DENSITY-DAMAGE RELATIONSHIPS AND CHEMICAL CONTROL OF THE NORTHERN CORN ROOTWORM, *Diabrotica barberi* (COLEOPTERA : CHRYSOMELIDAE), IN QUEBEC.

by

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Suggested short title:

DENSITY-DAMAGE RELATIONSHIPS AND CHEMICAL CONTROL OF *Diabrotica barberi*

FAISAL A. ELHAG

(٩٦) سُورَةُ العَلَقِ مَكِّيَّةٌ
وَآيَاتُهَا تِسْعَ عَشْرَةَ

بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ① خَلَقَ الْإِنسَانَ مِنْ عَلَقٍ ② اقْرَأْ وَرَبُّكَ الْأَكْرَمُ ③ الَّذِي عَلَّمَ
بِالْقَلَمِ ④ عَلَّمَ الْإِنسَانَ مَا لَمْ يَعْلَمْ ⑤

In the name of Allah, the Beneficent, the Merciful.

Read in the name of your Lord who created,
created man from clots of blood.
Read! your Lord is the most Bounteous,
Who has taught the use of the pen,
has taught man what he did not know.

Al-Quran: Chapter XCVI, Verses 1-5

ABSTRACT

Ph.D. Faisal Abdalla Elhag Entomology

DENSITY-DAMAGE RELATIONSHIPS AND CHEMICAL CONTROL OF THE NORTHERN CORN ROOTWORM, *Diabrótica barberi* (COLEOPTERA: CHRYSOMELIDAE), IN QUEBEC.

Economic injury levels (EIL) of northern corn rootworm (NCR) *Diabrótica barberi* stages, in greenhouse conditions, were calculated as 58-76 eggs, 15-19 first-instar larvae and 9-12 adults per plant. EIL and economic threshold under Quebec field conditions were calculated as 11-14 and 8-10 larvae/plant, respectively. A significant ($p \leq 0.05$) reduction in grain yield occurred at a minimum density of 150 eggs, 60 first-instar larvae and 21 adults per plant.

Among several insecticides tested by direct contact and in soil bioassays, PP993 (a new pyrethroid) and terbufos were the most effective against NCR larvae. LD50's of PP993, fonofos and chlorpyrifos against second-instar NCR larvae were calculated as 0.197, 0.883 and 0.661 ppm. Residues occurring in soil during peak larval population averaged 0.27, 3.4 and 2.65 ppm respectively. PP993 proved very competitive with fonofos and chlorpyrifos in its effectiveness against NCR larvae in the field. Fifty per cent of the parent PP993, fonofos and chlorpyrifos in soil had dissipated in 9, 12 and 11 weeks respectively, and only 20-30 per cent persisted through to the end of the growing season.

RESUME

Ph.D. Faisal Abdalla Elhag Entomologie

Les relations densité-dommage et le contrôle chimique de la chrysomèle des racines du mais, *Diabrotica barberi* (Coleoptera:Chrysomelidae), au Québec.

On évalua le niveau d'impact économique (NIE) des trois stades de la chrysomèle des racines du maïs (CRM), *Diabrotica barberi* à 58-76 oeufs, 15-19 larves de premier stade et 9-12 adultes par plante en serre. On calcula que le NIE et le seuil économique sur le terrain au Québec étaient de 11-14 et de 8-10 larves/plante, respectivement. Une réduction significative de rendement de grain ($p < 0.05$) se produisit à une densité minimale de 150 oeufs, de 60 larves de premier stade et de 21 adultes par plante.

Parmi les divers insecticides expérimentés par contact direct ou en presence de sol, PP993 (un nouveau pyréthrine synthétique) et terbufos furent les plus efficaces envers les larves de la CRM. Le DL_{50} dues au PP993, au fonofos et chlorpyrifos envers les larves de deuxième stade de la CRM ont été calculées comme étant 0.197, 0.883 et 0.661ppm. Les résidus se trouvant dans le sol pendant le pique de la population larvaire étaient en moyenne de 0.27, 3.4 et 2.65 ppm respectivement. PP993 s'est avéré très compétitif par rapport à fonofos et chlorpyrifos dans son efficacité contre les larves de la CRM sur le terrain. Cinquante pour cent des produits mères PP993, fonofos et chlorpyrifos se sont dissipés dans le sol en 9, 12 et 11 semaines respectivement, alors que 20-30 pour cent on persisté jusqu'à la fin de la saison de croissance.

To my late father.

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CLAIM TO ORIGINALITY

1. Economic injury levels (EIL) of NCR eggs and larvae on corn plants were determined under greenhouse conditions.
2. EIL of NCR adults on corn plants was determined under field micro- plot conditions.
3. EIL and economic threshold (ET) levels of NCR larvae on corn plants were determined for the first time in Quebec cornfields.
4. Efficacy of PP993 (a new pyrethroid) and fonofos MS in controlling NCR larvae were tested for the first time in Quebec and compared with several recommended soil insecticides.
5. A new method for residue analysis of PP993 using a gas chromatograph fitted with Ni^{63} electron-capture detector was developed.
6. Residue levels of PP993, fonofos and chlorpyrifos found in soils during the larval peak in Quebec cornfields were determined, compared with their LD50's, and recommendations for optimizing their rate of application were made.
7. Persistence of PP993, fonofos, and chlorpyrifos in cornfield soils through to the end of the growing season were determined.
8. LD50's of several insecticides against second instar NCR larvae were calculated by laboratory bioassay.
9. Effects of insecticide placement and application time in controlling NCR larvae were determined.
10. Possible phytotoxicity associated with the use of disulfoton at cultivation time was demonstrated.

11. A model for factors affecting NCR populations, EIL and ET was developed.
12. Methods for artificially infesting corn roots with NCR eggs and larvae were developed.
13. A new design of cage for trapping emerged adults from potted corn plants infested with NCR eggs and larvae was used.
14. A new design of cage for artificially infesting corn plants with NCR adults in field micro- plots was used.
15. Minimum density levels of NCR eggs, larvae and adults that caused significant reductions in grain yield were determined.
16. New recommendations for NCR control decision-making were formulated from the above mentioned findings.

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I. GENERAL INTRODUCTION

GENERAL INTRODUCTION

The northern corn rootworm (NCR), *Diabrotica barberi*, Smith and Lawrence, a native pest of North America, was first collected by Say (1824) in Colorado. It was first cited in the Montreal, Quebec, area by Chagnon (1938) and since then it did not appear in the local literature until it was reported by Guibord (1976) on corn (*Zea mays* L.) in Napierville. NCR is the only species of the genus *Diabrotica* occurring in Quebec that causes a serious threat to corn growing. In Ontario, however, the NCR and the western corn rootworm (WCR), *Diabrotica virgifera virgifera* (Le Conte), pose a chronic problem to corn growers and both species are present throughout all of the southwest (Bereza 1972; Ontario Ministry of Agriculture and Food 1974; Tyler and Ellis 1975; Fott and Timmins 1977; Smith 1979).

The NCR and WCR are very similar in their seasonal development cycle and both species overwinter as eggs in the soil. These hatch in late spring, and the larvae actively feed on the roots of corn, which impairs water and nutrient uptake by the plant. Severe infestation prunes root structures to the extent that a plant lodges in strong winds and rainstorms. As the plant continues to grow, it exhibits a characteristic 'goose neck' appearance. This lodging and crooked growth cause many of these plants to be missed by mechanical harvesters. The adult beetles are active in cornfields in late summer. They feed on ears, silk, and pollen and severe infestations can interfere with normal pollination.

The total area under corn in the United States and Canada constitutes *ca.* 30 million and 1.5 million ha, respectively (DeVault 1986; Metcalf 1986; Clutton 1987). In the U.S. alone, corn rootworms are responsible for insecticides being routinely applied to 12 - 16 million ha of corn, costing American farmers *ca.* $250 million (US) in insecticides and $750 million (US) in crop losses (De Vault 1986; Metcalf 1986). However, studies based on a realistic economic threshold (ET) indicate that only 10 to 19 per cent of the treated corn acreage had rootworm populations above the ET (Turpin and Maxwell 1976; Luckman 1978).

Crop rotation has been widely recommended for corn rootworms (CRW) control in the U.S. and Canada. However, recent studies (Krysan *et al.* 1986; Ostlie 1987) indicate that about half of the NCR egg population laid by adults from cornfields rotated annually diapaused for two years. Moreover, continuous crop rotation may perpetuate the development of resistant strains. For this reason a two-year crop rotation, with two non-host plants, was recommended (DeVault 1986; Krysan *et al.*1986; Olkowski 1986). However, more recent evidence of a three-year diapause of NCR eggs (Ostlie 1987) suggest that this tactic is not infallible.

Application of granular soil insecticides is generally made as a narrow band (18 cm) over the row at planting time with light incorporation provided by the planter press wheel or a chain dragged behind the planter press wheel. Chemical control is also possible at cultivation time with liquid formulations directed at the base of the corn plant and covered lightly with soil but no insecticides are presently registered for this use in Canada.

Chemical control has been considered the main management strategy for CRW since the successful use of chlorinated hydrocarbons in the late 1940s (Fulton 1946; Hill *et al*.1948). However, both NCR and WCR developed resistance to the cyclodiene soil insecticides throughout most of their distribution in the late 1950s and early 1960s (Bigger 1963; Patel and Apple 1966). Due to the problem of resistance and de-registration of most chlorinated hydrocarbons, organophosphate and carbamate soil insecticides have been used since. However, these have not proved as successful or consistent as the cyclodienes, probably because the newer compounds have limited persistence and are more readily degraded in the soil. For CRW control, a moderately persistent insecticide is recommended (Harris 1972).

Insecticide application for CRW control is further complicated by the recent development of CRW resistance to some organophosphate and carbamate insecticides (Caro *et al*. 1973; Williams *et al*. 1976; Ball 1981; DeVault 1986), in addition to their adverse effects on non-target organisms, and to environmental contamination. These problems necessitate the development of realistic economic threshold data and the rotation of insecticides from one class to another, along with crop rotation.

The objectives of this study were to:

1) Determine the relationship between a range of densities of different stages of NCR and damage caused to corn plants.

2) Develop an economic injury level for stages of NCR in greenhouse and field microplot experiments.

3) Estimate the populations of different stages of NCR in several commercial corn fields in southwest Quebec to determine the various factors affecting NCR populations; to establish economic injure level (EIL) and economic threshold (ET) for the damaging larval stage, to model factors affecting EIL and predict densities and damage-potential.

4) Determine the susceptibility of NCR larvae to several insecticides by laboratory bioassay.

5) Determine the field efficacy of the most promising insecticides tested in the laboratory.

6) Determine the influence of insecticide application time on NCR larval control.

7) Determine the influence of insecticide placement at different depths in soil on NCR larval control.

8) Determine the impact of different doses of PP993 (a new pyrethroid insecticide) on NCR larval control and to compare its effectiveness with several recommended soil insecticides.

9) Determine if insecticide residues, sufficient to exceed laboratory-determined larval LD50 values, persisted in corn-field soils at the time of peak larval hatch.

10) Determine if insecticide residues persisted in the cornfields through to the end of the growing season.

LITERATURE REVIEW

In this review, particular emphasis is given to aspects of northern corn rootworm (NCR) *Diabrotica barberi*, Smith and Lawrence, which are relevant to this project, up to 1987.

TAXONOMY

Classification

Northern corn rootworm (NCR), *Diabrotica barberi* Smith and Lawrence, is classified as follows (Borrer *et al.* 1976; Krysan *et al.* 1983):

Order	: Coleoptera
Sub Order	: Polyphaga
Superfamily	: Chrysomeloidea
Family	: Chrysomelidae
Subfamily	: Galerucinae
Tribe	: Galerucini
Genus	: *Diabrotica*
Species	: *barberi* Smith and Lawrence 1967.

The northern corn rootworm *Diabrotica barberi* was first described by Thomas Say (1824) as *Galleruca longicornis* from specimens he obtained on wild cucurbits in the mountains of Arkansas. The species was later included in the genus *Diabrotica* (Chevrolat 1837). However, the remarkable geographic variation in the possession of certain structures led Smith and Lawrence (1967) to recognize two subspecies; Say's species; as *D. longicornis longicornis* and a new subspecies as *D. longicornis barberi*. Based on field and laboratory studies of mating behaviour, sex pheromone response, habitat choice, morphometric analysis and geographical variation in color, Krysan *et al*. (1983) elevated both subspecies to species rank. They determined that *D. barberi* Smith and Lawrence and *D. longicornis* (Say) are distinct species whose ranges overlap in the central plains of the U.S. *D. longicornis* is normally collected from cucurbits while *D. barberi*, known as the northern corn rootworm (NCR), is most commonly collected from cornfields (Krysan *et al*. 1983).

MORPHOLOGY AND IDENTIFICATION

Adult

Based on information provided by Smith and Lawrence (1967), White (1969) and Krysan *et al*. (1983), adult specimens of *D. longicornis* (Say) and *D. barberi* Smith and Lawrence can be distinguished by the following key:

1. Antennae (except proximal segments), clypeus, tibiae and tarsi infuscated, often shiny piceous; elytra variable..................2

   Antennae, clypeus, tibiae and tarsi yellow or testaceous; elytra with humeral spots often absent. Humeral vittae rarely present, usually weakly colored ......*D. barberi* Smith and Lawrence (in part)

2. Scutellum usually piceous, Nebraska, Texas and Tamaulipas to Arizona and Chihuahua .... *D. longicornis* (Say)

   Scutellum yellow or testaceous, Pennsylvania and Quebec to Vermont and Massachusetts (in Georgia and South Carolina, scutellum may be piceous) .... *D. barberi* (in part)

<u>Pupa</u>

The pupa is of the exarate type, creamy white in color and with a mean length of 4.93 mm. The brownish eyes of the forming adult can be seen through the skin as well as a pair of brownish horny curved hooks at the tip of the abdomen. Two white erect hairs are visible between the antennae, with another pair above and between the eyes. Spiracles can be clearly seen as small paired brown rings on each of the first eight segments of the abdomen, but are less visible on the remaining three posterior segments (Forbes 1920; Dominique 1983). A pair of well-developed papillae on the venter near the apex of the abdomen distinguishes the female pupa from the male (George and Mintz 1966).

Larva

Boving (1927, 1929) published a detailed morphological description of the larvae of the southern (SCR), *Diabrotica undecimpunctata howardi* Barber, and northern corn rootworms (NCR), *Diabrotica barberi* Smith and Lawrence. Mendoza and Peters (1964) provided a key for the mature larva of northern, southern and western corn rootworms (WCR), *Diabrotica virgifera virgefera* Le Conte. According to Mendoza and Peters, the anal plate or pygidial shield on the ninth abdominal segment is very useful in separating the species. The head capsule is more elongate and with straighter sides in NCR as compared with the ovoid outline of the SCR. Dominique and Yule (1984) used capsule width as an indicator of NCR larval instar. They noted that the range of head capsule widths of the first, second and third larval instars were 219-276, 300-398 and 400-479 Um respectively.

Electrophoretic analysis of soluble isozymes is a rapid and useful method for distinguishing closely related species of a variety of organisms (Avise 1979; Jacobson and Hsiao 1983). Piedrahita *et al.* (1985), using horizontal starch gel-electrophoresis, reported that second and third larval instars of NCR and WCR species could be accurately identified with isocitrate dehydrogenase (IDH) and esterase (EST) enzymes.

Egg

The eggshell patterns of rootworm species are characterized by a network of polygons (primarily hexagons) covering the entire egg. Atyeo *et al.* (1964) showed that the eggshell thickening within interpoly gonal areas (secondary ridges) differs from one species of *Diabrotica* to another. The eggs of the WCR are lacking secondary ridges, whereas NCR and SCR can be identified according to the number of pits within a given polygon (Atyeo *et al.* 1964; Rowly and Peters 1972; Krysan 1986). Krysan (1986) noted that the number of pits per polygon ranges from 6-12 in NCR and 14-20 in SCR.

BIOLOGY

The biology of the northern corn rootworm complex in Illinois was studied by Forbes (1982), who concluded that the species diapaused in the egg stage and had a univoltine life cycle. The eggs are deposited singly or in chains in moist cracks in the soil of cornfields, between late August and mid-September, and begin to hatch about mid-June of the following year (Dominique and Yule 1984; Hein and Tollefson 1985). Forbes (1915) found that, hatching of NCR eggs in Illinois begins about 10 June and the larval stages continue up to 25 August. Variable hatching dates for NCR eggs in different geographical areas have been reported by several researchers (Britton 1937; Chiang and Sisson 1968; Bereza 1979, 1983; Dominique and Yule 1984). Some final instar larvae were observed in Ontario cornfields up to the second half of July, and in Quebec cornfields up to the end of July, respectively by Bereza (1979, 1983) and Dominique and Yule (1984). NCR larvae start to pupate in the soil by mid-July and pupation is usually complete by 12 September (Forbes 1915). In Ontario the pupal stage starts in the first half of July and is over by the second half of August (Bereza 1979, 1983). In southern Quebec, pupation takes place from the last week of June to about 20 August (Dominique and Yule 1984).

The threshold temperature for NCR egg development has been determined as 9.7°C in southern Quebec, 9.5°C in Wisconsin and 11.1°C in Minnesota by Dominique and Yule (1983a), Patel and Apple (1967), and Chiang and Sisson (1968), respectively. Thermal constants for egg development in the rhizosphere and based on air temperature have been determined respectively as 304 DD and 533 DD (Apple *et al.* 1971), 340 DD and 421-431 DD (Dominique and Yule 1983a). This variation in the thermal requirement for eclosion may be due to differences in shading of the eggs (Sechriest 1969; Chiang and Sisson 1968), geographical area (Wilde *et al.* 1972) and pre-conditioning of the eggs (George and Hintz 1966). Under laboratory conditions, a pre-chill period of 10 to 15 days at room temperature is required by the embryo to develop sufficiently to undergo normal diapause development (Dominique and Yule 1983b; George 1972; Jacobson 1985; Fisher *et al.* 1986). However, some eggs showed post-diapause characteristics without prior exposure to cold (Krysan 1972).

Patel and Apple (1967) predicted that some NCR eggs could hatch in the same year in the field, if the autumn is warm and prolonged. In contrast, Chiang (1965) in Minnesota found that approximately 0.3 per cent of the eggs diapaused for two years. Subsequently, Krysan *et al.* (1984) in studies in South Dakota found that about 40 per cent of the eggs that hatched were in diapause for two years. Krysan *et al.* (1986) confirmed that more than 50 per cent of *D. barberi* eggs diapaused for two years in fields where corn was rotated annually whereas only nine per cent of the eggs diapaused for two years in fields where corn was planted without rotation, thus demonstrating local population adaptation to cultural practices.

