***
BC	10	6.01549	0.60155	1.42925	0.18512
ABC	10	3.67304	0.36730	0.87270	0.56228
ERROR	72	30.30365	0.42088		

A = initial P. penetrans density B = matrix potential C = soil type

Table A32-3. Interactions of initial density of P. penetrans and soil moisture on area of navy bean roots

Initial density P. penetrans/100cm^3 soil	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	root area (cm^2)					
0	4.7	5.1	6.0	9.0	7.7	5.4
150	3.6	3.7	4.3	5.4	4.1	2.9
LSD (5 %) = 0.4						

Table A32-4. Interactions of soil type and initial density of P. penetrans

Soil Type	Initial population density (P_i/100cm^3 soil	
	0	150
	root area (cm^2)	
Sandy loam	7.4	4.5
Sandy clay loam	6.7	4.0
Clay loam	4.9	3.5
LSD (5 %) = 0.30		

Table A32-5. Interactions of soil moisture and soil type

Soil Type	Matrix potential (-Centibars)					
	1000	500	100	50	10	5
	root area (cm^2)					
Sandy loam	4.5	5.2	6.0	8.2	6.7	5.0
Sandy clay loam	4.8	4.5	4.9	7.5	6.0	4.4
Clay loam	3.2	3.5	4.6	5.9	4.9	3.1
LSD (5 %) = 0.52						

Table A33-1: Effect of P. penetrans on yield of dry beans grown at six different matrix potentials.

		Matrix potential (- Centibars)					
	P_1	1000	500	100	50	10	5 / 0.7
				Bean yield (g)			
Sandy Loam	0	1.27	1.60	2.24	2.64	1.47	0.93
	150	0.67	0.80	1.41	1.47	0.76	0.63
Sandy Clay	0	1.01	1.04	2.01	2.27	0.94	0.72
Loam	150	0.73	0.87	1.09	1.17	0.67	0.53
Clay	0	0.73	0.83	1.40	1.20	0.95	0.49
	150	0.45	0.62	0.82	0.69	0.70	0.30

(LSD 5%) = 0.23
P_1 = initial P. penetrans

Table A33-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	34.07674			
A	1	7.28001	7.28001	177.17721	0.00000***
B	5	13.65045	2.73009	66.44352	0.00000***
C	2	5.65517	2.82758	68.81627	0.00000***
AB	5	1.62074	0.32415	7.88895	0.00001***
AC	2	0.72540	0.36270	8.82723	0.00037***
BC	10	1.73485	0.17349	4.22220	0.00013***
ABC	10	0.45171	0.04517	1.09935	0.37451
ERROR	72	2.95849	0.04109		

A = initial soil density of P. penetrans B = matrix potential C = soil type

TableA33-3. Interactions of soil type and soil moisture on yield of navy beans

Soil Type	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Dry bean yield (g)					
Sandy loam	0.96	1.20	1.83	2.06	1.11	0.78
Sandy clay loam	0.87	0.96	1.55	1.72	0.80	0.62
Clay loam	0.59	0.72	1.11	0.95	0.83	0.40
LSD (5 %) = 0.16						

TableA33-4. Interactions of soil moisture and initial density of P. penetrans

Initial density (P_i/ 100 cm^3 soil)	Matrix potential (-centibars)					
	1000	500	100	50	10	5
	Dry bean yield (g)					
0	1.0	1.16	1.88	2.04	1.12	0.71
150	0.62	0.76	1.10	1.11	0.71	0.49
LSD (5 %) = 0.08						

TableA33-5. Interactions of soil type and initial density of P.penetrans

Soil Type	Initial population density (P_i/100cm^3 soil	
	0	150
	Dry bean yield (g)	
Sandy loam	1.69	0.96
Sandy clay loam	1.33	0.84
Clay loam	0.93	0.60
LSD (5 %) = 0.16		

Table A34-1: Effect of interactions of soil water potential, soil type and initial population densities of P. penetrans on root population densities of P. penetrans over time.

	Accumulated degree days ($DD_{10}D$)											
	285			1056			1407			1746		
	Soil water potential (- Centibars)											
	1000	50	5	1000	50	5	1000	50	5	1000	50	5
P_i	P. penetrans/g root											
Sandy Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	5	10	5	3	9	5	17	29	15	1	6	1
150	22	50	25	12	55	15	25	105	22	7	22	9
300	40	125	59	6	87	59	40	112	45	19	52	15
Clay Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	7	7	5	3	7	2	10	20	7	3	4	1
150	15	30	17	10	22	7	20	65	17	10	24	14
300	40	65	39	30	50	22	27	92	28	3	39	7
Sandy Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	7	14	5	4	10	2	22	42	24	4	8	6
150	35	98	30	12	22	15	24	190	52	20	80	20
300	72	138	98	64	122	77	42	287	62	32	72	44
(LSD 5%)		20			13			28			11	

P_i - initial P. pentrans density/$100cm^3$ soil

Table A34-2: Interactions of soil type, soil moisture and intial density of P. penetrans on root popualtion densities of P. penetrans at 1056 DD 10 C

Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	98681.43519			
A	2	3818.57407	1909.28704	15.69277	0.00000 ***
B	2	7763.46296	3881.73148	31.90464	0.00000 ***
C	3	54195.65741	18065.21914	148.48125	0.00000 ***
AB	4	1831.81481	457.95370	3.76400	0.00776 **
AC	6	10748.53704	1791.42284	14.72402	0.00000 ***
BC	6	7981.87037	1330.31173	10.93407	0.00000 ***
ABC	12	3581.51852	298.45988	2.45309	0.00967 **
ERROR	72	8760.00000	121.66667		

A = soil type
B = matrix potential
C = initial density of P. penetrans / 100 cm^3 soil.