Chiang *et al.* (1972) reported that hatching of NCR eggs increased with an increase in chill duration at 5°C but decreased with an increase in chill duration at 0°C and -5°C. Dominique (1983) noted that the egg viability of the Quebec population of NCR remained high, ranging from 65 to 90 per cent, when held under cool conditions for extended periods of 220 days at 5°C, but lost viability as the temperature decreased and duration of chill period increased.

Adult NCR emergence, in mid-July, was first noted by Forbes (1915) in Illinois. Ortman *et al.* (1974) observed that adult emergence ranged from late June in Missouri to mid-July in South Dakota. In Canada, NCR adults emerge in late July in Ontario (Bereza 1983) and in mid-July in southern Quebec (Dominique and Yule 1984; Matin 1983). Calkings *et al.* (1970) stated that both NCR and WCR adult populations peaked in early

September and suggested that if farmers harvested their crops before 1 September they would face lower rootworm populations in the following year. Musick *et al.* (1980) reported that adult population peaks of NCR and WCR depended on the time of corn sowing. They observed that populations of beetles from cornfields planted in May peaked later in the season, occurred over a longer period and declined at a slower rate than adults from corn planted in late April. In Quebec, adult populations of *D. barberi* peaked in mid-August. Then, during the second week of October, all NCR beetles died as a result of frost (Dominique and Yule 1984; Matin and Yule 1984a, b; Matin *et al.* 1984).

Dominique (1983) concluded from laboratory studies that the pre-oviposition period of *D. barberi* ranged from 11 to 19 days, with a mean of 14.9 days. The mean number of eggs per beetle in laboratory tests was 70 and 176.8 in 1979 and 1981 respectively. He also found that adult longevity ranged from 33 to 63 days, with an average of 45 days. He attributed the difference in fecundity to fewer beetles per oviposition cage and better egg extraction techniques used in 1981. Kuhlman (1970) showed that *D. longicornis* has a pre-oviposition period of 24.4 days, deposits 79.2 eggs per female and has a longevity of 86.2 days.

Humidity, temperature, soil moisture, soil type, soil surface conditions and perhaps certain chemical substances affect the location of oviposition and the number of eggs laid (Richardson 1925; Kirk *et al.* 1968; Dominique *et al.* 1983; Matin 1983). Dominique *et al.* (1983) observed that local Quebec farm soil with natural cracks was preferred over mechanically-disturbed soil for oviposition. However, Kuhlman *et al.* (1970) stated that, in Illinois, moist loosened or disturbed soil was more suitable for egg laying than compacted soil.

REARING

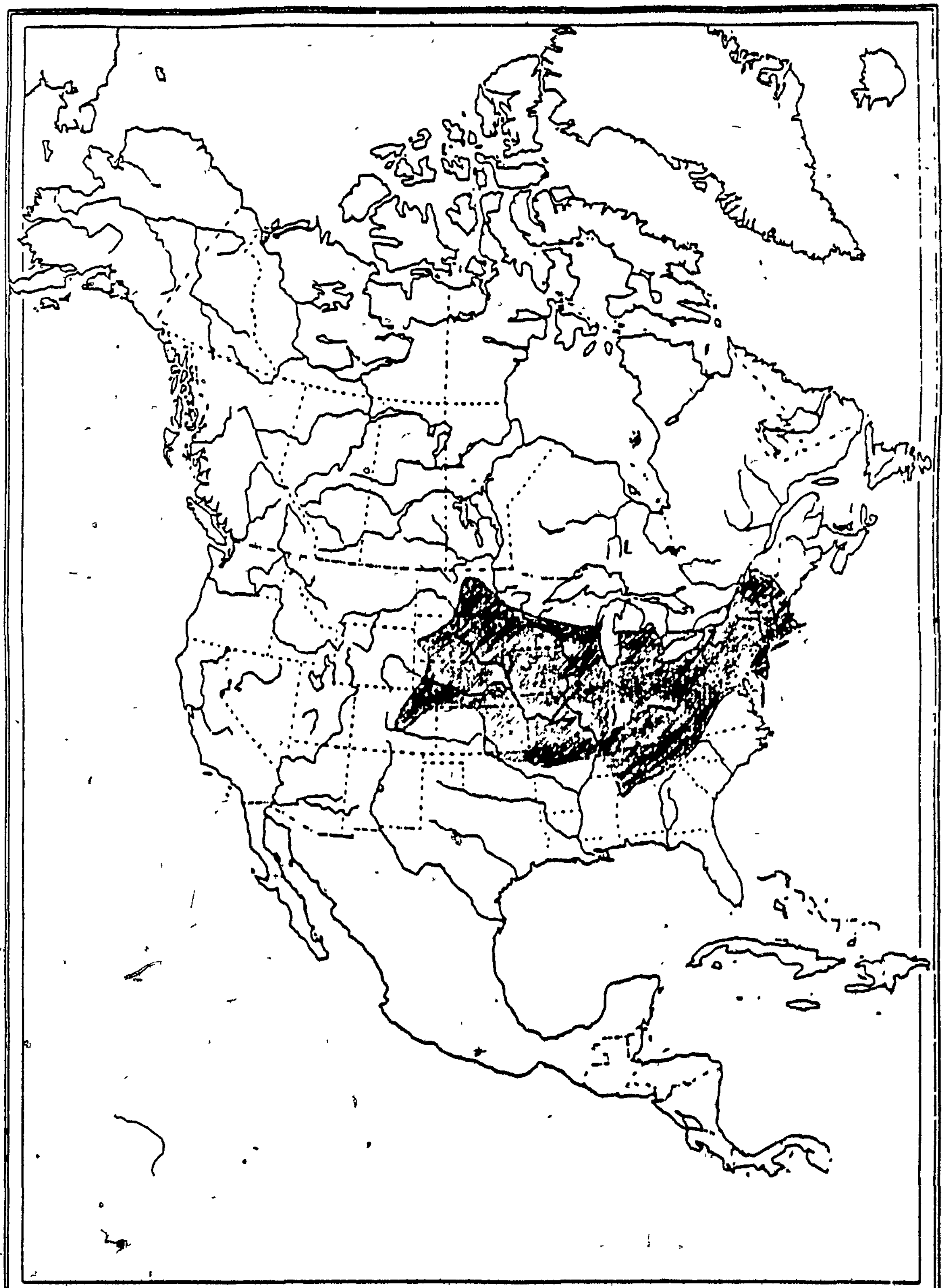
Rearing of corn rootworms has been improved by several workers since Howe and George (1966) first developed a technique for rearing NCR, WCR and SCR (Branson *et al.* 1975; Jackson and Davis 1978; Dominique and Yule 1983b; Jackson 1985, 1986). Rearing of adults on natural food provided satisfactory results in terms of egg numbers, egg viability and subsequent establishment of the larvae. However, the use of an artificial diet greatly reduced the cost and allowed for easier handling (Jackson 1975). Dominique and Yule (1983b) modified Jackson and Davis's (1978) rearing technique (eggs were hatched in water, and soil was added to the rearing box during pupation), thereby increasing the survival rate from first-instar larva to adult from 35 to 65 per cent.

DISTRIBUTION

The NCR, a native pest of North America, was first discovered by Say (1824) in Colorado. Harrington (1894) collected NCR specimens from the central U.S. plains. Webster (1901) showed that the NCR had spread from the central plains to the northeastern states. Webster (1908) and Krysan (1983) considered NCR to be a prairie species and that the population in Illinois and Missouri changed its host affinities to maize, thus expanding its range. There is evidence of a discontinuous range of expansion related to agricultural practices (Krysan and Branson 1983; Chiang 1973; Witkowski and Owens 1979). Climate is considered to be the limiting factor in the spread of the NCR (Krysan 1986). The range of *D. barberi* (Fig. 1) extends from Arkansas to Quebec (Krysan *et al.* 1983)

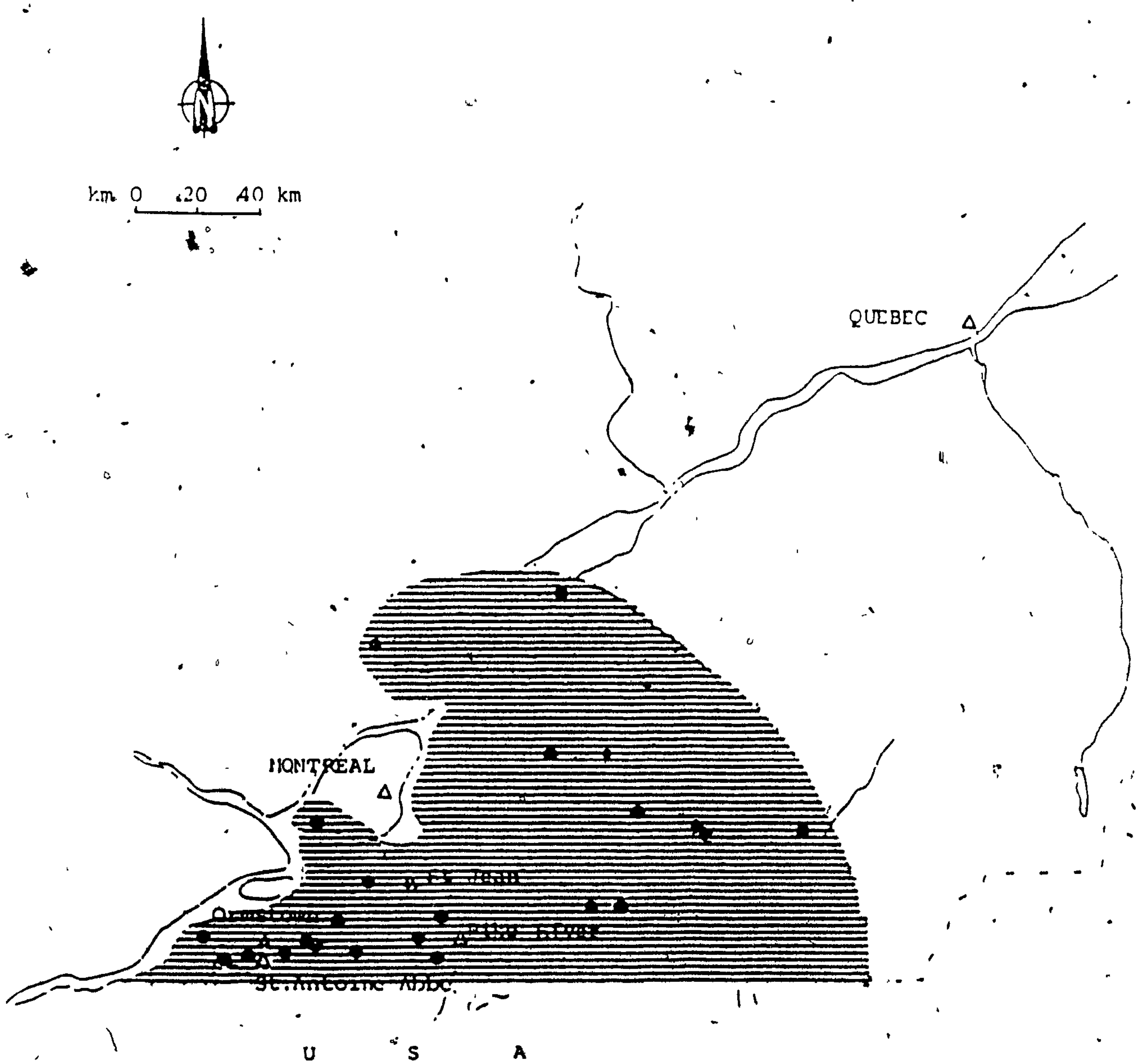
The NCR was first cited in the Montreal area of Quebec by Chagnon (1938). Since then it hadn't appeared in the local literature until it was reported by Guibord (1976) in Napierville. Ritchot *et al.* (1976) mentioned that the population of NCR appeared to be spreading in southern Quebec and its potential as a serious pest was great. By 1986, Ritchot reported that the range of the NCR extended to Saint Esprit, L'Assomption, Saint Davis and Lennoxville (C. Ritchot, Pers. Comm.; P. Martel, Pers. Comm.) (Fig. 2). In Ontario, the NCR is present throughout the southwest (Bereza 1972, 1983; Ontario Ministry of Agriculture and

Figure 1. Distribution of *Diabrotica barberi*.



After Krysan *et al.* (1983)

Figure 2. Distribution of *Diabrotica barberi* in Québec.



●Data from field observations and C Ritchot (St. Hyacinthe Research Station).

Food 1974; Tyler and Ellis 1975; Foott and Timmins 1977; Smith 1979). Bereza (1983) mentioned that the NCR is of less economic importance in eastern Ontario and is found at a very low density east of Kingston.

HOST RANGE

Forbes (1882) and Painter (1951) reported that corn was the only known host plant for NCR larvae. Metcalf *et al.* (1951) also mentioned that NCR larvae were known to attack only corn, though they would sometimes feed on certain unnamed native grasses. Branson and Ortman (1967b, 1971) noted that the NCR are able to complete their immature stages on 14 grass species other than corn. Although corn was probably the most favorable host for larval development, they showed that viable eggs were also laid by beetles reared as larvae on yellow foxtail, winter wheat, tall wheat grass, slender wheat grass and weeping lovegrass.

Forbes (1883, [illegible], 1927) stated that NCR adults feed on the pollen of *Chrysanthemum*, alfalfa, red clover, squash, pumpkin, sunflower thistle, ragweed, golden rod and several Compositae. Similarly, Chittenden (1905) showed that the adults feed on pollen of thistle, ragweed, golden rod and several Compositae. Cinereski and Chiang (1968), studying the pattern of movement of NCR adults inside and outside of cornfields, discovered that they feed on pollen of plant species belonging to Graminaceae, Compositae, Leguminasae and Cucurbitaceae. Within the corn rootworm complex, *D. barberi* is commonly collected in cornfields whereas sympatric *D. longicornis* is collected mainly from cucurbits (Krysan *et al.* 1983).

NATURE OF DAMAGE

The nature of injury caused by NCR larvae to the corn root system has been reported by several workers (Forbes 1885; Webster 1915; Howe and Britton 1937; Metcalf and Flint 1962; Palmer 1968; Apple and Patel 1963; Allemann 1979; Dominique 1983; Dominique and Yule 1984; Branson 1986). They concluded that the newly-hatched larva begins to feed on root hairs and the outer cortical tissue of young adventitious roots of corn plants. After two or three days, the larvae burrow into the cortical parenchyma. Tunnelling then occurs in the stele, the inner core of tissues containing the vascular bundles. As soon as the soft cortex of the roots grows to a tough lignified exodermis, the larvae leave these roots and attack fresh, younger ones. The larvae show a sequence of progressive movements at about weekly intervals toward new growth of root whorls (Dominique 1983; Branson 1986).

The larval feeding activity impairs water and nutrient uptake by the plant and the root system, making the plant susceptible to lodging in strong winds and storms (Palmer 1968). Lodged plants are characterized by "goose-necking" and may be missed by mechanical harvesters. Lodging also results in delayed growth which causes these plants to be out of cycle and results in incomplete fertilization (Palmer 1968).

The adverse effect on pollination that may be caused by adult feeding depends on the time of corn fertilization and on beetle density. Scott (1946), studying the effect of adult beetles on fertilization in north central Tennessee, concluded that in several heavily infested plantings (100 adults/plant) only 50 per cent of the kernels were fertilized. Bereza (1983) reported that, if feeding by adults takes place prior to pollination, partially barren ears result. He mentioned that in Ontario most of the corn is pollinated before the adult population peaks and thus ear damage is not common. However, if corn is planted late, or if a late-maturing hybrid is used and a large number of beetles are present, economic damage could occur.

Beetles prefer to feed on the younger, more succulent ears and silk (Dominique 1983). When the silks and tassels dry out, the husk is invaded and kernels at the tip of the ears are hollowed out and eaten (Dominique and Yule 1984). Derr *et al.*(1964) noted that the beetles are attracted in a descending order of preference to corn kernels, squash blossom, pistillate branches of corn silk, corn leaves and corn roots. When the corn silks dry out, adult beetles disperse to surrounding flowering plants, feed on pollen and then return to the cornfield to oviposit (Dominique 1983).

SAMPLING

Population estimates can be classified as absolute estimates, population intensity, relative estimates and population indices (Southwood 1978). Most field sampling research on the corn rootworm has been of the population intensity type expressed as numbers per plant (Fisher and Bergman 1986).

Morris (1955) mentioned three basic considerations for designing an insect sampling program:

(i) selecting the universe to be sampled;

(ii) choosing the sample unit;

(iii) determining the optimal stratification and distribution of the sampling units. Sampling methods of all the stages of *D. barberi* in southern Quebec have been developed intensively by Matin (1983), Matin and Yule (1984a, b) and Matin *et al.* (1984).

Eggs

NCR eggs are commonly sampled by soil cores of varied diameter taken at different depths and in a number of spatial patterns within the selected field (Ruesink 1986). Gunderson (1964) and Chiang *et al.* (1969) proposed the use of a golf cup cutter for NCR egg sampling. Patel and Apple (1967) used two types of cores: a 2 cm diameter x 23 cm deep auger and a 5 cm diameter x 10 cm deep golf cup cutter. Howe and Shaw

(1972) suggested a trowel method in which two subsamples were taken on either side of the corn stalk. Ruesink and Shaw (1983) and Ruesink (1986) introduced a gasoline-powered trencher: a 10 cm x 2 m trench is cut to a 30 cm depth and one or more 0.5 L samples are taken from each trench.

Matin (1983) studied extensively the spatial distribution of NCR egg populations in southern Quebec fields and concluded that, for determining the total eggs laid for the season, 48 (5 x 10 x 15 cm deep) soil sample should be taken in late October or after the first frost but before plowing. A 5 x 10 x 20 cm deep sample, taken by the end of May, is recommended for estimating the overwintered egg population (Matin and Yule 1984b).

Larvae and Pupae

Since NCR larvae are intimately associated with corn roots, direct counting of rootworms in the soil and roots is the most appropriate way of estimating densities (Matin 1983). The most common types of soil units used to sample larval and pupal rootworm populations in the field are:

(i) plant area soil samples;

(ii) soil cores;

(iii) soil cubes or blocks.

Chiang *et al.* (1969) estimated the larval population using a 10 cm diameter x 20 cm deep core. Over 90 per cent of the larval population is found within 10 cm around the plant base and to a depth of 10 cm (Sechriest 1969; Bergman *et al.* 1981). Musick and Fairchild (1971) and Gould (1979) suggested a core sample with the corn plant in the middle. Apple *et al.* (1977) recommended a sample unit/plant of 18 x 18 x 10 cm for estimating the larval population. Matin (1983) observed that 50 per cent of the larval and pupal population is found in a 20 x 20 x 10 cm deep sample unit with the corn stalk in the centre of the 20 cm square.

Adult

Adult population estimates during the oviposition period are recommended for making larval control decisions for the following year (Luckmann 1978; Pruess *et al.* 1974). Adult counting procedures are widely accepted and utilized in integrated pest management (IPM) programs (Michael and Mayo 1983). The method of sampling NCR adults by direct counting on the corn plant was proposed by Chiang and Flaskard (1965). Adult counting techniques on the entire plant are shown by Matin *et al.* (1984) to be a more economical and less time-consuming method than the use of emergence traps. Moreover, whole plant counts are found to be less variable than beetle counts from plant ears (Steffey *et al.* 1983). Matin and Yule (1984a) noted that by the second week of August in southern Quebec cornfields, 40 per cent of the beetles were found inside the axils of leaves and from 40 to 50 per cent on the silks and ear tips. They also reported that beetle counts taken before sunrise on 40 randomly selected plants gave a reasonably accurate estimate of their field's populations, with a standard error of less than 10 per cent of the mean. To help minimize the cost of sampling, Foster and Steffey (1982), Stamm *et al.* (1985) and McAuslane *et. al.* (1987) suggested the use of a sequential sampling plan for corn rootworm adults.

Various cage designs erected a few days to a week before adults are first observed in the field have been utilized for monitoring adult emergence (Branson and Ortman 1967; Pruess *et al.* 1968; Musick and Fairchild 1970; Short 1970; Hill and Mayo 1974; Ruppel *et al.* 1978; Fisher 1980; Matin and Yule 1984a; Hein and Tollefson 1984; Hein *et al.* 1985; Tollefson 1986). It appears to make little difference whether the cages cover the whole plant or the plants are cut off at ground level before being caged (Fisher 1984). The use of unbaited Pherocon AM[R] pheromone traps and ear-level cylindrical sticky traps for NCR adult monitoring and larval damage prediction has been shown to be as effective as the standard adult counting procedure (Hein and Tollefson 1984, 1985b; Karr 1984; Tollefson 1986). However, Matin *et al.* (1984) demonstrated that yellow vinyl sticky tag traps are suitable for detecting and monitoring beetle emergence and activity but not for absolute population estimation.

ECONOMIC THRESHOLD AND ECONOMIC INJURY LEVEL

Development of the Concept

A number of serious problems have arisen with widespread and indiscriminate use of pesticides: residues, resistance, pest resurgence, secondary pest outbreaks and environmental pollution. To help manage these problems, Stern *et al.* (1959) developed the concept of economic threshold (ET) to serve as a means for more rational use of insecticide.

Some of the ideas of ET, as well as those of economic injury level (EIL), were first put forward by Pierce (1934) when he posed the questions: Is all insect attack to be computed as assessable damage? If not, at what point does it become assessable? Is control work warranted when damage is below that point? Shotwell (1935) was probably the first to answer Pierce's first question by establishing a relationship between the density of grasshoppers and potential crop damage. He designed a rating system of five categories based on density: normal, light, moderate, heavy and very heavy and pointed out that the damage threshold density was in the moderate category. This concept was not developed, however, until Stern *et al.* (1959) restated and emphasized the relation to damage as an economic threshold. They defined ET as the density at which control measures should be determined (initiated) to prevent an increasing pest population from reaching the economic injury level (EIL).

This latter term was defined by them as the lowest population density that causes economic damage (ED). Finally, economic damage was defined by Stern (1966) as the amount of injury that will justify the cost of control. From an economist's point of view, Headley (1972) defined ET as the level to which a given pest population should be reduced to achieve the point where marginal revenue just exceeds marginal cost.

Several authors introduced new expressions such as "action threshold", "action level", "action threshold level", "dynamic action threshold level", "inaction threshold", "control threshold", "insect injury threshold", "critical injury threshold", and "critical population threshold" for ET and EIL (FAO 1966; Sylven 1968; Cancelado and Radcliffe 1979; Sterling 1984; Walgenbach and Wyman 1984; Yencho *et al.* 1986). Smith (1969), Ba-angood and Stewart (1980) and Pedigo *et al.* (1986) analysed these terms and, though they agreed to some extent with the name changes proposed, they concluded that ET and EIL should be easily understood and in common use.

Pedigo *et al.* (1986) stated that, while Stern *et al.* (1959) had been able to develop a theory for pest management based on ecological principles, they could not describe economic damage mathematically in terms of its components. This inadequate definition of ED delayed the calculation of ET and EIL for a decade after the original paper of Stern *et al.* (1959). Headley (1972), Stare and Pedigo (1972), Ogunlana and Pedigo (1974), Norton (1976), Chiang (1979, 1982), Mumford and Norton

(1984) and Pedigo *et al.* (1986) provided formulae for the practical calculation of ED, ET and EIL.

Economic Threshold and Economic Injury Level of NCR

Realistic ET and EIL are very important parameters in control decision-making. They vary according to changing climatic conditions, economics of crop production and marketing, cultural practices and control costs. Luckmann (1978) noted that in Illinois in 1974-75, of the 57 to 67 per cent of total corn growing area treated with soil insecticides to control CRW, only 11 to 19 per cent of the acreage had root damage above the ET. In Indiana in 1972-1974, 40 per cent of the corn growing area was treated with granular insecticides at planting time, yet less than 10 per cent required treatment (Turpin and Maxwell 1976). With a treatment cost of $10 (US) per acre, Metcalf (1982) showed that, in the corn belt in 1980, a saving of $100 million (US) could have been achieved by observing a realistic ET.

Damage to corn by CRW larvae is mainly evaluated by the extent of lodging, reduction in yield, root damage rating, root volume and plant pull resistance. Mayo (1986) analysed these methods of evaluation and concluded that root damage rating has been accepted as a standard method of damage and insecticide evaluation. Apple *et al.* (1977) reported that 11.6-22 larvae/plant caused 7.5-25.5 per cent reduction in yield. Pimentel *et al.* (1978) noted that a mean density ranging from 0.4-1.0

larvae/plant resulted in 7 to 22 per cent yield loss in New York State. In southern Ontario, Smith (1979) estimated a yield loss of 2.5 per cent per one NCR larva. Apple (1971) in Wisconsin reported a reduction in yield of 0.86 per cent per one NCR larva. Petty *et al.* (1969) in Illinois worked out a regression equation for NCR: loss (per cent) = 0.001 + 0.765x, where x = number of larvae/plant. In Iowa, an ET of 10 NCR/plant has been accepted by most of the researchers (Peters 1963). Where a normal yield was 125 bu/acre in Iowa, Hills and Peters (1971) reported a reduction in yield of 5.8 bu/acre for every adjusted root damage rating unit on a 1 to 6 scale.

An ET of 1.0 to 1.15 NCR and WCR adults/plant has been calculated by Pruess *et al.*(1974); Shaw *et al.* (1975); Luckmann (1978); Stamm *et al.* (1985). Anonymous (1982) provided a survey of field corn insect pest thresholds from around the U.S. In this study it was stated that the ET of corn rootworm for the following season was five NCR beetles/plant in Georgia, Indiana, Illinois, Kentucky, Missouri and Pennsylvania. It was also noted in the same paper that, in Indiana, the average number of NCR beetles likely to produce an economic larval population the following season ranged from 1 to 2.8 NCR adults/plant. Recently in the U.S. and Canada, several authors have mentioned the importance of establishing a practical ET which suits local conditions (Metcalf 1980, 1982; Ellis 1982; Stamm *et al.* 1985; Ritchot 1985, 1986a, 1986b; Krysan *et al.* 1986; Olkowski 1986).

CONTROLS MEASURES

Corn rootworms are effectively controlled by soil insecticides and crop rotation. Other cultural practices such as plowing, time of sowing and use of resistant varieties will affect the CRW population but are not intended primarily to control it. Other controls, such as biological management, pheromones and sterile male release are not presently utilized with CRW (Luckmann 1978).

Cultural and Biological Control

Forbes (1882) suggested that crop rotation would control NCR because the pest has one generation per year, overwinters in the egg stage and the larvae are relatively immobile and have a very narrow host range. Gillette (1912) recommended crop rotation as a method for controlling CRW. However, Bigger (1932) reported that crop rotation failed to control NCR. This method was not employed again until the 1940s when CRW reappeared as a potential pest on irrigated maize in Kansas and Nebraska (Hill *et al.* 1948; Krysan and Branson 1983).

Recently, with increased awareness of insecticide problems, crop rotation is again recommended by several authors for CRW control in the U.S. and Canada (Luckmann 1978; Bereza 1983; Felsot and Steffey 1985; Ont. Ministry of Agriculture and Food 1985; De Vault 1986; Krysan *et al.* 1986; Mayo 1986; Olkowski 1986; Ritchot 1985, 1986a, 1986b). However, Kaufman (1986, cited by De Vault 1986) argued that NCR eggs laid in 1985 might hatch, not in 1986 when soy beans were alternated with corn, but in 1987. Krysan *et al.* (1986) confirmed Kaufman's hypothesis by showing that one-half of the egg population of *D. barberi* laid by adults in cornfields rotated annually diapaused for two years, whereas only nine per cent of eggs collected from adults where corn is planted without rotation diapaused for two years. It appears that crop rotation could perpetuate the selection of two-year biotypes of corn rootworm. To avoid this problem, De Vault (1986), Krysan *et al.* (1986) and Olkowski (1986) suggested a two-year, with two non-host plants, crop rotation. However, evidence of damage by NCR to corn plant from a three-year diapause eggs suggest that this approach is not infallible (Ostlie 1987).

Graham and Tate (1944) found that CRW damage was significantly less in plots plowed in the fall than those plowed in the spring. Chiang *et al.* (1971) and Chiang (1973) noted that any tillage practices that would increase exposure of the soil to winter cold would reduce rootworm populations in the following season. Matin and Yule (198[illegible]a) observed that fall plowing of a cornfield caused some direct destruction of the newly-laid eggs, but by the following spring the overall effect of fall plowing had significantly increased survival. Calkins and Kirk (1969) showed that, when winter precipitation is plentiful, fall or spring plowing had no effect on the NCR and WCR population in the next season. Chiang *et al.* (1971) stated that, in a minimum tillage field, placing corn rows midway between the rows of the preceding year may reduce larval survival and rootworm infestation.

Chiang (1970) reported that without added manure, mites were responsible for a 20 per cent reduction in the CRW infestation. With manure added, the reduction in population was 63 per cent.The parasitic nematode, *Neoplectana carpocapsae* (= *Steinernema feltiae*), has a wide host range, including the larvae of *Diabrotica* (Poinar 1979). Poinar (1983) and Thurston (1987) demonstrated in field studies that *N. carpocapsae* significantly reduced larval populations of the CRW. In laboratory testing, Kuhlman (1970) and Wilde (1971) found that tachninid larvae, *Celatonia diabrotica*, were very effective against NCR and WCR.

Some experimental corn hybrids showed significantly reduced CRW larval damage. Deep-rooted corn lines with the ability to produce regrowth roots would withstand CRW damage better than shallow rooted corns (Wilson and Peters 1973; Owens *et al.* 1974; Welch 1977; Sutter *et al.* 1981; Branson *et al.* 1983; Branson 1986).

Chemical Control

In the past, chemical control has been the major management strategy for suppressing corn pests (Chiang 1978). Chlorinated hydrocarbon insecticides such as DDT and BHC were first applied by Fulton (1946) and Hill *et al.* (1948) against SCR and WCR, respectively. Mumma *et al.* (1949) introduced the use of toxaphene to the above-mentioned recommendations. The cyclodiene insecticides, aldrin, chlordane and heptachlor, were also effective CRW larvicides (Ball and Hill 1953; Ball and Roselle 1954). However, it soon became apparent that continuous reliance on these persistent, related chemical materials was misplaced, the end result being the development of insecticide resistance and environmental contamination (Roselle *et al.* 1959; Weekman 1961; Ball and Weekman 1962; Bigger 1963).

Thus the chlorinated hydrocarbons were replaced by organophosphorus and carbamate insecticides. Roselle *et al.* (1961) suggested the use of diazinon for CRW control. Weekman and Ball (1963) noted that band treatment of diazinon and phorate in granular formulations gave the most promising results. Several other organophosphate and carbamate insecticides, bux-ten, carbaryl, fensulfothion, fonofos, chlorpyrifos, disulfoton, terbufos and carbofuran, were found to be very effective for larval corn rootworm control (Apple 1960, 1961; Peters 1964,1965; Musick and Fairchild 1967; Apple *et al.* 1969). However, other similar trials showed that diazinon, phorate, carbaryl, bux-ten, terbufos and carbofuran were less effective in soils that had been pre-conditioned with repeated applications of these chemicals (Caro *et al.* 1973; Williams *et al.* 1976; Felsot *et al.* 1981, 1985; Kaufman *et al.* 1981; Ball 1981; De Vault 1986; Olkowski 1986). The genetically-based resistance of CRW to some organophosphate and carbamate insecticides necessitates the rotation of these chemicals. Luckmann (1978) stated that the rotation of a carbamate with an organophosphate delayed the selection of resistance. Ellis (1982) and Ellis and Beattie (1984) blamed many of the failures of granular insecticides on the inadequate calibration of applicators, failure to use spreaders, failure to use wind guards, and poor incorporation into soils.

Metcalf (1980) emphasized that the observation of realistic ET's, reduction of application rates, and environmental safety, are the most important factors for pesticide management. Recently, with the development of IPM strategies, research has begun to focus on factors such as selectivity and environmental safety of chemicals. Eder and van Keyserlingk (1985) mentioned that pyrethroids have a very promising future in insect pest management. Levine (1985) and Oleson and Tollefson (1985) reported that a pyrethroid (PP993 1.5G) applied at the rate of about 0.142 kg (AI/ha) significantly reduced larval damage.

Application of chlorinated hydrocarbon insecticides at a cost of $5.5 (US)/ha provided a return of $4.25 (US) for every dollar expended (Olkowski 1986). Metcalf (1980) noted that, with the average price of corn at $2.20 (US)/bu and carbofuran costing $21.6 (US)/ha, the benefit /cost ratio of insecticide use is $3.12:1.00 (US). However, Headley (1975) emphasized that, by including other social costs for pesticide usage, the true benefit/cost ratio would be reduced greatly.

INSECTICIDE RESIDUES

The physicochemical properties of an insecticide are of major importance in determining its effectiveness in the soil. Harris (1969) classified insecticides into three groups according to their persistence: i.e. slightly, moderately and highly residual. Most organochlorines are highly persistent, whereas granular formulations of organophosphorus and carbamate insecticides are only moderately persistent in most soils. CRW control requires a moderate residual activity of an insecticide so that it remains biologically active through the peak larval population (Harris 1972; Luckmann 1978; Felsot *et al.* 1985; Mayo 1986).

The average time for degradation of DDT in soil was estimated to be 10 years, followed by dieldrin at eight, chlordane at four and aldrin at three (Edwards 1966). Harris (1969) noted that the insecticidal activity of diazinon, parathion, chlorpyrifos and phorate disappeared within two to four weeks after application to a standard soil. On the other hand, carbofuran, fensulfothion and Bay 27289 remained active for 16 weeks. Fonofos, carbofuran, terbufos and chlorfenvinphos appear to be relatively persistent in the soil (Beynon *et al.* 1968; Read 1969). Several other authors confirmed the moderate persistence of granular formulations of many organophosphorus and carbamate insecticides (Rawlins 1966; Onsager and Rusk 1969; Williams *et al.* 1976; Miles and Harris 1978; Gorder *et al.* 1980, 1982).

The persistence of insecticides in the soil depends on their physicochemical properties, soil type, temperature, moisture, dosage, method of application and micro-organisms present in the soil (Harris 1964, 1966, 1967, 1972; Harris and Lichtenstein 1961; Burkhardt and Fairchild 1967; Campbell *et al.* 1971; Suett 1971; Belanger and Hamilton 1979; Belanger *et al.* 1982; De Vault 1986). Belanger *et al.* (1982) found that, following the growing season, 40 to 48 per cent of the fonofos applied had been retained by an organic soil. Mathur *et al.* (1976) estimated that about 60 per cent of the fonofos and more than 90 per cent of the carbofuran initially applied was lost from the soil within 125 days. Saha *et al.* (1974) reported that 33 to 35 per cent of fonofos applied as granules remained in the soil four months after application, whereas about 38 to 41 per cent remained from an emulsifiable concentrate. Only three to 10 per cent of the fonofos was retained by the soil for 29 months. Chlorpyrifos and diazinon applied as granules to soil persisted for about a month (Tashiro and Kuhr 1978). Carbofuran residues in soil persisted from four to 10 weeks after application (Goder *et al.* 1982). However, rapid degradation of carbofuran was detected in soils that were exposed to repeated applications (Caro *et al.* 1973; Williams *et al.* 1976; Talekar *et al.* 1977; Felsot *et al.* 1981; Harris *et al.* 1984; De Vault 1986).

The literature concerning the analysis of the newer pyrethroids, especially in soil, is rather limited compared to that available for other classes of insecticide (Papadopoulou-Mourkidou 1983). Kaufman *et* *al.* (1977, cited by Williams and Brown 1979) and Belanger *et al.* (1979) found that permethrin persisted intact in the soil for an initial 28 days and then slowly declined for the rest of the season. Williams and Brown (1979) obtained similar results with permethrin persistence in another soil.

111. DENSITY-DAMAGE RELATIONSHIPS

A. EXPERIMENTAL ASSOCIATIONS

1. INTRODUCTION

The quantitative relationship between NCR density and reduced corn yield is essential to establishing an economic injury level, which is considered basic for any successful management program. During 1985-1986 studies were made in a greenhouse and at the seed farm of Macdonald College and in a propagation room at the Agriculture Canada Research Station in St. Jean-sur-Richelieu. This was to study the effects of larval damage to corn roots and yield resulting from artificial infestation with different densities of NCR eggs, larvae and adults.

2. MATERIALS AND METHODS

1. GREENHOUSE AND PROPAGATION ROOM EGG DENSITY EXPERIMENT

1985 Experiment. In 1985, an experiment was conducted in the greenhouse and duplicated in the propagation room to study the effects of larval damage on corn roots and yield resulting from inoculation of different densities of NCR eggs.

The study consisted of four levels of infestation, 0, 10, 50 and

100 NCR eggs/plant, repeated five times in a randomized complete block design (RCBD). Hybrid corn Pioneer® 3994 seeds were planted in 16 L pots on 4 March, 1985 and in 12 L pots on 26 February, 1985, respectively, at the Macdonald College greenhouse and St. Jean propagation room. Plants were grown under a photoperiod regime of 14 L: 10 D and at approximately 25°C (Shaw 1977; Jugenheimer 1985). Plants were watered twice per week and fertilized weekly with a dilute solution of 20:20:20, NPK. The eggs were obtained from adults collected in the summer of 1984 in cornfields at Pike River and St. Antoine Abbe'. Eggs were collected in 8.5 cm petri dishes half-filled with sifted moist soil (60 mesh) (Dominique and Yule 1983b), then kept at room temperature for 10 days, washed with tap water through a series of 20, 40 and 50 mesh sieves. Eggs were finally stored in 5 cm petri dishes filled with sterilized distilled water and kept at 5°C for more than 120 days, to break diapause (Branson *et al.* 1975). Overwintered eggs were pre-incubated for 10 days prior to inoculation in a dark incubator held at 23±2°C and only healthy-looking (opalescent) eggs were used in this study. Infestations were done on 01 April at the Macdonald College greenhouse, and 18 March, 1985 at the St. Jean propagation room. Potted plants were inoculated with each specific egg density using a pipette together with a glass rod for perforating the soil.