TableA34-3. Interactions of soil type and soil moisture on final root densities of P. penetrans associated with navy bean

Soil Type	Matrix potential (-Centibars) 1000	50	5
	Final population density (P. penetrans/g root)		
Sandy clay loam	.5	38	20
Clay loam	11	20	8
Sandy loam	20	39	24

LSD (5 %) = 6

Table A34-4. Interactions of soil type and initial density of P. penetrans

Soil Type	Initial population density (P_i/100cm^3 soil) 0	25	150	300
	Final population density (P. penetrans/g root)			
Sandy laom	0	6	27	50
Sandy clay loam	0	4	13	34
Clay loam	0	5	16	87

LSD (5 %(= 8

TableA34-5. Interactions of soil moisture and initial density of P. penetrans

Matrix potential (-Centibars)	Initial population density (P_i/100cm^3 soil) 0	25	150	300
	Final population density (P. penetrans/100cm^3 soil)			
1000	0	3	11	33
50	0	9	33	86
5	0	3	12	53

LSD(5 %) = 8

Table A35-1: Effect of interaction of soil water potential, soil type and different initial population densities of P. penetrans on soil population densities of P. penetrans over time.

	Accumulated degree days ($DD_{10}C$)											
	285			1056			1407			1746		
	Soil Water potential (-Centibars)											
P_i	1000	50	5	1000	50	5	1000	50	5	1000	50	5
	P. penetrans/100cm^3 soil											
Sandy Clay Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	5	9	5	5	25	5	2	10	4	6	49	8
150	12	25	12	5	30	10	4	12	5	17	60	30
300	19	51	15	2	36	6	3	14	4	19	98	47
Clay Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	3	4	5	11	25	5	2	6	2	9	22	15
150	7	17	7	6	14	6	3	13	4	15	35	12
300	7	34	10	5	12	6	4	14	7	27	122	44
Sandy Loam												
0	0	0	0	0	0	0	0	0	0	0	0	0
25	6	9	7	10	47	8	12	20	4	29	81	25
150	19	52	15	19	45	17	10	22	8	99	144	55
300	18	69	24	18	62	22	15	34	9	60	244	62

(LSD 5%) = 7

P_i - initial P. penetrans density per 100cm^3 soil.

Table A.35-2: Interactions of soil moisture, soil type and P. penetrans on soil densities of P. penetrans at 1056 $DD_{10}C$.

Analysis of variance

Source Total	DF	SS	MS	F	Sig Level
	107	26759.21296			
A	2	3203.62963	1601.81481	41.99951	0.00000 ***
B	2	6956.90741	3478.45370	91.20490	0.00000 ***
C	3	6789.21296	2263.07099	59.33762	0.00000 ***
AB	4	1466.75926	366.68981	9.61459	0.00000 ***
AC	6	2027.70370	337.95062	8.86105	0.00000 ***
BC	6	2499.31481	416.55247	10.92199	0.00000 ***
ABC	12	1069.68519	89.14042	2.33726	0.01363 *
ERROR	72	2746.00000	38.13889		

A = soil type
B = matrix potential
C = initial density of P. penetrans / 100 cm^3 soil

TableA36-1: Effect of soil moisture, soil type and intital population densities of Pratylenchus penetrans on final population densities of P. penetrans

Soil Type									
Sandy Clay Loam				Clay Loam			Sandy Loam		
Soil Water Potential (-Centibars)									
Initial density P. penetrans/ 100cm^3 soil	1000	50	5	1000	50	5	1000	50	5
	Final population density (P_f/100^3 soil)								
0	0	0	0	0	0	0	0	0	0
25	7	54	9	12	26	16	33	89	31
150	24	82	39	25	59	26	121	224	75
300	38	150	62	29	160	50	92	316	106

LSD (5%) = 20

Table A36-2: Analysis of variance.

Source	DF	SS	MS	F	Sig. Level
Total	107	501728.32407			
A	2	53163.85185	26581.92593	94.32099	0.00000 ***
B	2	97191.62963	48595.81481	172.43316	0.00000 ***
C	3	190846.32407	63615.44136	225.72749	0.00000 ***
AB	4	16591.92593	4147.98148	14.71834	0.00000 ***
AC	6	32874.81481	5479.13580	19.44169	0.00000 ***
BC	6	73556.14815	12259.35802	43.50004	0.00000 ***
ABC	12	17212.29630	1434.35802	5.08955	0.00000 ***
ERROR	72	20291.33333	281.82407		

A = soil type B = matrix potential C = initial density of P. penetrans/ 100 cm^3 soil.

Table A36-3. Interactions of soil type and soil moisture on final population densities of P. penetrans

Soil type	Matrix potential (-Centibars) 1000	50	5
	Final population density (P_f/100cm^3 soil		
Sandy clay loam	20	72	27
Clay loam	17	61	23
Sandy loam	47	150	53
LSD (5 %) = 0			

TableA36-4. Interactions of soil moisture and initial population density of P. penetrans

Matrix potential (-Centibars)	Initial population density (P_i/100cm^3)soil 0	25	150	300
	Final population density (P_f/100cm^3 soil			
1000	0	17	40	53
50	0	48	120	208
5	0	19	47	73
LSD (5 %) = 12				

TableA30-5. Interaction of initial population density

Soil type	Initial population density (P_i/100cm^3 soil) 0	25	150	300
	Final population density (P_f/100cm^3 soil)			
Sandy clay loam	0	23	52	83
Clay loam	0	18	37	80
Sandy loam	0	43	119	171
LSD (5 %) = 12				

Table A37-1: Effect of interactions of soil water potential, soil type and different initial population densities of P. penetrans on navy bean root weight over time.