Corn plants were pollinated daily during the silking period by hand shaking of the stem, until all silks had dried. Mature plants were harvested on 29 May and 5 July, 1985, at the propagation room and the greenhouse, respectively. At harvesting time, plant height was measured from the first node above ground to the base of the tassel. The ears were harvested separately and oven dried at 65°C until constant weight was obtained. They were then shelled and the weight of kernels was recorded. Harvested plants were cut down at the base and the root system was washed with a water jet. Root volume was determined by a water displacement technique (Fig. 3), and the extent of larval damage to the roots was evaluated through the root damage rating technique developed by Hills and Peters (1971).

1986 Experiment. A similar experiment, with only slight modifications from the 1985 egg density study, was carried out at the Macdonald College greenhouse in 1986.

Hybrid corn Pioneer® 3925 seeds were sown in 16 L pots on 25 February, 1986, and harvested on 26 June, 1986. In this experiment, high densities of infestation, 0, 50, 100, 150 and 200 NCR eggs/plant, were repeated five times in a RCBD. The egg handling procedure was the same as in the 1985 experiment except that the eggs were stored in Limbro® Tissue Culture multi-well plates filled with sterilized distilled water. Inoculation took place in two equal dosages on 16 and 23 March, 1986, to simulate the egg hatching pattern in cornfields (Dominique 1983). Emerging adults were trapped in a fibreglass net erected around the base of the plant and fitted with an inverted vial at the top (Fig. 4). The vials were designed to allow entry but prevent escape of the adults. During adult emergence, cages were observed daily and adults found in the vials were counted and removed.

At harvesting time, stem circumference at the first node above ground and plant height were recorded. Harvesting and root processing procedures were the same as in the 1985 experiment.

Egg densities, grain yield and root damage rating are expressed as linear regression functions in the result section. Data were analysed by means of the analysis of variance procedure (ANOVA) of the statistical analysis system (SAS) (SAS Institute, 1979) in the mainframe computer at Macdonald College. Duncan's multiple range tests were used to determine significance of differences, between mean yields and root ratings at different infestation densities.

ii. SEED FARM EGG DENSITY EXPERIMENT

A field test of the effects of naturally-occurring infestations of NCR on corn yield was made at the Macdonald College seed farm during 1985 and 1986.

Before plowing on 18 October, 1985, 18 soil samples were taken from around the base of eight plants selected at random to a depth of 5

Figure 3. Water displacement technique for determining root volume.

Figure 4. Emergence trap for NCR adults.

cm from an Ormstown cornfield, where an average population of seven adults/plant had occurred earlier in the fall. Samples were brought to the laboratory in double plastic bags, stored at $5^{0}C$, then transferred to the seed farm in mid-November, 1985. Single, double and triple soil samples were spread in an area of 160 x 75 cm on 1 x 2 m plots at the seed farm. They were then turned over with a shovel to a depth of 15 cm in order to give an egg population the same as, double, and triple, the actual field population found at Ormstown. Each plot was isolated with a sheet of plastic buried to a depth of 50 cm to prevent larval dispersal between plots. Check plots were similarly treated and treatment and check plots were replicated three times in a RCBD.

Three soil samples (5 cm diameter, 15 cm deep) were taken from each plot on 1 May, 1985, using a golf cup cutter to determine the (relative) number of eggs per sample. Pioneer® 3925 corn hybrid seeds were planted in the plots 15 May, 1985 and thinned to eight plants after emergence. The experimental units were hand-weeded, and after height and stem circumference measurements had been recorded, all plants were harvested in early October, 1985 and their root systems were dug out (20 x 20 cm and 20 cm deep) for root rating evaluation.

Data were analysed through the ANOVA and general linear method (GLM) procedures of SAS. Duncan's multiple range tests were used to determine significance of differences between mean root ratings and grain yields at different egg densities.

iii. GREENHOUSE LARVAL DENSITY EXPERIMENT

A study was conducted in 1986 at the Macdonald College greenhouse to determine the quantitative relationship between different densities of NCR larvae and root damage and resultant yield.

The study consisted of five levels of infestation, 60, 30, 15, 5 and 0 NCR larvae/plant, repeated five times in a RCBD. These densities were selected so that the highest would exceed the full range of field densities found at the St. Antoine Abbe' cornfield during the 1984 season where extensive corn damage was seen to occur (mean larval density 13.7/plant; highest larval density, 50/plant).

Pioneer® 3925 hybrid corn was planted in 16 L pots on 1 March, 1986. These were watered twice per week and fertilized weekly with a dilute solution of 20:20:20 NPK. Plants were grown under a photoperiod of 14 L:10 D regime at approximately 25°C.

On 7 March, 1986 and a week later, approximately 2400 NCR eggs, previously surface-sterilized in 2.5 per cent Alconox® detergent for five minutes, were incubated in five Limbro® Tissue Culture multi-well plates filled with sterilized distilled water and held in a dark incubator at 23±2°C. Using a moist #2 camel's hair brush and a glass rod to perforate the soil, the corn roots were infested during the first two weeks of April, 1986 in five equal batches to simulate the time range over which eggs hatch, and the rate at which larval infestation takes place in the cornfields of southwest Quebec (Dominique 1983). After the last infestation had been carried out, all plants were caged individually with fibreglass netting fitted with a vial on the top to trap emerging adults. Cages were checked daily after the first adult was observed and trapped adults were counted and removed.

After stem circumference at the first node above ground and plant height measurements were taken, the ears were harvested on 26 June, 1986. The root systems were washed clean and root volumes determined using a water displacement technique (Fig. 3). The root masses were examined for larval feeding, and damaged roots were graded on a one-to-six scale (Hills and Peters 1971; Wilson and Peters 1973).

Data were analysed using the ANOVA procedure of the SAS Institute (1979). Duncan's multiple range test was used to determine significance of differences between mean yields, root ratings and number of adults that emerged from each larval density plot.

iv. SEED FARM LARVAL DENSITY EXPERIMENT

This study was undertaken in field microplots at the Macdonald College seed farm to assess damage caused by NCR larvae to corn roots under semi-field conditions.

Pioneer® 3994 hybrid corn was planted in 10 x 18 cm pressed peat pots in the greenhouse at Macdonald College on 10 May, 1985. Plants were sown and infested indoors to allow the establishment of NCR larvae in the roots, and to avoid the possibility of the mite or ant predation that had been observed by Matin (1983) at the seed farm microplots in earlier trials. Using a moist, fine camel's hair brush, the roots of the corn plants were infested with three densities (20, 10 and 0) late first instar NCR larvae/plant. Infestation took place over a period of 10 days ending 24 June, 1985. A week later, after the last infestation had been made, all plants were transferred to outdoor field microplots. The treated plants were replicated five times in a RCBD.

Due to below-average rainfall in the summer of 1985, supplementary irrigation was necessary. On 27 September, 1985, the plants were cut off at ground level and the root systems were dug out and examined for larval damage.

A regression formula was calculated for larval density and root rating. The data were analysed using the ANOVA procedure of the SAS Institute (1979), and Duncan's multiple range test was used to determine significance of differences between mean root ratings at different larval densities.

V. SEED FARM ADULT DENSITY EXPERIMENT

This study was conducted at the Macdonald College seed farm to evaluate the effect of different densities of adult NCR on the following season's corn crop.

1984-1985 Experiment. Nine field microplots (1 x 2 m), planted with corn on 21 May, 1984, were caged with fibreglass mosquito netting to a height of 1.5 m on 5 August, 1984. NCR beetles collected from cornfields at Pike River and St. Antione Abbe' were released in the cages in mid-August, 1984. Infestation rates were designed to provide three density levels (35, 7 and 0) of NCR adults/plant, reflecting the range of adult populations found in southwest Quebec cornfields in the summer of 1984. The treatment plots were replicated three times in a RCBD. Following the death of the beetles in October 1984 after a frost, the cages were removed, plants were harvested and the plot soils were turned over with a shovel to simulate routine fall-plowing.

The field microplots were sown with Pioneer® 3994 corn on 20 May, 1985, and thinned after plant emergence to 15 plants per plot. Due to the dryness of that summer, supplementary irrigation had to be provided. All plants were harvested on 10 October, 1985 and the root damage caused by the resultant larval population was assessed.

1985-1986 Experiment. The adult density experiment was repeated in the summers of 1985 and 1986 with some modifications from the 1984/85 study. In this experiment (1985-86), 15 cages (30 x 20 x 20 cm) were infested on 12 August, 1985 with five densities (35, 21, 14, 7 and 4) of field-collected NCR adults/plant. The cages were kept in an incubator maintained at 23$\pm$2^{o}C, 65-70 per cent RH and LD 16:8 photoperiod (Dominique and Yule 1983b). Beetles were fed immature corn ears, silks and an artificial diet (Sutter *et al.* 1971). Eggs collected from each cage were kept at room temperature for 10 days then stored at 5^{o}C in petri dishes filled with sterilized soil (Branson *et al.* 1975).

In mid-November 1985, the eggs from each of these specific densities were inoculated at the seed farm into strips 160 x 75 cm and 15 cm deep in 2 x 1 m plots. The plots were replicated three times in a RCBD. On 15 May,1986, each plot was planted with Pioneer^{R} 3925 corn hybrid and later thinned to eight plants after emergence. Each plot was isolated with a 50 cm deep sheet of plastic to prevent larval migration between plots. By early October all corn ears were hand-harvested after plant height and stem circumference measurements had been taken. Three plants from each plot were chosen at random for root rating evaluation.

A regression formula was calculated for adult density and yield, and root rating. The data were analysed using the ANOVA procedure of the SAS Institute (1979), and Duncan's multiple range test was used to determine significance of differences between mean yields and root ratings associated with different adult densities.

3. RESULTS AND DISCUSSION

i.a. RESULTS OF GREENHOUSE AND PROPAGATION ROOM EGG DENSITY EXPERIMENTS

Results of the ANOVA tests for the Macdonald greenhouse and St. Jean propagation room (1985), and the Macdonald greenhouse (1986) egg density experiments, are given in Tables 1a and b. In Table 1a results show that, in the 1985 experiments, there is no significant ($p > 0.05$) reduction in yield whatever the egg density. However, when higher densities were included in the 1986 experiment (Table 1b), a significant ($p \leq 0.05$) reduction in yield resulted. The data in Tables 1a and b also show that the root damage rating was significantly ($p < 0.01$) influenced by the treatments. Neither of the 1985 treatments showed any significant change in plant height or root volume, whereas in the 1986 experiment, a significant ($p < 0.05$) difference in root volume was obtained. The results in Table 1b demonstrate that stem circumference and adult emergence from treated plants were significantly different at $p < 0.05$ and $p < 0.01$ respectively.

The results obtained from Duncan's multiple range test at $p \leq 0.05$ of the means of different variables, are given in Tables 2 and 3 for the 1985 and 1986 experiments, respectively. In agrreement with the ANOVA test for 1985 experiment , there was no significant difference in corn

TABLE 1

ANALYSIS OF VARIANCE PROCEDURE FOR GREENHOUSE AND PROPAGATION ROOM EGG DENSITY EXPERIMENTS

(a) 1985

LOCATION	SOURCE	VARIABLE	D.F.	F-VALUE	PR > F	
Macdonald	Treatment	Height	3	0.13	0.9421	
		Yield	3	1.65	0.2176	
		Volume	3	0.82	0.4994	
		Root rating	3	23.10	0.0001	**
St. Jean	Treatment	Height	3	1.00	0.4200	
		Yield	3	1.72	0.2038	
		Volume	3	2.49	0.0973	
		Root rating	3	26.81	0.0001	**

(b) 1986

LOCATION	SOURCE	VARIABLE	D.F.	F-VALUE	PR > F	
Macdonald	Treatment	Height	4	0.47	0.7549	
		Yield	4	3.58	0.0235	*
		Volume	4	3.15	0.0368	*
		Root rating	4	31.69	0.0001	**
		Circumference	4	3.23	0.0338	*
		Adults	4	36.86	0.0001	**

* Significant at $p = 0.05$

** Significant at $p = 0.01$

TABLE 2

MEAN PLANT HEIGHT, YIELD, VOLUME AND ROOT DAMAGE RATING OF MACDONALD GREENHOUSE AND ST. JEAN PROPAGATION ROOM EXPERIMENTS IN 1985

Eggs/plant	Height (cm)		Yield (g)	
	Macdonald	St.Jean	Macdonald	St.Jean
0	205 a	155 a	99 a	94 a
10	199 a	150 a	96 a	95 a
50	203 a	162 a	91 a	89 a
100	206 a	157 a	89 a	84 a

Eggs/plant	Volume (ml)		Root damage rating	
	Macdonald	St.Jean	Macdonald	St.Jean
0	337 a	319 a	1.0 a	1.0 a
10	325 a	315 a	1.2 a	1.2 a
50	307 a	277 a	2.6 b	3.0 b
100	301 a	276 a	3.6 c	4.8 c

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

TABLE 3

MEAN PLANT HEIGHT, STEM CIRCUMFERENCE, ADULTS EMERGED, YIELD, VOLUME AND ROOT DAMAGE RATING OF MACDONALD GREENHOUSE EXPERIMENT (1986)

Eggs/ plant	Height (cm)	Circ-um. (cm)	Adults emerged	Yield (g)	Root volume (ml)	Root damage rating
0	212 a	7.4 a	0.0 a	109 a	316 a	1.0 a
50	213 a	7.3 a	3.4 b	107 ab	313 a	2.0 b
100	210 a	7.1 ab	6.2 c	104 abc	298 ab	3.4 c
150	206 a	6.7 ab	10.8 d	96 bc	277 b	4.0 cd
200	207 a	6.4 b	11.4 d	93 c	274 b	4.4 d

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

yield regardless of egg density and therefore the data were not subject to further analysis. In the 1986 experiment, a significant reduction in yield resulted at 150 and 200 eggs/plant from the check and 50 eggs/plant. There was no significant reduction in yield between 100 and 150 eggs/plant or 150 and 200 eggs/plant.

Significant root damage was obtained with as few as 50 eggs/plant. Significant differences in stem circumference and root volume were detected at 100 eggs/plant and 200 eggs/plant, respectively.

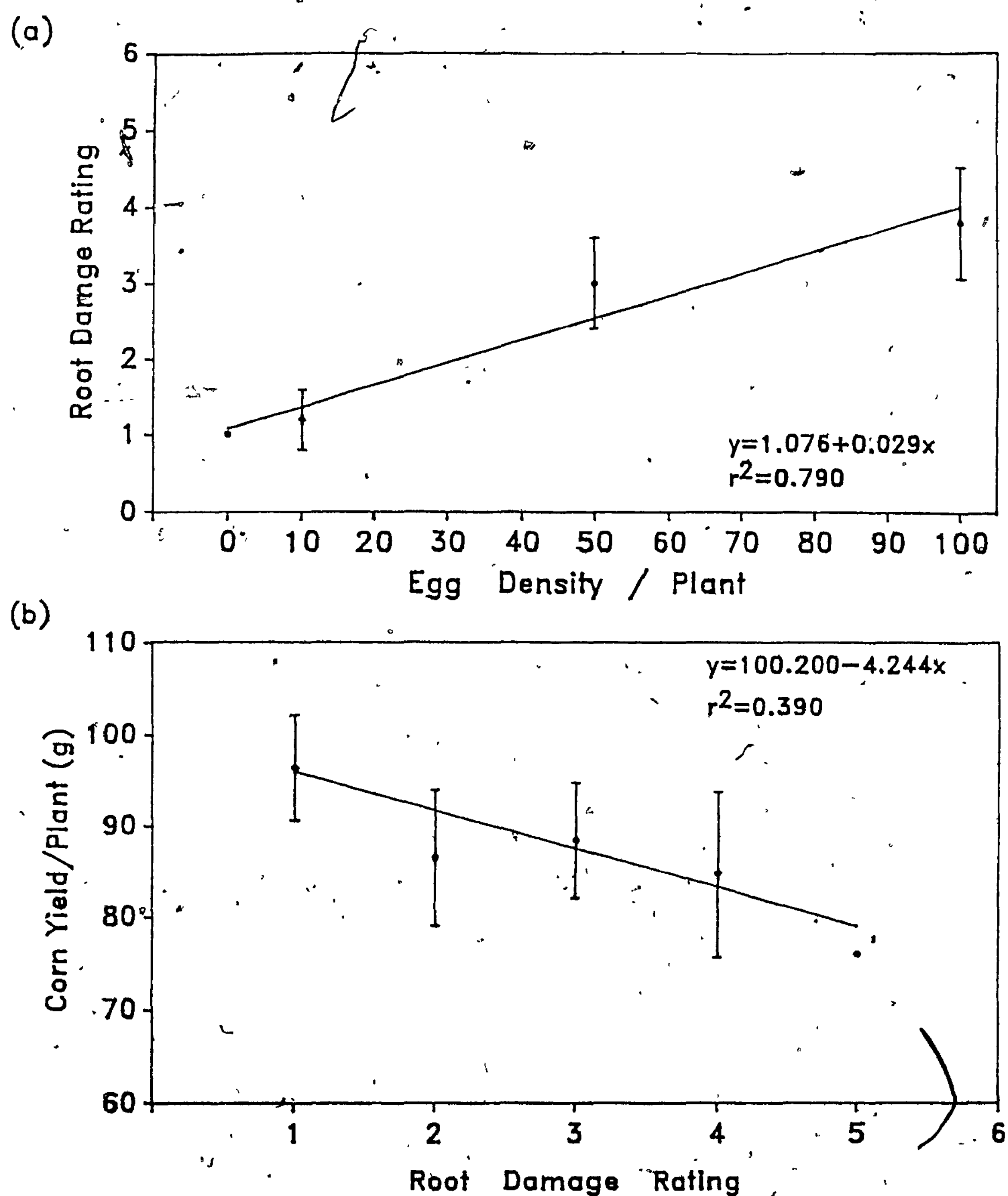
Data relating the dependent variable (egg density/plant) with the independent variables (yield and root damage rating) and within the independent variables are expressed as linear regression functions and are shown in Figs. 5 and 6, respectively, for the Macdonald greenhouse and St. Jean propagation room experiments. Figs. 7 and 8 show the relationships between the dependent variable and the independent variables (yield, root damage rating and emerging adults) and within the independent variables that resulted from the Macdonald greenhouse experiment in 1986. Coefficients of determination (r^2) were all indicative of significant relationships (Steel and Torrie 1980; Zar 1984) between the above-mentioned variables.