	Accumulated degree days ($DD_{10}C$)											
	285			1056			1407			1746		
	Soil water potential (- Centibars)											
	1000	50	5	1000	50	5	1000	50	5	1000	50	5
P_i	Root weight (g/plant)											
Sandy Clay Loam												
0	0.99	1.58	1.12	1.77	3.07	2.37	1.20	1.73	1.45	0.94	1.21	0.97
25	1.29	1.59	1.22	1.73	3.27	1.95	1.17	1.99	1.33	0.90	1.31	0.98
150	0.82	1.07	0.84	1.34	1.64	1.33	0.71	1.25	1.10	0.67	0.74	0.56
300	0.74	0.86	0.75	1.12	1.29	1.13	0.66	0.98	1.01	0.48	0.72	0.48
Clay Loam												
0	0.86	1.33	0.98	1.88	2.63	2.07	2.08	1.89	1.44	1.10	1.12	1.01
25	0.77	0.97	0.83	1.55	2.49	2.13	1.75	2.20	1.15	1.04	1.07	0.76
150	0.76	0.84	0.72	1.03	1.40	0.93	0.99	1.0	0.77	0.76	0.75	0.54
300	0.61	0.69	0.58	0.92	1.14	0.92	0.80	0.78	0.62	0.42	0.70	0.49
Sandy Loam												
0	1.63	1.07	0.92	2.11	3.51	2.46	2.38	1.94	1.62	1.56	1.23	1.25
25	1.65	1.26	1.11	1.93	3.12	2.43	2.12	2.20	1.33	1.40	1.34	0.91
150	0.88	0.83	0.79	1.59	1.90	1.67	1.13	1.14	0.86	0.86	0.70	0.49
300	0.74	0.64	0.62	1.01	1.91	0.92	1.07	0.98	0.80	0.82	0.55	0.40
(LSD 5%)		0.24			0.48			0.46			0.21	

P_i = initial P. penetrans density per $100/cm^3$ soil

Table A 37-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	12.60262			
A	2	1.15390	0.57695	13.11280	0.00001 ***
B	2	0.63904	0.31952	7.26192	0.00134 **
C	3	4.86009	1.62003	36.81966	0.00000 ***
AB	4	1.26843	0.31711	7.20715	0.00006 ***
AC	6	0.67422	0.11237	2.55393	0.02677 *
BC	6	0.18640	0.03107	0.70608	0.64568
ABC	12	0.65260	0.05438	1.23601	0.27626
ERROR	72	3.16793	0.04400		

Table A 37-3: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	65.77282			
A	2	3.73247	1.86623	10.65635	0.00009 ***
B	2	11.98907	5.99453	34.22930	0.00000 ***
C	3	32.20174	10.73391	61.29158	0.00000 ***
AB	4	0.53728	0.13432	0.76698	0.55021
AC	6	0.25537	0.04256	0.24303	0.96060
BC	6	2.97217	0.49536	2.82856	0.01576 *
ABC	12	1.47546	0.12295	0.70208	0.74434
ERROR	72	12.60927	0.17513		

A = soil type B = matrix potential C = initial density of P. penetrans

Table A.37-4: Analysis of variance

Source	DF	SS	MS	F	Sig Level
Total	107	39.14379			
A	2	1.17088	9.58544	3.43078	0.03774 *
B	2	2.68390	1.34195	7.86406	0.00081 ***
C	3	17.37643	5.79214	33.94293	0.00000 ***
AB	4	2.56533	0.64133	3.75832	0.00783 **
AC	6	1.05935	0.17656	1.03466	0.41015
BC	6	1.77939	0.29657	1.73793	0.12451
ABC	12	0.22217	0.01851	0.10850	
ERROR	72	12.28633	0.17064		

Table A37-5: Analysis of variance

Source	DF	SS	MS	F	Sig Level
Total	107	12.42147			
A	2	0.45950	0.22975	6.42061	0.00272 **
B	2	0.96383	0.48191	13.46758	0.00001 ***
C	3	6.89858	2.29953	64.26249	0.00000 ***
AB	4	0.75519	0.18880	5.27615	0.00088 ***
AC	6	0.36886	0.06148	1.71803	0.12909
BC	6	0.18738	0.03123	0.87274	0.51929
ABC	12	0.21173	0.01764	0.49309	0.91237
ERROR	72	2.57640	0.03578		

A = soil type B = matrix potential C = initial density of *P. penetrans*

TableA37-6. Interactions of initial density and soil moisture on weight of navy been roots

Initial density of *P. penetrans*/ $100cm^3$ soil	Matrix potential (-centibars)		
	1000	50	5
	root weight (g)		
0	1.2	1.2	1.1
25	1.1	1.2	0.9
150	0.8	0.7	0.5
300	0.6	0.7	0.5

LSD (5 %) = .12

TableA37-7. Interactions of soil type and initial density of *P. penetrans*

Soil Type	Initial population density ($P_i/100cm^3$ soil)			
	0	25	150	300
	root weight (g)			
Sandy loam	1.0	1.1	0.7	0.6
Sandy clay loam	1.1	0.9	0.7	0.5
Clay loam	1.3	1.2	0.6	0.6

LSD (5 %) = 0.12

TableA37-8. Interactions of soil moisture and soil type

Soil Type	Matrix potential (- Centibars)		
	1500	50	5
	root weight (g)		
Sandy loam	0.7	0.8	0.7
Sandy clay loam	1.0	0.9	0.7
Clay loam	0.7	0.7	0.8

LSD (5 %) =

Table A38-1: Effect of interactions of soil water potential, soil type and different initial population densities of P. penetrans on navy bean shoot dry weight over time.