The consistency in the F-values (Table 1) indicate that root damage ratings are the most sensitive measurements in these studies. In the 1986 experiment, adults emerged from the treated plants appear to be as sensitive a measurement as the root damage rating. Yield response appears

Figure 5. Data from Macdonald greenhouse egg density experiment (1985; df=18).

a. Regression for root damage rating vs. rate of artificial infestation of NCR egg density per plant.

b. Regression for corn yield per plant vs. root damage rating.



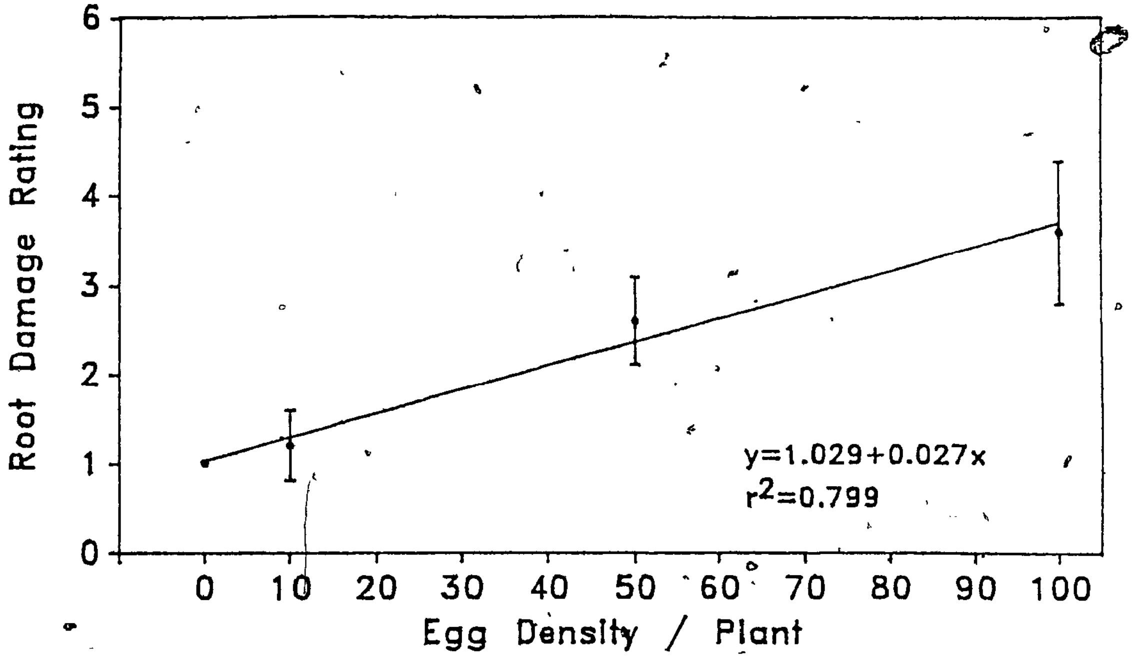
• Single observation

Figure 6. Data from St.Jean propagation room egg density experiment (1985; df=18).

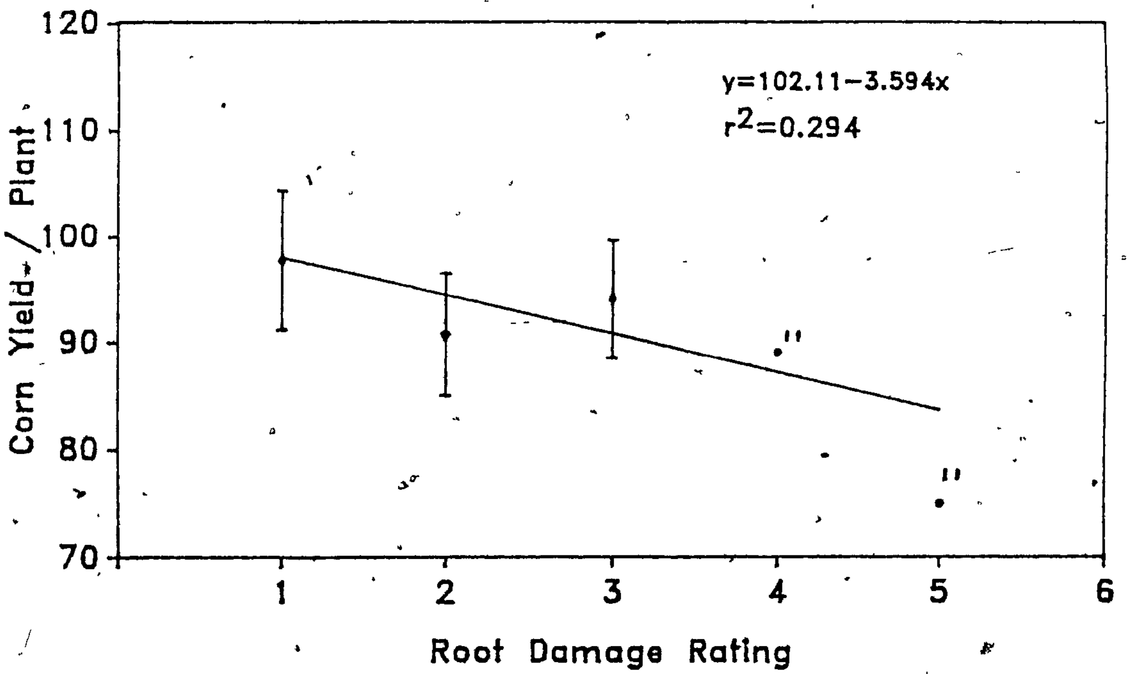
a. Regression for root damage rating vs. rate of artificial infestation of NCR egg density per plant.

b. Regression for corn yield per plant vs. root damage rating.

(a)



(b)



" . Single observation

to be the third most sensitive measurement in 1986, whereas in the 1985 experiment yield was not significantly influenced by the treatment. This could be attributed to the fact that yield responses were greater at higher densities. Plant height, stem circumference and volumetric measurement are liable to variation in relation to the growth of individual plants. They hold particular promise for evaluating phytotoxicity (Oleson and Tollefson 1985) and varietal responses (Sutter *et al.* 1981).

Average yield loss estimated from 86 experiment show that root damage ratings of 2, 3, 4, 5 and 6 caused a yield reduction of 4, 8, 13, 17 and 18 per cent, respectively. These results conform with those of Sutter *et al.* (1981) who worked with WCR. The nature of the damage caused by WCR is similar to NCR (Chiang 1973; Krysan 1986). Sutter *et al.* (1981) found significant yield reduction at 100 eggs/plant, whereas in my experiments 100 eggs/plant failed to produce a significant reduction in yield. In some cases, particularly with insects not attacking the actual crop product, very dense populations can be tolerated with no significant loss in yield (Southwood and Norton 1973). In this experiment an egg density of as low as 150 eggs/plant resulted in significant yield reduction from the check, whereas Chiang *et al.*(1980) did not detect any significant yield loss at densities below 600 WCR eggs/plant. This discrepancy may be attributed to the difference in species, viability of the eggs, method of infestation, drought conditions and chemical residues in the field. It should also be noted that our investigation on egg density-damage relationship was conducted under green

Figure 7. Data from Macdonald greenhouse egg density experiment (1986; df=23).

a. Regression for corn yield per plant vs. rate of artificial infestation of NCR egg density per plant.

b. Regression for root damage rating vs. rate of artificial infestation of NCR density per plant.

c. Regression for NCR adults emerged per plant vs. rate of artificial infestation of NCR egg density per plant.

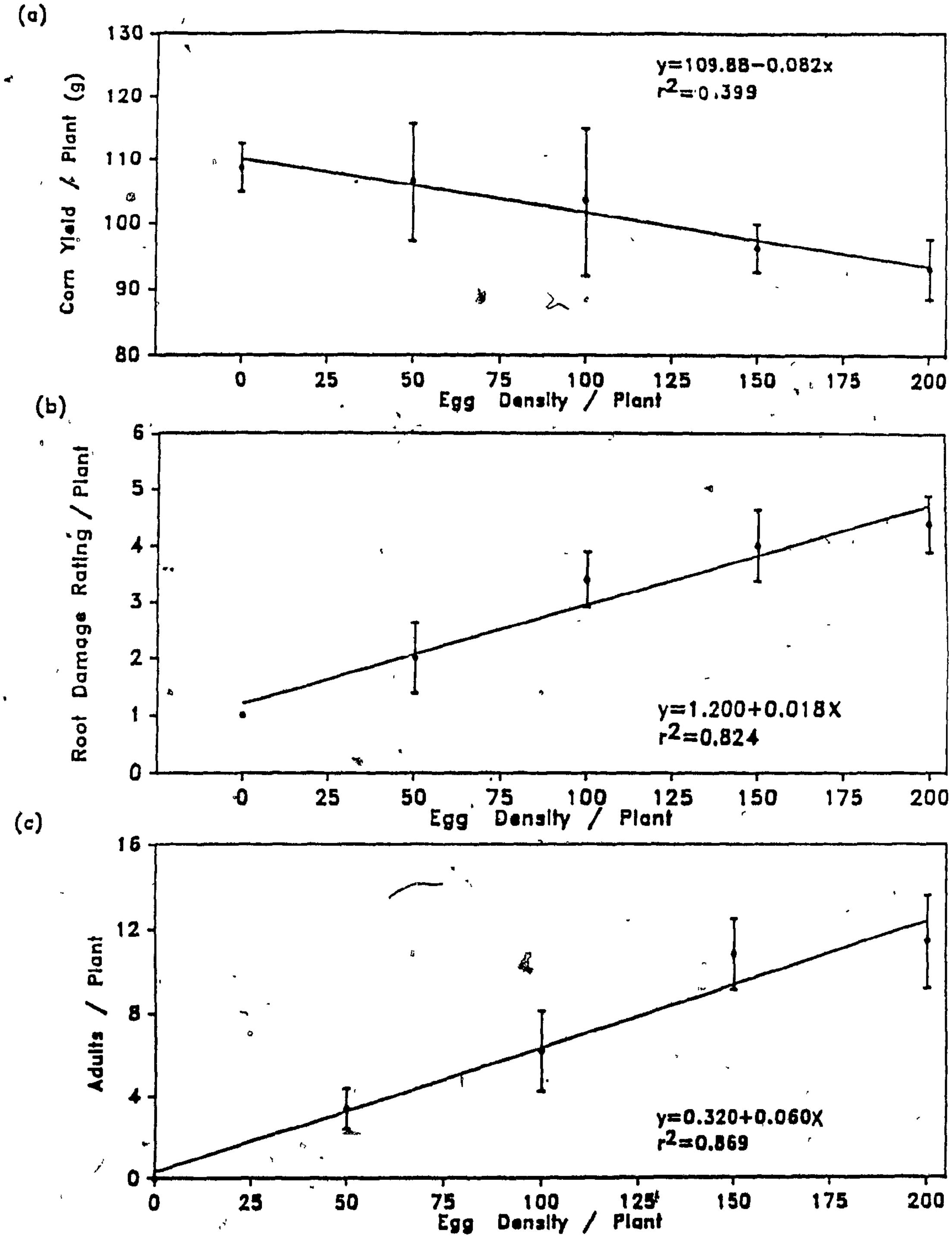
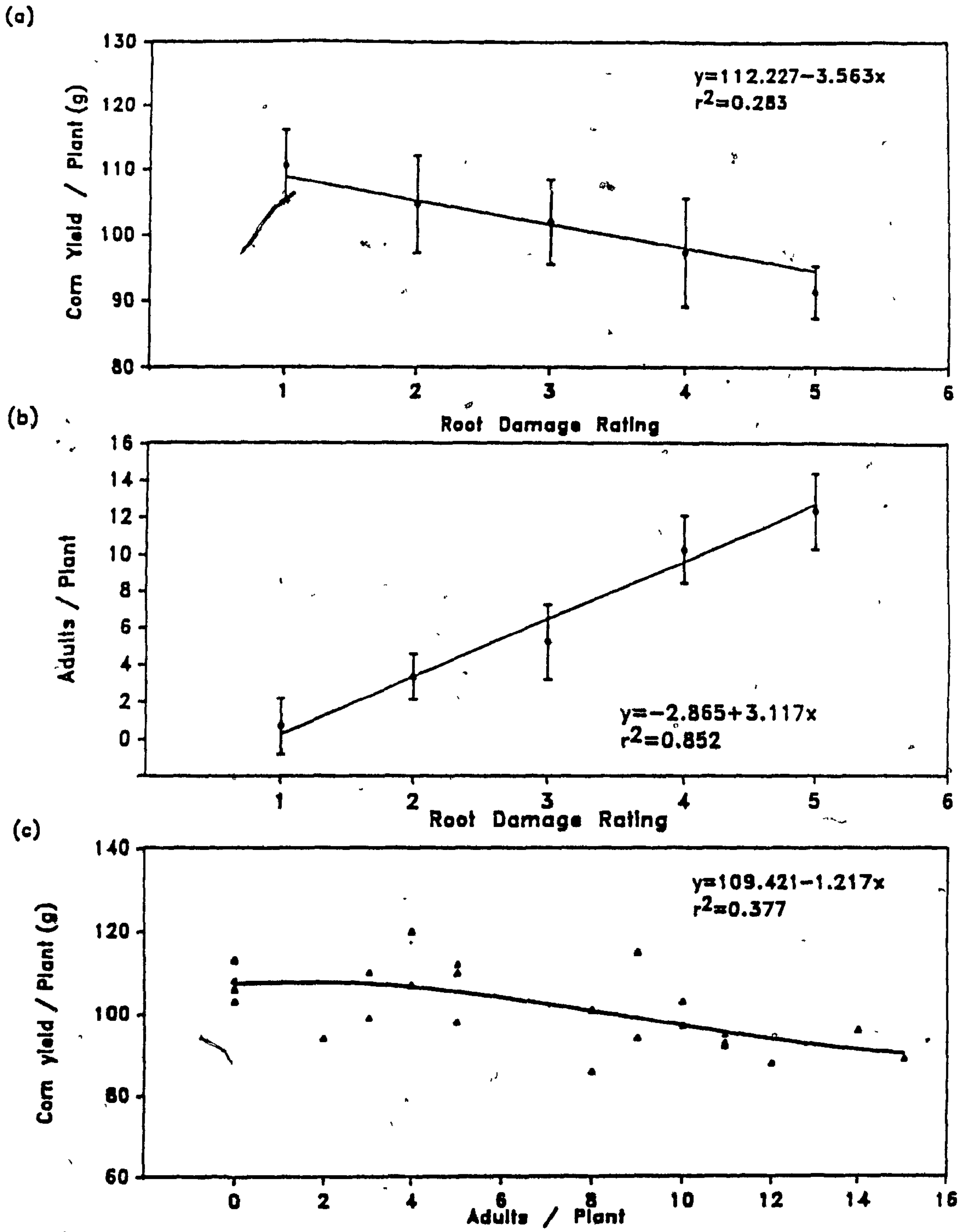

(a)
y=109.88−0.082x
r2=0.399
Corn Yield / Plant (g)
Egg Density / Plant
(b)
y=1.200+0.018X
r2=0.824
Root Damage Rating / Plant
Egg Density / Plant
(c)
y=0.320+0.060X
r2=0.869
Adults / Plant
Egg Density / Plant

Figure 8. Data from Macdonald greenhouse egg density experiment (1986; df=23).

a. Regression for corn yield per plant vs. root damage rating

b. Regression for NCR adults emerged per plant vs. root damage rating.

c. Regression for corn yield per plant vs. NCR adults emerged per plant.


(a)
y=112.227−3.563x
r2=0.283
Corn Yield / Plant (g)
130
120
110
100
90
80
1
2
3
4
5
6
Root Damage Rating
(b)
y=−2.865+3.117x
r2=0.852
Adults / Plant
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
Root Damage Rating
(c)
y=109.421−1.217x
r2=0.377
Corn yield / Plant (g)
140
120
100
80
60
0
2
4
6
8
10
12
14
16
Adults / Plant

house conditions. One might expect higher yield losses under variable field conditions of drought, rainfall, wind, soil type and soil fertility, as reported by Chiang (1973); Chiang *et. al*. (1980); Henry and Bereza (1979).

i.b. DISCUSSION OF ECONOMIC DAMAGE AND ECONOMIC INJURY LEVELS CALCULATED FROM RESULTS OF (a).

The economic damage to a given plant stage is the amount of damage required to cause enough monetary loss to offset the cost of using artificial control measures (Stern 1966). Economic damage (Table 4) was calculated using the formula of Stone and Pedigo (1972) as follows:

$$\text{Economic Damage kg/ha} = \frac{\text{Cost of chemical control (\$/ha)}}{\text{Wholesale value of corn (\$/t)}}$$

The average wholesale price of grain corn in Quebec from 1980 to 1985 and for 1986-87 was \$153 and \$115 / t, respectively (Anonymous 1986; Fultan 1986; Irvine 1986). The cost of chemical control ranged from \$39 to \$50/ha (Table 4), depending on the type of insecticide, dosage and method of application (P. Martel, Pers. Comm. 1987; G. Letendre, Pers. Comm. 1987).

Economic injury level (EIL) is the lowest population density that will cause economic damage (Stern *et al*. 1959; Stone and Pedigo 1972). EIL for the egg stage under greenhouse conditions (Table 4) was cal

TABLE 4

COST OF CHEMICAL CONTROL, ECONOMIC DAMAGE AND AVERAGE ECONOMIC INJURY LEVELS (EIL) OF GREENHOUSE AND PROPAGATION ROOM EGG DENSITY EXPERIMENTS (1985-1986)

Insecticide	Cost of chemical control $/ha	Economic damage (kg/ha;grain loss)		EIL			
		1980-85	1986-87	1980-85		1986-87	
				eggs/ plant	RDR*	eggs/ plant	RDR*
PP993 (1G)	50.00	327	435	63	2.7	84	3.2
chlorpyrifos (Lorsban 15G)	49.00	320	426	62	2.7	82	3.2
fonofos (Dyfonate 20G)	39.70	259	345	50	2.4	67	2.5
terbufos (Counter 20G)	39.38	257	342	49	2.4	68	2.5

* Root Damage Rating

culated using the method of Ogunlana and Pedigo (1974), by solving the regression equation as follows:

$$y = a + bx, \text{ or } x = \frac{-(a - y)}{b}$$

where a is the expected yield at zero level infestation and y is the expected yield below which the value of the crop loss is greater than the cost of chemical control. The term (a - y) is the intercept minus the expected yield, or the economic damage. Therefore, the EIL is:

$$x = -\frac{\text{(economic damage)}}{\text{b (negative term)}}$$

$$= \frac{\text{Economic damage}}{\text{Slope of regression line (as positive term)}}$$

Economic injury level could also be calculated as follows:

$$= \frac{\text{Economic damage}}{\text{loss associated with one insect}}$$

Economic injury level and economic threshold are dynamic parameters. The most important factors involved are, the ratio of control cost to the market value of the crop, environmental conditions, and pest and plant population densities.