	Accumulated degree days ($DD_{10}C$											
	285			1056			1407			1746		
	Soil water potential (- Centibars)											
	100	5	5	100	50	5	100	50	5	100	50	5
P_i	Dry weight (g/plant)											
Sandy Clay Loam												
0	0.47	0.67	0.52	1.32	2.48	1.46	0.74	0.96	0.64	0.36	0.52	0.50
25	0.44	0.60	0.48	1.25	2.21	1.37	0.71	0.80	0.57	0.33	0.49	0.43
150	0.43	0.59	0.43	0.88	1.34	0.90	0.55	0.72	0.48	0.24	0.40	0.37
300	0.39	0.50	0.42	0.65	1.03	0.71	0.38	0.48	0.31	0.19	0.29	0.21
Clay Loam												
0	0.35	0.47	0.40	1.51	2.62	1.91	0.84	0.75	0.42	0.37	0.47	0.36
25	0.36	0.43	0.38	1.12	1.74	1.35	0.76	0.65	0.41	0.36	0.43	0.34
150	0.35	0.41	0.36	0.87	1.02	0.95	0.71	0.50	0.35	0.28	0.34	0.31
300	0.30	0.33	0.27	0.64	0.82	0.75	0.53	0.32	0.30	0.18	0.31	0.24
Sandy Loam												
0	0.46	0.73	0.47	1.57	3.21	2.12	0.71	0.84	0.66	0.38	0.64	0.52
25	0.42	0.70	0.45	1.51	1.85	1.65	0.66	0.81	0.58	0.36	0.60	0.49
150	0.41	0.63	0.48	0.96	0.73	0.90	0.50	0.68	0.48	0.28	0.55	0.31
300	0.38	0.51	0.40	0.78	0.43	0.92	0.45	0.43	0.28	0.19	0.32	0.25
(LSD 5%)		.06			0.48			0.12			0.08	

P_i = initial density of P. penetrans/$100cm^3$ soil

Table A.38-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level	
	107	1.47711				
A	2	0.41291	0.20645	58.93825	0.00000	***
B	2	0.48054	0.24027	68.59132	0.00000	***
C	3	0.19293	0.06431	18.35925	0.00000	***
AB	4	0.08447	0.02112	6.02891	0.00031	***
AC	6	0.00522	0.00087	0.24841	0.95844	
BC	5	0.03092	0.00515	1.47113	0.20031	
ABC	12	0.01791	0.00149	0.42610	0.94813	
ERROR	72	0.25221	0.00350			

Table A.38-3: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level	
	107	53.99690				
A	2	0.28710	0.14355	0.82580	0.44199	
B	2	5.04424	2.52212	14.50897	0.00001	***
C	3	27.90791	9.30264	53.51515	0.00000	***
AB	4	0.66839	0.16710	0.96126	0.43413	
AC	6	1.52282	0.25380	1.46005	0.20420	
BC	6	5.13001	0.85500	4.91855	0.00029	***
ABC	12	0.92055	0.07671	0.44130	0.94094	
ERROR	72	12.51589	0.17383			

A = soil type B = matrix potential C = initial density of *P. penetrans*

Table A.38-4: Analysis of Variance

Source Total	DF	SS	MS	F	Sig Level
	107	4.07567			
A	2	0.08476	0.04238	4.22134	0.01847 *
B	2	0.86943	0.43471	43.29909	0.00000 ***
C	3	1.82852	0.60951	60.70891	0.00000 ***
AB	4	0.38965	0.09741	9.70257	0.00000 ***
AC	6	0.02719	0.00453	0.45141	0.84168
BC	6	0.07828	0.01305	1.29952	0.26848
ABC	12	0.07497	0.00625	0.62231	0.81650
ERROR	72	0.72287	0.01004		

Table A.38-5: Analysis of variance

Source Total	DF	SS	MS	F	Sig Level
	107	1.75855			
A	2	0.09656	0.04828	10.84464	0.00000 ***
B	2	0.41603	0.20801	46.72491	0.00000 ***
C	3	0.75521	0.25174	56.54629	0.00000 ***
AB	4	0.07674	0.01919	4.30964	0.00350 **
AC	6	0.03375	0.00562	1.26335	0.28511
BC	6	0.00760	0.00127	0.28453	0.94250
ABC	12	0.05212	0.00434	0.97564	0.47994
ERROR	72	0.32054	0.00445		

A = soil type B = matrix potential C = initial density of P. penetrans

Table A38-6. Interactions of soil moisture and *P. penetrans* on shoot dry weight of navy beans.

Initial density *P. penetrans*/100cm^3 soil	Matrix potential (-centibars) 1000	50	5
	Shoot dry weight (g)		
0	0.37	0.54	0.46
25	0.35	0.51	0.42
150	0.27	0.43	0.33
300	0.18	0.31	0.24
LSD (5 %) = 0.04			

Table A38-7. Interactions of soil type and soil moisture

Soil type	Matrix potential (-centibars) 1000	50	5
	Shoot dry weight		
Sandy loam	0.28	0.42	0.38
Sandy clay loam	0.30	0.39	0.31
Clay loam	0.31	0.53	0.39
LSD (5 %) = 0.04			

Table A38-8. Interactions of soil type and initial density of *P. penetrans*.