FIGURE 9. EFFECTS OF CONTROL COST/CORN PRICES RATIO ON THE EIL OF NCR EGGS

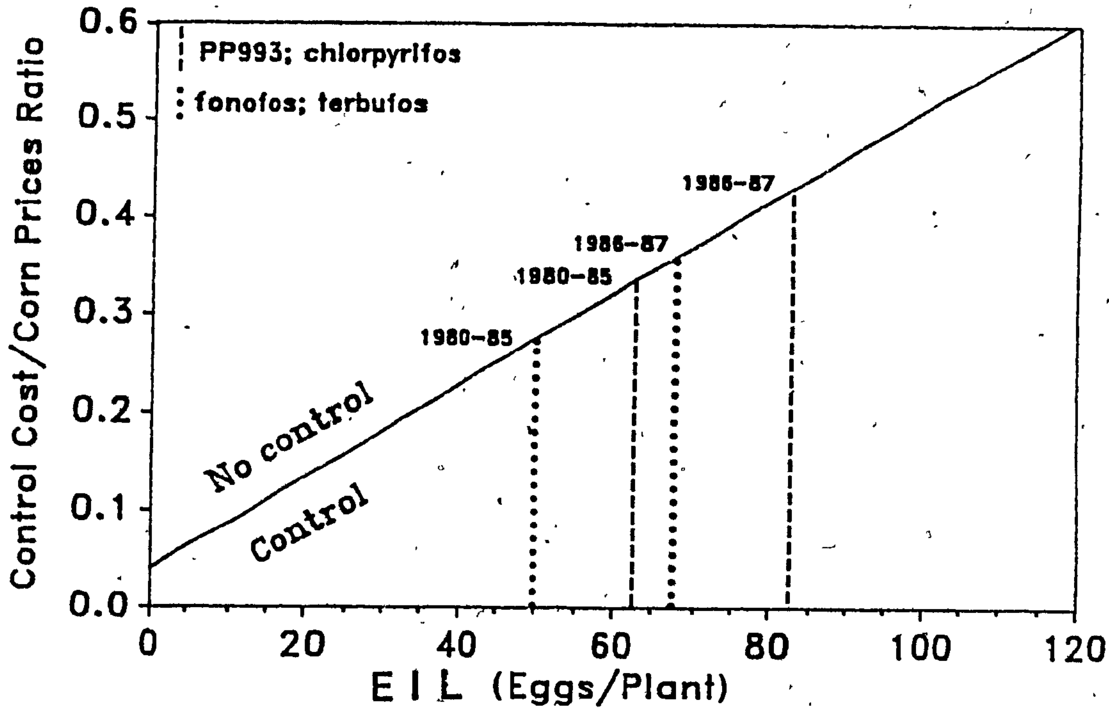


Table 4 and Fig 9. show that EIL was greatly affected by the cost of control/corn prices ratio. Based on this ratio, EIL varies from 50 to 63 eggs/plant for the 1980-85 period and from 68 to 84 eggs/plant for the 1986-87 period. Up to now, there has been no EIL established in the literature for the NCR egg stage to facilitate comparison. However, this range corresponds to 2.4 to 3.2 root damage ratings in the 1 to 6 scale developed by Hills and Peters (1971), which is in general agreement with Sutter *et al*. (1980), who found that three units of root damage ratings are considered as the EIL.

ii. SEED FARM EGG DENSITY EXPERIMENT

ANOVA of the results indicated that root damage rating was greatly affected ($p < 0.01$) by the treatment (Table 5). Plant height, stem circumference and yield showed no significant effects due to treatment. The results obtained from Duncan's multiple range test at $p = 0.05$ of the means of different variables are shown in Table 5. Root damage ratings at level two (6.1 eggs/ sample) egg density are significantly different from the check plot. A significant difference was also detected between the means of level three (7.8 eggs/sample) and level two.

The main reason for the lack of significant effects of egg densities on yield (Table 5) might be due to the adverse effect of below -normal minimum temperature (Appendix 1) during June and July 1986. Dominique and Yule (1983a) observed that 340 and 421 to 431 accumulated degree days above the threshold temperature for development (9.7°C) are required by NCR eggs in the rhizosphere and air temperatures, respectively, for first eclosion of NCR eggs in southwest Quebec. They noted that under normal weather conditions in this area, the thermal requirements for hatching are usually met by the first week of June. In 1986, the thermal requirements for the eclosion of eggs were met only on 5 July 1986 (Appendix 1). From the weather data collected at Macdonald seed farm (Appendix 1), one might expect that either the prolonged chill period affected the hatchability of the eggs (Chiang 1965; Patel and Apple 1967; Dominique and Yule 1983b), or by the time larvae started to hatch (5 July

TABLE 5

DUNCAN'S MULTIPLE RANGE TEST OF THE MEANS OF PLANT HEIGHT, STEM CIRCUMFERENCE, YIELD AND ROOT DAMAGE RATINGS OBTAINED FROM SEED FARM EGG DENSITY EXPERIMENT.

Treatment (eggs/sample)	Height (cm)	Stem Circum. (cm)	Yield (g)	Root damage rating
Control (0.4)	157 a	7.5 a	127 a	1.1 a
Level 1 (2.4)	151 a	7.2 a	130 a	1.3 ab
Level 2 (6.1)	150 a	7.0 a	125 a	1.8 b
Level 3 (7.8)	149 a	7.4 a	121 a	2.7 c

Means followed by the same letter in the same column are not significantly different at ($p > 0.05$; Duncan's multiple range test).

1986), corn plants were old enough to resist their attack or to provide adequate nutrition to NCR.

The significant relationships between yield reduction and insect numbers play a partioularly important role in establishing EIL. Because of no significant effect of egg densities on corn yield in this experiment, no EIL could be determined.

iii. GREENHOUSE LARVAL DENSITY EXPERIMENT

Root damage ratings, stem circumference and adults emerged from treated plants were all affected by the larval density treatments. Yield was significantly affected ($p = 0.0278$) by larval damage. Neither plant height nor root volume showed any significant change.

In Table 6 the significance of differences obtained with Duncan's multiple range test at $p = 0.05$ of the means of several variables are shown. Adults emerging from treated plants, root damage ratings, and stem circumference, were greatly affected by different larval densities. Significant reduction in yield was detected at an infestation level of 60 larvae/plant compared with the check and five larvae/plant. Medium densities (15 and 30 larvae/plant) failed to produce any significant reduction in yield from the check or from 60 larvae/plant. Plant height and root volume remained unchanged at different larval densities.

Data relating the larval densities with the dependent variables (yield, root damage ratings and emerged adults) and within the dependent variables are illustrated in Figs. 10 and 11. Based on the regression line given in Fig. 10a, one larva/plant is responsible for a loss in yield of 0.366g per plant or 0.273 per cent.

Economic damage and economic injury levels were calculated using the formula of Stone and Pedigo (1972) and Ogunlana and Pedigo (1974),

TABLE 6

DUNCAN'S MULTIPLE RANGE TEST OF THE MEANS OF PLANT HEIGHT, STEM CIRCUMFERENCE, GRAIN YIELD, ROOT DAMAGE RATING AND ROOT VOLUME FOR FIVE LARVAL DENSITIES OF GREENHOUSE INFESTATION

Treatment (larvae/ plant)	Height (cm)	Stem Circumference (cm)	Adults emerged	Yield (g)	Root damage rating	Root volume (ml)
0	223 a	7.6 ab	0.0 a	115 a	1.0 a	313 a
5	218 a	7.7 a	0.4 a	116 a	1.2 a	310 a
15	213 a	7.1 bc	2.4 b	109 ab	2.2 b	305 a
30	211 a	6.6 cd	5.0 c	102 ab	2.8 b	298 a
60	209 a	6.3 d	9.2 d	95 b	4.2 c	286 a

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

Figure 10. Data from Macdonald greenhouse larval density experiment (df=23).

a. Regression for corn yield per plant vs. rate of artificial infestation of NCR larval density per plant.

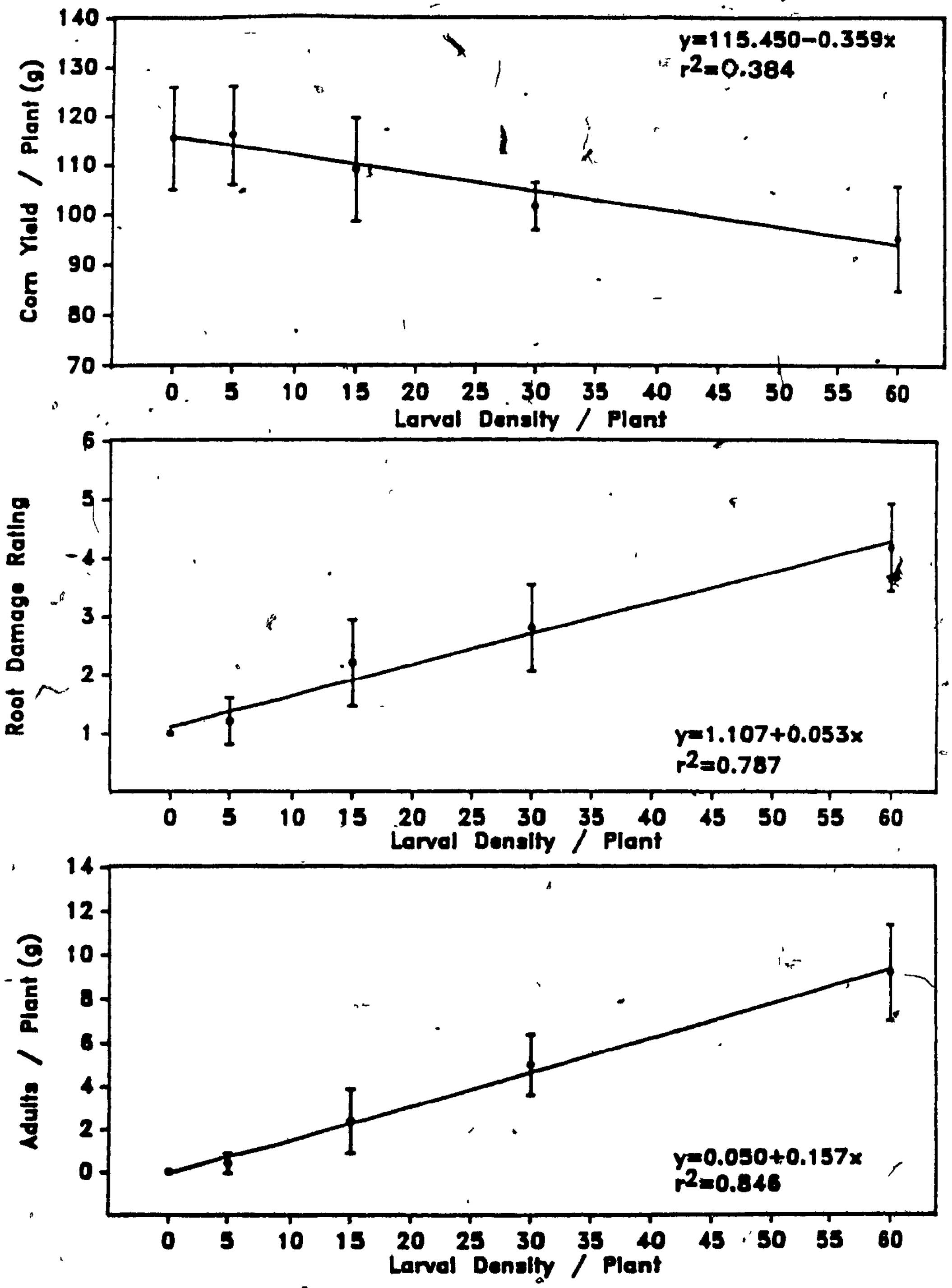
b. Regression for root damage rating vs. rate of artificial infestation of NCR larvae per plant.

c. Regression for adults emerged per plant vs. rate of artificial infestation of NCR larvae per plant.

(a)

(b)

(c)



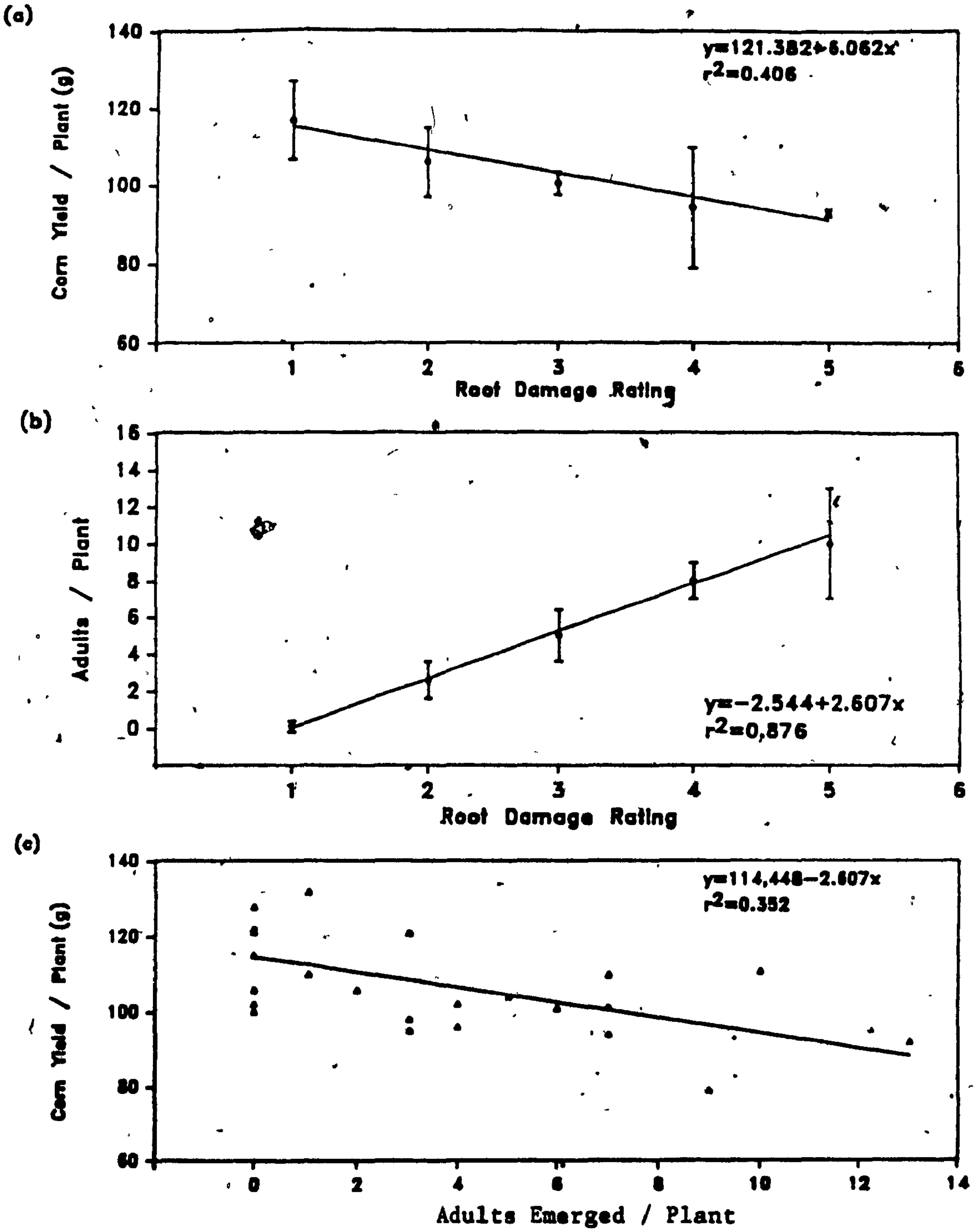
y=115.450-0.359x
r2=0.384
Corn Yield / Plant (g)
Larval Density / Plant
y=1.107+0.053x
r2=0.787
Root Damage Rating
Larval Density / Plant
y=0.050+0.157x
r2=0.846
Adults / Plant (g)
Larval Density / Plant

Figure 11. Data from Macdonald greenhouse larval density experiment (df=23).

a. Regression for corn yield per plant vs. root damage ratings

b. Regression for NCR adults emerged per plant vs. root damage rating.

c. Regression for corn yield per plant vs. NCR adults emerged per plant.


(a)
y=121.382+6.062x
r2=0.406
Corn Yield / Plant (g)
Root Damage Rating
(b)
Adults / Plant
y=-2.544+2.607x
r2=0,876
Root Damage Rating
(c)
Corn Yield / Plant (g)
y=114,448-2.607x
r2=0.352
Adults Emerged / Plant

respectively, as described in section III.A.3.i.b. Table 10 shows the calculated EIL's for different types of insecticides for 1980-85 and 1986-87 periods. The market value of grain corn in Quebec was ca. $153 (Anonymous 1986) for 1980-85 and $115 (Fulton 1986; Irvine 1986) for 1986-87. The present cost of chemical control is given in Table 7 (G. Letendre, Pers. Comm 1986; P. Martel, Pers. Comm. 1986). Table 7 shows that the EIL vary from 13 to 16 and 17 to 21 larvae/plant, respectively for the period between 1980-85 and 1986-87. Fig.12 shows that the EIL's for NCR larvae were greatly affected by the control cost/corn price ratio.

Root damage rating and adults emerged from treated plants are the most sensitive parameters for evaluating the effect of larval damage on corn plants. However, adults emerged from treated plants may not be as good as root damage rating at a higher rate of infestation. This is due to the phenomenon of competition between the larvae observed by Chiang *et. al.* (1980) and Sutter *et al.* (1981). Moreover, due to a shortage of cracks in the soil surface under greenhouse conditions, one might expect a lower ratio of emerged adults as compared with field conditions. Root damage ratings are consistent and less time consuming than root volume measurements. Also, it is difficult to apply volumetric measurements in field conditions due to the large volume of soil sample required and the resultant breakage of some roots.