Soil Type	Initial population density (P_i/100cm^3 soil) 0	25	150	300
	Shoot dry weight (g)			
Sandy loam	0.46	0.42	0.34	0.23
Sandy clay loam	0.40	0.38	0.31	0.25
Clay loam	0.51	0.48	0.38	0.25
LSD (5 %) = 0.04				

Table A39-1: Effect of interactions of soil water potential, soil type and different initial population densities of P. penetrans on height of navy bean over time.

	Accumulated degree days ($DD_{10}C$)											
	285			1056			1407			1746		
	Soil water potential (-Centibars)											
	1000	50	5	100	50	5	100	50	5	1000	50	5
P_i	Plant Height (cm)											
Sandy Clay Loam												
0	4.2	8,2	6.1	9.0	19.3	11.9	12.5	26.4	16.4	14.2	27.0	16.5
25	4.3	8.3	5.3	7.5	14.8	10.1	13.6	18.9	13.4	13.4	18.7	13.9
150	3.3	5.3	3.1	7.8	12.9	9.0	9.6	15.7	11.9	9.5	17.1	11.8
300	2.9	4.9	3.4	6.4	11.2	7.9	8.5	16.4	10.9	9.2	17.3	11.7
Clay Loam												
0	3.5	5.5	4.3	6.5	16.1	8.4	12.8	23.3	15.1	12.7	25.2	15.3
25	3.3	4.7	3.5	7.6	12.4	7.7	12.3	18.9	13.2	12.5	15.7	13.1
150	3.4	4.3	3.3	6.2	11.5	7.8	10.1	13.8	10.3	10.1	14.3	10.4
300	3.1	4.0	3.4	5.9	9.2	7.1	7.7	12.9	8.4	9.0	13.2	10.2
Sandy Loam												
0	6.8	12.4	8.9	11.3	21.2	15.2	17.4	32.2	18.5	17.1	32.1	18.5
25	4.9	10.4	6.8	9.6	16.6	11.3	14.9	21.2	16.5	14.7	20.6	16.5
150	3.5	6.6	4.9	7.7	14.3	8.6	10.5	17.6	11.8	10.6	17.7	12.6
300	3.3.	5.2	3.9	6.5	12.8	7.3	7.8	16.2	8.7	10.9	16.1	11.9
(LSD 5%)		0.8			1.8			2.0			2.1	

P_i = initial density of P. penetrans per/$100cm^3$ soil

Table A.39-2: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	553.37667			
A	2	123.72167	61.86083	123.08346	0.00000 ***
B	2	144.18667	72.09333	143.44289	0.00000 ***
C	3	144.25296	48.08432	95.67256	0.00000 ***
AB	4	23.12667	5.78167	11.50368	0.00000 ***
AC	6	57.18870	9.53145	18.96457	0.00000 ***
BC	6	18.69037	3.11506	6.19799	0.00003 ***
ABC	12	6.02296	0.50191	0.99865	0.45917
ERROR	72	36.18667	0.50259		

Table A.39-3: Analysis of variance

Source Total	DF	SS	MS	F	Sig. Level
	107	1731.11657			
A	2	164.20019	82.10009	30.96926	0.00000 ***
B	2	871.45130	435.72565	164.36160	0.00000 ***
C	3	358.95657	119.65219	45.13443	0.00000 ***
AB	4	10.48426	2.62106	0.98870	0.41931
AC	6	49.34204	8.22367	3.10208	0.00928 **
BC	6	70.80870	11.80145	4.45167	0.00069 ***
ABC	12	15.00019	1.25002	0.47152	0.92502
ERROR	72	190.87333	2.65102		

A = soil type B = matrix potential C = initial density of P. penetrans

Table A.39-4: Analysis of variance

Source Total	DF	SS	MS	F	Sig Level
	107	3176.40917			
A	2	147.12389	73.56194	24.10989	0.00000 ***
B	2	1302.53722	651.26861	213.45293	0.00000 ***
C	3	1186.28991	395.42997	129.60196	0.00000 ***
AB	4	29.62889	7.40722	2.42771	0.05551
AC	6	84.66870	14.11145	4.62502	0.00050 ***
BC	6	179.55315	29.92552	9.80807	0.00000 ***
ABC	12	26.92741	2.24395	0.73545	0.71239
ERROR	72	219.68000	3.05111		

Table A.39.5: Analysis of variance

Source Total	DF	SS	MS	F	Sig Level
	107	2921.13185			
A	2	176.72074	88.36037	25.45322	0.00000 ***
B	2	1158.43574	579.21787	166.85034	0.00000 ***
C	3	1004.12074	334.70691	96.41616	0.00000 ***
AB	4	24.97204	6.24301	1.79837	0.13854
AC	6	34.10815	5.68469	1.63754	0.14926
BC	6	254.90870	42.48478	12.23823	0.00000 ***
ABC	12	17.91907	1.49326	0.43015	0.94627
ERROR	72	249.94667	3.47148		

A = soil type B = matrix potential C = initial density of P. penetrans

Table A40-1: Effect of soil type, soil moisture and initial population density of *Pratylenchus penetrans* on yield of navy beans

	Soil Type								
	Sandy clay loam			Clay Loam			Sandy Loam		
	Soil Water Potential (-Centibars)								
P_i	1000	50	5	1000	50	5	1000	50	5
	Navy bean yield (g/ plant)								
0	1.57	2.28	1.90	0.58	1.63	0.89	1.14	2.84	2.13
25	1.18	2.0	1.68	0.52	1.34	0.60	1.05	2.67	1.12
150	0.39	0.89	0.59	0.25	0.65	0.36	0.68	1.39	0.88
300	0.21	0.64	0.37	0.16	0.38	0.17	0.25	0.86	0.53

LSD (5%) = 0.24

Table A40-2: Analysis of Variance

Source Total	DF	SS	MS	F	Sig. Level
	107	59.78197			
A	2	8.83454	4.41727	74.32427	0.00000 ***
B	2	11.87054	5.93527	99.86585	0.00000 ***
C	3	27.82724	9.27575	156.07220	0.00000 ***
AB	4	1.34493	0.33623	5.65740	0.00051 ***
AC	6	2.30981	0.38497	6.47741	0.00002 ***
BC	6	2.22939	0.37157	6.25189	0.00003 ***
ABC	12	1.08639	0.09053	1.52328	0.13578
ERROR	72	4.27913	0.05943		

A = soil type B = matrix potential C = initial density of *P. penetrans*

Table A40-3. Effect of interactions of soil type and *P. penetrans* on yield of navy beans.

Soil Type	Initial population density (P_i/100cm^3 soil)			
	0	25	150	300
	Yield (g)			
Sandy clay loam	1.92	1.62	0.63	0.41
Clay loam	1.03	0.82	0.42	0.24
Sandy loam	2.04	1.62	0.98	0.55
LSD (5 %) = 0.16				

Table A40-4. Interactions of soil moisture and initial population density of *P. penetrans*.

Matrix potential (-Centibars)	Initial population density (P_i/100cm^3 soil			
	0	25	150	300
	Yield (g)			
1000	1.09	0.92	0.44	0.21
50	2.25	2.0	0.98	0.63
5	1.64	1.13	0.61	0.35
LSD (5 %) = 0.16				

Table A40-5. Interactions of soil type and soil moisture

Soil Type	Matrix potential (-Centibars)		
	1000	50	5
	Yield (g)		
Sandy clay loam	0.83	1.46	1.34
Clay loam	0.38	0.99	0.50
Sandy loam	0.78	1.94	1.17
LSD (5 %) = 0.14			

Table A41. Effect of different densities of Glomus fasciculatus on growth and yield of navy beans.

G. fasciculatus spores/100 cm^3 soil	Fresh Wt. g/plant	Dry Wt. g/plant	leaf area cm^2 plant	Pt. height cm	Dry bean yield g/plant
0	12.17a	2.88a	314.58a	19.68a	2.29a
10	14.72b	3.24ab	318.91a	20.28ab	2.43ab
50	15.0b	3.44ab	329.38a	20.93ab	2.66ab
100	17.53c	3.85b	408.94b	23.43bc	2.95bc
500	19.68d	3.92c	429.89b	25.27d	3.33c
1000	20.80d	4.64c	454.28b	27.69d	3.39c

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newmans Keuls Multiple Range test.

Table A42. **Effect of different densities of** G. fasciculatus on area, weight and length of navy bean roots and on mycorrhizal root infection and number of spores of G. fascicultus.

Glomus sp spores/ 100 cm^3 soil	Root area cm^2/plant	Root weight g/plant	Root length cm/plant	% root infectiom	No. of spores/ 100 cm^3 soil
0	17.5a	4.0a	18.18a	0a	0a
10	20.61a	4.71a	18.78a	11ab	34a
50	21.88a	4.72a	21.91a	21bc	68a
100	34.28b	5.19ab	28.62b	31cd	148b
500	36.37b	6.19b	32.23c	39d	396c
1000	38.57b	7.28c	37.03d	63d	612c

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the student Newmans Keuls Multiple Range test.

Table A43. Percent Infection of root systems of navy beans by G. fasciculatus

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Percent infection						
Control	0a	0a	0a	0a	0a	0a	0a
Glomus sp.	11a	21c	43b	61b	74c	76c	68c
P. penetrans	0a	0a	0a	0a	0a	0a	0a
P. penetrans + Glomus sp.	7b	13b	39b	53b	57b	59b	57b

TableA44. Spore density of G. fasciculatus associated with navy beans

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Spore density / 100 cm^3 soil						
Control	0a	0a	0a	0a	0a	0a	0a
Glomus sp.	245b	49b	88b	190b	15b	300b	655b
P. penetrans	0a	0a	0a	0a	0a	0a	0a
P. penetrans + Glomus sp.	201b	100a	87 b	146b	105b	265b	603b

Control = 0 P. penetrans + 0 Glomus fasciculatus
Glomus sp. = 1000 G. fasciculatus spores/ 100 cm^3 soil
P. Penetrans = 300 P. penetrans per 100cm^3 soil
P. penetrans + Glomus sp. = 300 P. penetrans = 1000 Glomus sp. spores per 100cm^3 soil

Column means followed by the same letter(s) are not significantly different (P = 0.05) according to the Student Newman Keuls Multiple Range test.