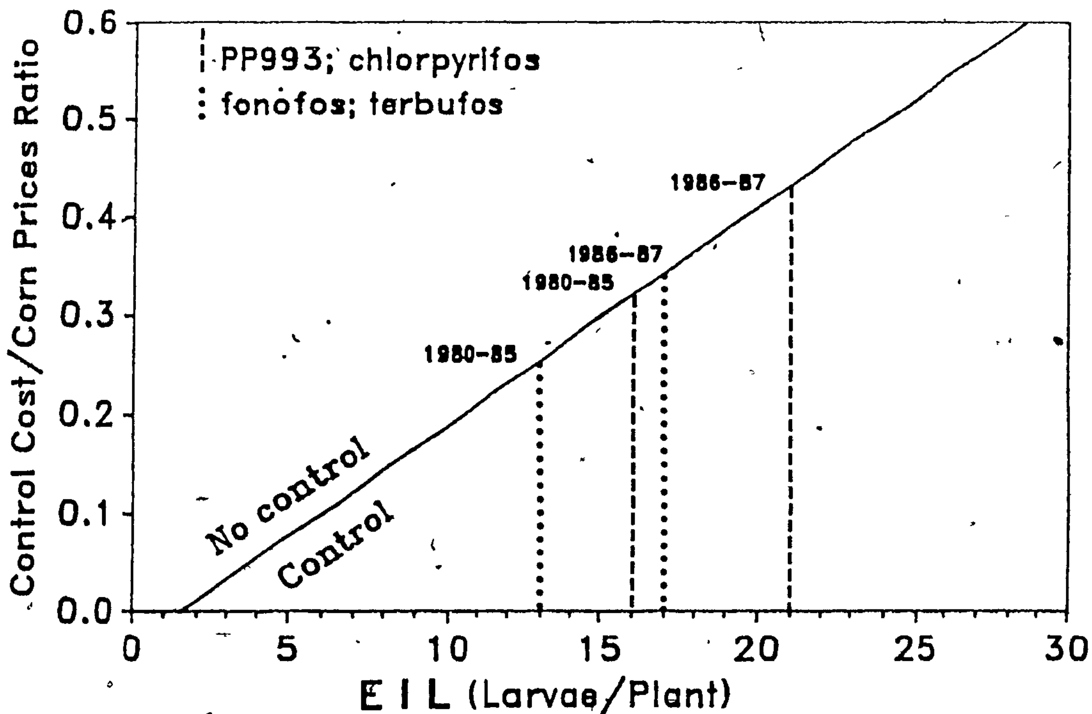
Yield is the most practical but least sensitive criterion for

TABLE 7

COST OF CHEMICAL CONTROL, ECONOMIC DAMAGE AND ECONOMIC INJURY LEVELS (EIL) FOR THE GREENHOUSE LARVAL DENSITY EXPERIMENT (1986)

Insecticide	Cost of chemical control $/ha	Economic damage (kg/ha;grain loss)		EIL (larvae/plant)	
		1980-85	1986-87	1980-85	1986-87
PP993 (1G)	50.00	327	435	16	21.2
chlorpyrifos (Lorsban 15G)	49.00	320	426	16	21.0
fonofos (Dyfonate-20G)	39.70	259	345	13	17.0
terbufos (Counter 20G)	39.38	257	342	13	17.0

FIGURE 12. EFFECTS OF CONTROL COST/CORN PRICES RATIO ON THE EIL OF NCR LARVAE



measuring insect-plant relationship. Mayo (1986) reported that yield differences must exceed 30 to 62.5 bushels per ha before statistically significant effects can be detected. In this experiment, yield was significantly decreased only at the 60 larvae/plant density.

Economic injury level varies from 13 to 16 and 17 to 21 first-instar larvae, respectively, for the period between 1980-85 and 1986-87. Variation in economic injury levels within the same period is due to the cost of control; variation between the two periods is a result of mark prices of corn. By adjusting economic injury levels to second instar larvae, the values vary from 8 to 10 and 11 to 14 second instar larvae per plant, respectively, for the 1980-85 and 1986-87 period. These results are quite close to the level of 10 NCR larvae/plant reported by Peters (1963) in Iowa.

iv. SEED FARM LARVAL DENSITY EXPERIMENT

Analysis of variance of the results showed that root damage ratings were highly significant. Data relating root damage ratings to larval density are illustrated in Fig. 13. This regression line was linear and significant. Duncan's multiple range test at p=0.05 (Table 8) shows that 20 larvae per plant produced root damage significantly different from the check, whereas 10 larvae per plant failed to produce any statistically significant root damage. Measurement of plant height, stem circumference and yield were unreliable in this experiment, due to adverse weather conditions, particularly drought, that prevailed during June and July,1985.

Ten and 20 larvae/plant produced a root damage rating of 2.4 and 3.4, respectively. This range of root damage rating falls within the range of economic injury levels (13 to 21 larvae/plant) observed at the greenhouse larval density experiment. These results are also in fair agreement with the economic injury levels observed by Sutter *et al.* (1980). Hills and Peters (1971) noted a 4.6 per cent reduction in yield for every adjusted root damage rating. Based on this percentage loss in yield one might expect under normal conditions 10 to 20 larvae/plant to produce less than 9 to 14 per cent loss in yield from the check.

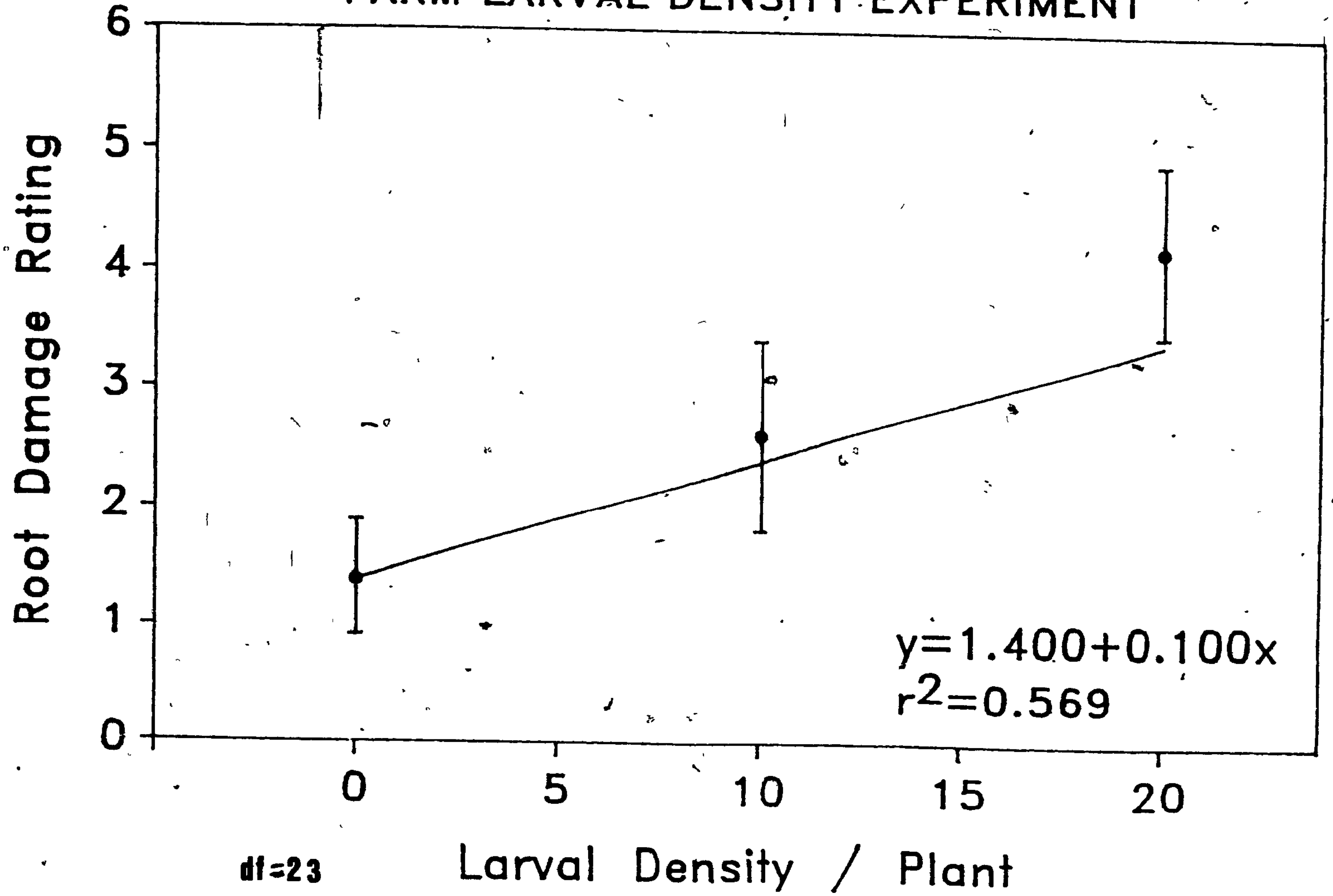
TABLE 8

DUNCAN'S MULTIPLE RANGE TEST OF THE MEANS OF ROOT DAMAGE RATING FOR SEED FARM LARVAL DENSITY EXPERIMENT

Treatment (larvae/plant)	Root Damage Rating
0	1.4 a
10	2.4 ab
20	3.4 b

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

FIGURE 13. REGRESSION FOR ROOT DAMAGE RATING VS. NCR LARVAL DENSITY PER PLANT. (DATA OBTAINED FROM SEED FARM LARVAL DENSITY EXPERIMENT



V. SEED FARM ADULT DENSITY EXPERIMENT

1984-1985 Experiment Analysis of variance indicated that root damage ratings were highly affected by adult density. The result of Duncan's multiple range test of the means are shown in Table 9. The data show significant difference in root damage at seven adults/plant compared to the check. There is also significant root damage difference between 36 adults/plant and seven adults/ plant. The relationship between root damage ratings and adult density is illustrated in Fig. 14. The regression line indicates that the relationship is linear and the coefficient of determination ($r^2 = 0.638$) is highly significant.

Economic injury levels were not calculated due to lack of yield data in this experiment. However, the 2.4 root damage rating resulting from seven adults/plant falls within the EIL's observed in the greenhouse larval density experiment in 1986 (Table 7).

1985-1986 Experiment. Analysis of variance showed that root damage rating was highly affected by adult densities. Though yield was the second most sensitive parameter, it was not significantly ($p = 0.1363$) affected by the treatment. Plant height and stem circumference were the least sensitive parameters.

Results of Duncan's multiple range test are given in Table 10. The

TABLE 9

DUNCAN'S MULTIPLE RANGE TEST OF THE MEANS OF ROOT DAMAGE RATINGS OBTAINED FROM SEED FARM ADULT DENSITIES EXPERIMENT (1985-86)

Treatment (Adults/plant plant)	No. of samples	Root Damage Rating
0	35	1.4 a
7	35	2.4 b
35	35	4.9 c

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multible range test).

FIGURE 14. REGRESSION FOR ROOT DAMAGE RATING VS. NCR ADULT DENSITY PER PLANT. DATA OBTAINED FROM SEED FARM ADULT DENSITY EXPERIMENT (1984/85)

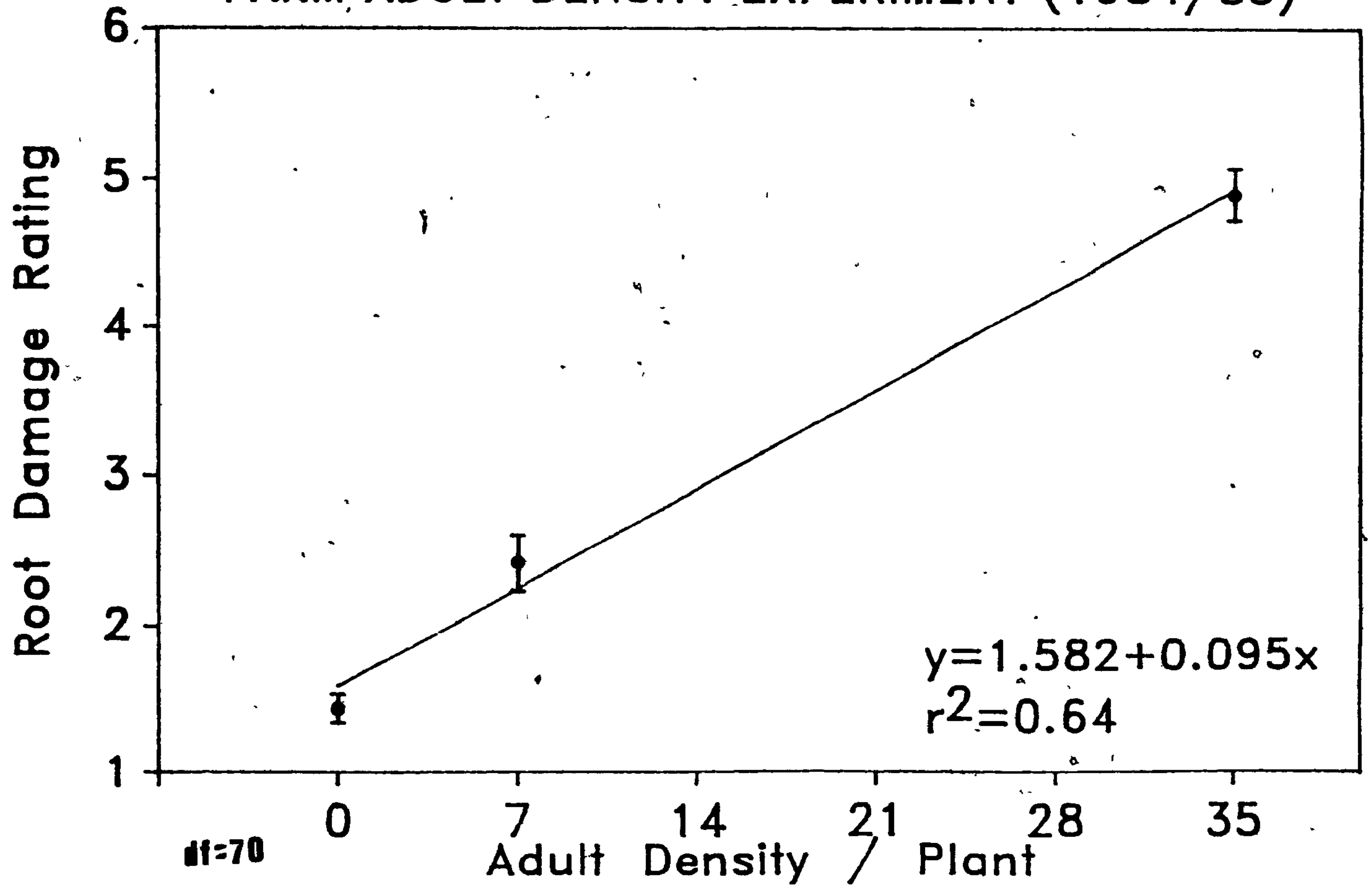


TABLE 10

MEANS OF PLANT HEIGHT, STEM CIRCUMFERENCE, YIELD AND ROOT DAMAGE RATINGS OF SEED FARM ADULT DENSITY EXPERIMENT (1986)

Treatment (adult/ plant)	Plant height (cm)	Stem circum. (cm)	Yield (g)	Root damage rating
0	160 a	7.6 a	126 a	1.3 a
4	159 a	7.3 a	125 a	1.4 a
7	149 a	7.2 a	117 ab	1.6 a
14	151 a	6.9 a	115 ab	2.1 b
21	154 a	7.0 a	109 b	2.7 c
35	153 a	7.0 a	107 b	3.5 d

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

results indicate that root damage rating was the most sensitive measurement for effects of level of beetle infestation : as few as 14 adults/plant had a highly significant effect on root damage. Seven adults/plant failed to produce any significant difference from the check. Significant reduction in yield from the check and four adults/plant was obtained at 21 to 35 adults/plant. Neither plant height nor stem circumference showed significant differences at any of the levels of infestation used.

The relationships between adult densities and the dependent variables (yield and root damage ratings) and within the dependent variables themselves, are illustrated in Fig. 16. On the basis of the regression line, 4, 7, 14, 21 and 35 adults/plant caused 1.1, 7.0, 9.2, 13.7 and 15.5 per cent reduction in yield, respectively.

Economic injury levels based on the price of corn from 1980 to 1985 (ca. \$153/t; Anonymous 1986) and 1986-87 (ca. \$115/t; Fulton 1986; Irvine 1986) and the present control cost (\$39 to \$50/ha; G. Letendre, Pers. Comm. 1987; P. Martel, Pers. Comm. 1987), are given in Table 11. Economic injury levels (Table 11) were calculated according to Ogunlana and Pedigo (1974) as described in section III.A.3.i. Fig. 16 shows that the EIL's for NCR adults was greatly affected by the control cost / corn price ratio.

In the 1985-86 experiment, EIL varies from 7.9 to 10 and 10.7 to

Figure 15. Data from Macdonald seed farm adult density experiment (1986; df=142).

a. Regression for corn yield per plant vs. rate of artificial infestation of NCR adults per plant.

b. Regression for root damage rating vs. rate of artificial infestation of NCR adult per plant.