TableA45. Effect interactions of P. penetrans and G. fasciculatus on fresh weight of navy bean plants.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Shoot fresh weight (g)						
Control	1.55b	3.33a	9.20b	12.10b	6.78b	3.42a	2.59b
Glomus sp.	1.99b	6.26b	16.04c	19.03d	13.06d	6.21a	3.20b
P. penetrans	1.86a	1.99a	5.64a	7.97a	3.93a	2.51a	1.33a
P. penetrans + Glomus sp.	0.68b	3.00a	10.69b	15.78c	9.20c	5.74b	1.79a

TableA46. Effect of interactions of P. penetrans and G. fasciculatus on shoot dry weight of navy beans.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Shoot dry weight (g)						
Control	0.21a	0.84b	1.90b	2.99b	1.23b	0.68b	0.49b
Glomus sp.	0.62c	1.26c	3.20c	4.95c	2.39c	1.07c	0.94c
P. penetrans	0.16a	0.44a	0.80a	1.54a	0.67a	0.26a	0.19a
P. penetrans + Glomus sp.	0.43b	0.75b	2.02b	3.05b	1.34b	0.69b	0.29ab

Control + = 0 P. penetrans + 0 G. fasciculatus
Glomus sp. = 1000 G. fasciculatus spores / 100 cm^3 soil.
P. penetrans = 300 P. penetrans per 100cm^3 soil
P. penetrans + Glomus sp. = 300 P. penetrans + 100 Glomus sp. spores per 100cm^3 soil

Column means followed by the same letters are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A47. Effect of interactions of P. penetrans and G. fasciculatus on leaf area of navy bean plants.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Leaf area (cm^2)						
Control	21.50a	90.92a	282.21b	393.99b	190.67b	41.06b	10.90ab
Glomus sp.	39.44ab	151.10b	427.52c	478.31c	242.14c	86.76d	16.68b
P. penetrans	16.17a	80.04a	141.69a	251.31a	100.19a	19.99a	5.27a
P. penetrans + Glomus sp.	51.92b	113.66ab	287.39b	375.29b	105.59a	71.45c	8.33ab

TableA48. Effect of interactions of P. penetrans and G. fasciculatus on height of navy bean plants.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Plant height (cm)						
Control	6.30a	9.00a	14.70b	19.30b	22.80b	25.00b	25.70c
Glomus sp.	9.10b	13.20b	20.30c	27.10c	27.30c	28.60c	28.80d
P. penetrans	5.80a	8.30a	9.40a	12.00a	16.30a	16.70a	16.90a
P. penetrans + Glomus sp.	7.90b	10.30a	16.20b	18.70b	20.60b	24.00b	24.60b

Control + = 0 P. penetrans + 0 G. fasciculatus
Glomus sp. = 1000 G. fasciculatus spores / 100 cm^3 soil
P. penetrans = 300 P. penetrans per 100 cm soil
P. penetrans + Glomus sp. = 300 P. penetrans + 1000 Glomus sp. spores per 100cm^3 soil

Column means followed by the same letters are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table 49. Effect of interactions of P. penetrans and G. fasciculatus on weight of navy bean roots.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Root weight (g)						
Control	0.85b	1.94b	3.60b	3.83b	2.15b	1.50b	0.95b
Glomus sp.	1.68c	3.48c	6.30c	5.78c	4.14c	3.21c	1.62c
P. penetrans	0.53a	1.13a	1.85a	1.71a	0.98a	0.55a	0.41a
P. penetrans + Glomus sp.	0.92b	2.27b	4.17b	3.69b	2.18b	1.23ab	0.72b

Table 50. Effect of interactions of P. penetrans and G. fasciculatus on area of navy bean roots.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Root area (cm^2)						
Control	5.91a	10.16a	16.26b	19.10b	14.52a	9.27b	5.20b
Glomus sp.	10.45b	16.76b	27.77c	30.93c	29.14b	13.34c	8.43c
P. penetrans	5.03a	7.61a	11.38a	13.09a	11.78a	6.28a	3.21a
P. penetrans + Glomus sp.	6.79a	9.64a	14.25b	16.44b	12.97a	9.60b	4.76b

Control + = 0 P. penetrans + 0 G. fasciculatus
Glomus sp. = 1000 G. fasciculatus spores / 100 cm^3 soil
P. penetrans = 300 P. penetrans per 100 cm^3 soil
P. penetrans + Glomus sp. = 300 P. penetrans + 100 Glomus sp. spores per 100cm^3 soil

Column means followed by the same letters are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A51. Effect of interactions of *P. penetrans* and *G. fasciculatus* on length of navy bean roots.

	Day of Growth						
	14	28	42	56	70	84	98
	Accumulated degree days ($DD_{10}C$)						
	185	372	545	715	924	1112	1314
Treatment	Root length (cm)						
Control	5.50b	10.30b	17.30b	24.30c	19.50b	13.90b	12.20c
Glomus sp.	8.90c	16.80c	28.60c	38.20d	27.90c	18.50c	17.30d
P. penetrans	3.00a	7.30a	11.10a	13.60a	11.70a	8.60a	8.10a
P. penetrans + *Glomus* sp.	5.90b	11.30b	13.70a	18.30b	17.00b	11.40b	10.80b

Control + = 0 *P. penetrans* + *G. fasciculatus*
Glomus sp. = 1000 *G. fasciculatus* spores/100 cm^3 soil
P. penetrans = 300 *P. penetrans* per 100cm^3 soil
P. penetrans + *Glomus* sp. = 300 *P. penetrans* + 1000 *Glomus* sp. spores per 100cm^3 soil

Column means followed by the same letters are not significantly different (P = 0.05) according to the student Newman Keuls multiple range test.

Table A52: Susceptibility of five dry bean varieites to P. penetrans and control of P. penetrans with an input of aldicarb (Temik 15 G).

Bean Variety Treatment, Formulation and rate	Yield (cwt./A)	DD 10C 207	485	636	872	966	1173	1281	485	636	872	966	1173	1281
		Pratylenchus penetrans at DD												
		N./100cm^3 soil							No./g root tissue					
Sanilac.	12.44a**	134a	25b	14a	104e	39b	142c	518c	130b	320b	249b	448b	134a	74c
Seafarer	16.76b	126a	16ab	5a	88bc	11a	40ab	338bc	113b	36a	15a	82a	56a	37ab
Tuscola	17.99b	116a	15ab	12a	84bc	23a	44bc	324bc	174b	40a	9a	162a	136a	26a
Montcalm Kidney	10.30a	128a	18ab	19a	51bc	17a	71b	332bc	138b	62b	80a	408b	490b	63bc
Charlevoix Kidney	18.53	133a	10a	4a	32ab	18a	53ab	184ab	45a	27a	9a	179a	152a	34ab
Sanilac + Temik 15G 2.01b a.i./A	19.91b	131a	5a	2a	12a	4a	14a	34a	10a	18a	4a	18a	8a	4a
Seafarer + Temik 15G 2.0 lb a.i./A	25.06c	168a	4a	8a	6a	2a	4a	18a	2a	15a	2a	8a	5a	5a
Tuscola + Temic 15G 20.1b a.i./A.	24.21c	125a	1a	2a	4a	5a	5a	8a	17a	6a	3a	11a	4a	4a
Montcalm Kidney + Temik 15G 2.0 lb a.i./A	22.29c	149a	2a	4a	11a	7a	12a	16a	5a	22a	3a	16a	9a	2a
Charlevoix Kidney + Temik 15G 1.0 lb a.i./A.	25.83c	140a	5a	2a	12a	4a	7a	15a	2a	10a	5a	5a	3a	2a

*$DD_{10\,C}$ accumulated degree days base 10C = $\frac{\text{(min. daily temp. + max. daily temp)}}{2}$ x 0.556

**Column means followed by the same letter are not significantly different (P = 0.05) according the Student Newman Keuls multiple range test.

Table A 53: Population dynamics and control of Pratylenchus penetrans associated with navy beans(1978).

Treatment formulation and rate per acre	Yield cwt/acre	Pratylenchus penetrans at DD_{10} 1*C													
		No. per 100cm^3/soil								No. per g root tissue					
		171	300	495	750	1044	1205	1272	1301	495	750	1044	1205	1272	1301
Check	19.2c	54a	57b	65b	24ab	46b	23b	49b	30b	79c	69b	105b	32b	67b	27c
Temik 15G 0.75 lb ai/acre	22.5d	52a	56a	7a	2a	13a	5a	5a	8a	3ab	0a	2a	1a	5a	6ab
Temik 15G 1.5 lb ai/acre	24.4d	59a	59b	14a	1a	4a	1a	11a	13a	3ab	1a	5a	0a	2a	2a
Vydate 10G 3 lb ai/acre	24.8d	51a	55b	12a	1a	7a	7a	14a	7a	3ab	4a	8a	1a	3a	2a
Nemamort 8E 1b/acre	16.8bc	65a	18a	17a	1a	13a	6a	7a	8a	10b	9a	16a	1a	4a	11ab
Nemamort 8E 24 lb/acre	14.5b	53b	11a	19a	2a	14a	1a	7a	8a	5ab	3a	17a	1a	11a	19bc
Nemamort 8E 36 lb/acre	10.0a	52a	7a	12a	5a	7a	5a	11a	13a	4ab	2a	20a	1a	5a	18bc
Nemacur 15G 5 lb/ai/acre	16.96bc	46a	54b	9a	1a	11a	1a	4a	4a	1a	0a	6a	1a	4a	2a

*1 DD_{10} = accumulated degree days (base 10 C).

**2 Column means followed by the same letters are not significantly different according to the Student Newman Keuls Multiple Test (P = 0.05).

TableA 54: Population dynamics and control of P. penetrans associated with navy beans (1979).

Treatment, Formulation and Rate of Acre	Yield (cwt/A)	Pratylenchus penetrans at DD*												
		No./100cm^3 soil							No./g root tissue					
		207	485	636	872	966	1173	1221	485	636	872	966	1173	1221
Check.	13.91a	117a	41b	56b	48b	125b	72b	250b	145c	200b	48c	328b	103b	25b
Vydate L 1.0 lb a.i./A.	16.76ab	89a	15a	12a	12a	20a	17a	85a	16a	76a	6ab	17a	9a	4a
Vydate L 1.o lb a.i./A plus 1.0 lb a.i/A foliar spray.	22.21bcd	98a	20a	7a	10a	34a	13a	80a	17a	12a	6ab	12a	16a	4a
Terr-o-cide 54-45 1.0 gal./A	16.52ab	132a	18a	14a	13a	20a	16a	54a	72b	120a	24ab	4a	8a	11ab
Temik 15G 0.5 lb a.i./A	19.14abc	121a	35b	17a	33ab	24a	19a	122a	41a	104ab	37bc	45a	20a	14ab
Temik 15G 1.0 lb a.i./A	21.29bcd	116a	12a	11a	20a	10a	12a	51a	15a	12a	16ab	18a	14a	5a
Temik 15G 1.5 lb a.i./A	24.14cd	111a	6a	8a	13a	6a	10a	38a	8b	6b	10ab	10a	9a	3a
Temik 15G 2.0 lb a.i./A	25.06d	122a	7a	5a	9a	3a	5a	34a	4a	4a	3a	9a	5a	3a

*DD = accumulated degree days 10CF = $\frac{(\text{min. temp.} + \text{max. temp})}{2} - 50F \times 0.566$

**Column means followed by the same letter are not significantly different (P = 0.05) according to the Student Newman Keuls multiple range test.

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