c. Regression for corn yield per plant vs. root damage rating

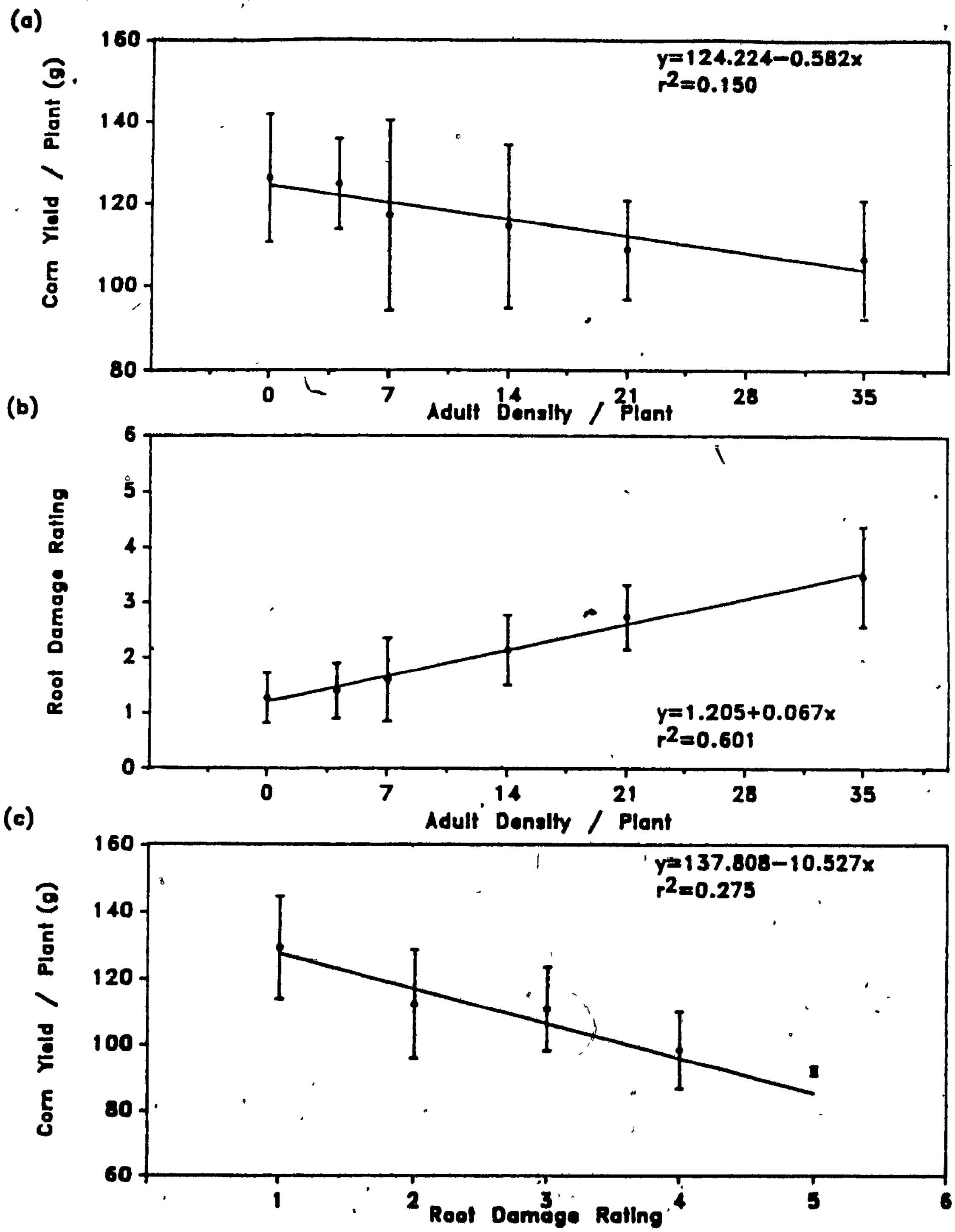
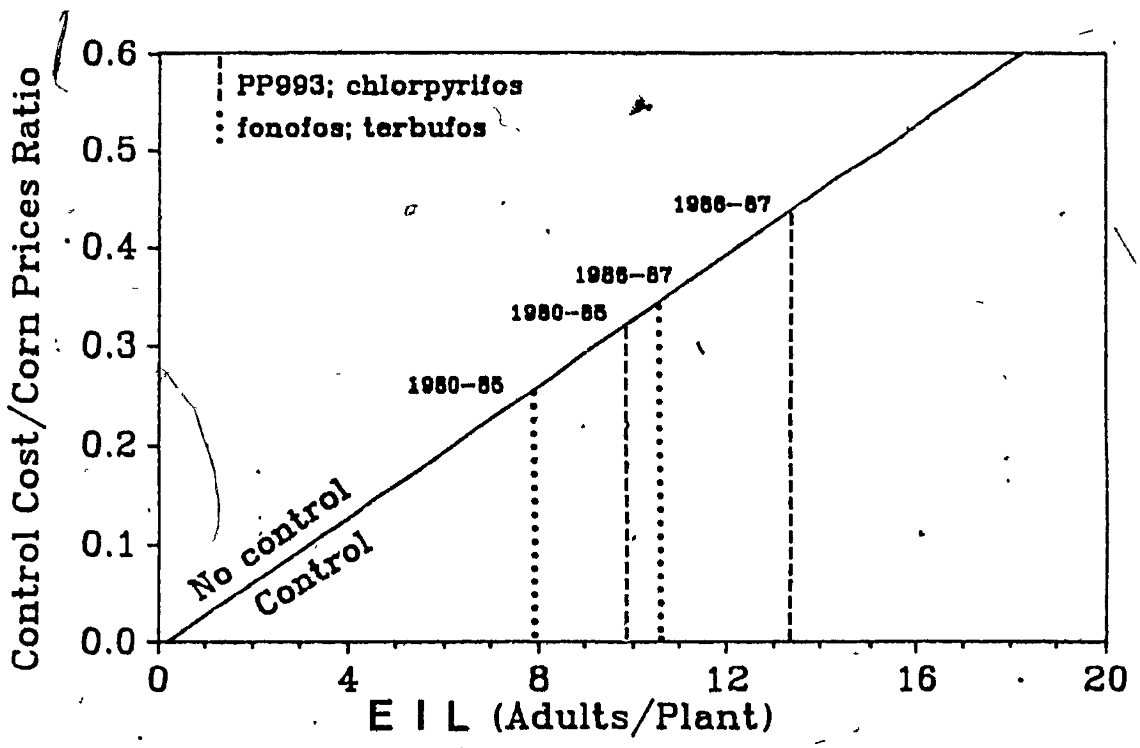

(a)
y=124.224−0.582x
r2=0.150
Corn Yield / Plant (g)
Adult Density / Plant
(b)
y=1.205+0.067x
r2=0.601
Root Damage Rating
Adult Density / Plant
(c)
y=137.808−10.527x
r2=0.275
Corn Yield / Plant (g)
Root Damage Rating

TABLE 11

COST OF CHEMICAL CONTROL, ECONOMIC DAMAGE AND ECONOMIC INJURY LEVELS (EIL) OF SEED FARM ADULT DENSITIES EXPERIMENT (1985-86)

Insecticide	Cost of chemical control ($/ha)	Economic damage (kg/ha;grain loss)		EIL (adults/plant)	
		1980-85	1986-87	1980-85	1986-87
PP993 (1G)	50.00	327	435	10.0	13.3
chlorpyrifos (Lorsban 15G)	49.00	320	426	9.8	13.1
fonofos (Dyfonate 20G)	39.70	259	345	8.0	10.7
terbufos (Counter 20G)	39.38	257	342	7.9	10.7

FIGURE 16. EFECTS OF CONTROL COST/CORN PRICES RATIO ON THE EIL OF NCR ADULTS



13.3 respectively, based on the 1980-85 and 1986-87 prices (Table 11). The high EIL may also have been due to adverse weather conditions prevailing during the experiment resulting in lower damage per adult than would normally occur. An EIL of five adults/plant was established in Indiana, Georgia, Illinois and several other localities (Anonymous 1982). Whereas an EIL of 1-1.5 adults/plant was reported by Apple *et al.* (1971); Pruss *et al.* (1974); Shaw *et al.* (1974); Luckmann (1978) and Stamm *et al.* (1985). The reasons for the discrepancy are not fully understood.

III. B. FIELD ASSOCIATIONS

1. INTRODUCTION

Quantitative changes in the various stages of NCR population, economic injury level, economic threshold and factors affecting development of EIL were studied in cornfields at St. Antoine Abbe', Ormstown, Pike River and St. Jean from the fall of 1984 to the summer of 1986. The sampling methods utilized in these studies were developed by Matin (1983). The approximate area of the study fields in all locations was 3 ha. All the fields have been continuously cultivated with corn since the early 1970s. Only one of them has been treated with insecticide since then, that being Pike River where carbofuran was applied once in 1977. The St. Antoine Abbe' field was rotated to wheat in 1985 so that the experiments intended for this field were continued in Ormstown, a nearby field with a similar NCR population.

2. MATERIALS AND METHODS

i. EGG POPULATION ESTIMATES

Fall Population. This study was began on 1 October, 1984, in a St. Antoine Abbe' cornfield, after harvesting but before plowing, to estimate the total number of eggs deposited during the fall. The field was divided into 24 strata, and two randomly-selected quadrat soil samples of 20 x 20 cm and 10 cm deep were dug out from each stratum (Matin 1983). The samples were brought to the laboratory in plastic bags and stored at 5°C pending extraction. To facilitate egg extraction from the soil samples, made up mainly of clay loam soils, a dispersing solution comprising 180 g sodium hexametaphosphate and 20 g sodium bicarbonate dissolved in 4 L of water was used. After soaking the samples overnight, eggs were extracted using a modified Ladell apparatus as described by Matin and Yule (1986), where soil is agitated in a saturated solution of Mg_2SO_4 and eggs were decanted through number 10 and 40 sieves and retained in a number 50 sieve. Recovered eggs were transferred to a petri dish using a plastic wash bottle with a saturated Mg_2SO_4 solution. Eggs were identified following the desqription of Atyeo *et. al*. (1969) and counted using a pipette under a dissecting microscope (Matin 1983).

Spring Population. This experiment was conducted in the St. Antoine Abbe' cornfield on 8 April, 1984 and in the Ormstown, Pike River and St. Jean cornfields in early April, 1985. Forty eight randomly-selected soil samples of 20 x 20 cm and 20 cm deep were taken from each field. The procedures used for egg sampling, storage and extraction were the same as described for the fall egg population experiment.

Fall and spring egg populations were estimated, and percentage reduction in fall population due to winter mortality was calculated. Overwintered egg population was related to the previous season's adult population and subsequent larval population. Mean crowding (x^*) (Lloyd 1967) and k value of the negative binomial distribution (Elliott 1977) were calculated. The data were analysed using the ANOVA and GLM procedures of the SAS Institute (1979) and Duncan's multiple range test was used to determine significance of differences between the mean populations of different fields.

ii. LARVAL POPULATION ESTIMATES, ECONOMIC INJURY LEVEL, AND ECONOMIC THRESHOLD

A study was conducted during the summers of 1984 and 1985 to estimate NCR larval population and to develop EIL and ET in several cornfields in Southwest Quebec. These were the same cornfields where egg population studies were made. Since larval and pupal stages of NCR in southwest Québec cornfields overlap greatly in time (Dominique 1983), thus making it very difficult to estimate their populations separately, they were considered together as a major immature stage. The larval stage peaks around mid-July in southwest Quebec (Dominique 1983; Matin 1983). Accordingly, samples were collected on 20 and 21 July, 1984 in St. Antoine Abbe', and in 1985 at Ormstown, Pike River and St. Jean.

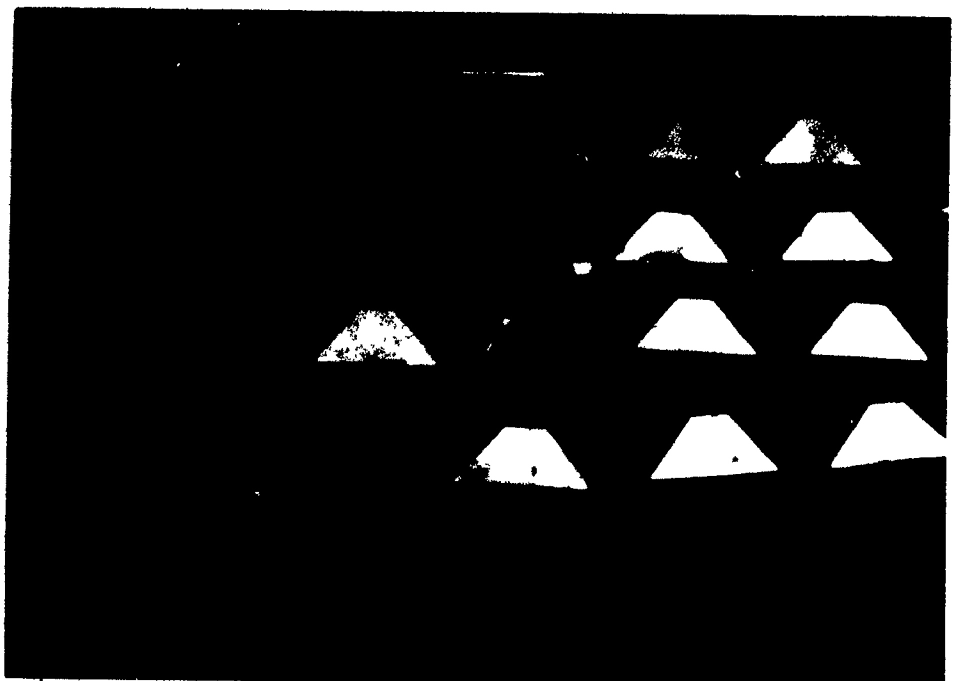
Forty-eight plants were selected at random from the St. Antoine Abbe' cornfield in 1984, while 80 plants were taken from Ormstown, Pike River and St. Jean cornfields in 1985. The selected plants were cut down at ~~ground~~ level and soil samples of 20 x 20 cm with the corn plant at their centers were dug out to a depth of 10 cm (Matin 1983). Samples were brought to the laboratory in plastic bags (60 x 40 cm) and stored at

5^{0}C pending examination. Samples (soil and roots) were hand- sorted and examined visually for second and third instar larvae, pre-pupae and pupae. Soil particles were crumbled gently for possible pupal cells and roots were evaluated for larval damage by the root rating index of Hills and Peters (1971). After carrying out damage rating, the roots were cut off at the base of the nodes and peeled to inspect for possible boring larvae. Larvae found inside the roots were added to the previous count. The roots were then collected in a wire mesh basket and held with a cloth at the top of a plastic container half-filled with water. The roots were exposed under a behavioral heat extractor for four days (Hill 1969; Kempson *et al.* (1963) (Fig. 5). Larvae falling from the sample due to the heat gradient were collected and counted and their number added to those previously found by visual examination.

On 19 and 20 October, 1985, another 80 plants were selected at random from the same fields, harvested, and their root systems were dug out for root damage rating. Corn ears were labelled separately and dried at 65^{0}C until constant weights were obtained. They were then shelled and the kernel weight recorded. Grain yield and larval density per plant were regressed against root damage rating, and an EIL and ET were calculated by using the formula of Ogunlana and Pedigo (1974) and Michaud 1987; G. Boivin, Pers. comm. (1987) respectively.

Larval populations were estimated for all fields under study and their numbers were related to the previous spring egg population and sub

Figure 17. Behavioral extractor for extracting larvae from plant roots.



sequent adult population. Mean larval density ($\bar{x}$), mean crowding (x^*) (Lloyd 1967), variance, standard error and k values of the negative binomial distribution (Elliott 1977) were calculated. Data were analysed using the ANOVA and GLM procedures of SAS (SAS Institute 1979). Duncan's multiple range test was used to determine significance of differences between the mean populations of different fields.

iii. ADULT POPULATION ESTIMATES

A study was conducted during the summers of 1984-1986 to estimate NCR adult populations in several fields of grain corn in southwest Quebec. These were the same fields where egg and larval population studies were carried out. For the purpose of this study, the sampling universe (*ca*. 3ha) was divided into four equal parts. Twenty-one, 15 and 20 plant samples from each section were selected at random from the following locations respectively: St. Antoine Abbe' and Pike River (1984); Ormstown, Pike River and St. Jean (1985); St. Antoine Abbe', Ormstown and Pike River (1986). The sampling system was used as recommended by Matin and Yule (1984b), in mid-August, when 50 per cent of the silks had dried.

Each plant sample was examined thoroughly from base to tip following the technique developed by Matin (1983). This involved examination of:

(i) the soil surface around the base of the plant

(ii) stem leaves and leaf axils

(iii) silks and eartips

(iv) tassels.

Beetle counts at all locations were started at about 05:10 h and completed by about 06:20 h while the beetles were least active. Sunrise during this period took place at approximately 05:55 h.

The mean, standard error, variance and k value of the negative binomial distribution were estimated. Adult population estimates were related to the previous larval count and the following spring egg population. The effect of crop rotation at Ste Antoine Abbe' in 1985 on the NCR population was evaluated in relation to the populations of other fields. The trends in NCR population change, that occurred during the study period were compared with previous population estimates made by Matin (1983) at Pike River from 1979 to 1982. These trends were presented in graph form. Factors affecting population changes, EIL and ET were presented in a descriptive model. The data were analysed using the ANOVA and GLM procedures of tbe SAS Institute (1979), and Duncan's multiple range test was used to determine significance of differences between the mean populations of different fields.

3. RESULTS AND DISCUSSION

i. EGG POPULATION ESTIMATES

NCR egg population estimates for the fall and spring of 1984 and 1985 are given in Table 12. The data show that egg population reduction due to overwintering mortality was highly significant (78 per cent). However, the spring egg population at St. Atoine Abbe' in 1985 was significantly increased compared to spring 1984, by 58 per cent. In 1985, there was a significant difference in the spring egg population between the St. Antoine Abbe' and St. Jean cornfields, but neither the Pike River nor Ormstown spring egg populations showed any significant difference from those at St. Antoine Abbe' and St. Jean.

The mean crowding (x^*) of egg population in the fields under study was calculated (Table 13) using Lloyd's (1967) method of solving the following formula:

$$x^* = \frac{\bar{x} + (s^2 - 1)}{\bar{x}}$$

where s^2 is the sample variance. The ratio of mean crowding to mean density ($x^*/\bar{x}$), which was measured with Morisita's (1967) index, indicates the degree of departure from randomness. This ratio equals unity in random (Poisson) distribution, is smaller than unity in regular (uniform) distribution and greater than unity in contagious (aggregated) distribution. The ratio of mean crowding to the mean densities in all fields

TABLE 12

INTRA- AND INTER- GENERATION POPULATION CHANGES OF NCR AT ST. ANTOINE ABBE'(SAA), PIKE RIVER, ORMSTOWN AND ST. JEAN BETWEEN 1984 AND 1986

Location	Eggs/ plant	Reduction from fall to spring egg pop.(%)	Larvae/ plant	Reduction from eggs to larvae (%)	Adult/ plant	Reduction from larvae to adults (%)	% decrease in adult pop. from previous season
(1984)							
SAA	285 c (Fall)						
	26 a		13.7 a	47.3	7.0 a	49.0	
Pike River					7.7 a		
(1985)							
SAA	62 b	78			--*		
Ormstown	43 ab		13.1 a	70.0	6.9 a	47.3	1.4
Pike River	44 ab		13.8 a	68.6	7.8 a	43.5	
St. Jean	28 a		8.9 b	68.2	4.8 b	46.1	
(1986)							
SAA					0.9 d		88.0
Ormstown					2.5 c		63.0
Pike River					2.0 c		74.0

Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$; Duncan's multiple range test).

*Rotated to wheat.

TABLE 13

MEAN, STANDARD ERROR OF THE MEAN, VARIANCE, MEAN CROWDING AND MORISITA'S INDEX FOR SPRING EGG POPULATION IN SOUTHWEST QUEBEC

Location	No. of samples	Mean±S.E. (egg/ plant)	Variance (S^2)	Mean crowding(x^*)	k of NBD	$x^*/x = I^{\bullet}$
(1984)						
SAA[1] (Fall)	24	a 290±34	27693	384	3.07	1.33
(1985)						
SAA[1]	48	b 62±10.6	5401	148	0.71	0.40
Ormstown	48	bc 44±7.3	2548	101	0.72	2.28
Pike River	48	bc 43±7.6	2064	109	0.92	2.51
St. Jean	48	c 28±4.8	1123	67	0.72	2.39

Means followed by the same letter in the same column are not significantly different (p > 0.05; Duncan's multiple range test).

• Morisita's Index.
1 St. Antoine Abbe'

varied from 1.33 to 2.51 and indicated that the distribution of NCR eggs was contagious (aggregated). Southwood (1978) noted that Morisita's index has a great advantage over other methods of distribution determination because it fits for any number of samples. However, the k of negative binomial distribution (NBD) was widely used and suggested by several ecologists (Bliss and Owen 1958; Harcourt 1965; Southwood 1978) as an adequate measure of distribution for most contagious insect populations. According to Southwood (1978) the smaller the value of k, the greater the extent of aggregation, whereas a larger value of k (eg. 8 or more) indicates that the distribution is approaching the Poisson (random) series. During this study, the values of k of NBD varied from 0.71 to 3.07 and indicated that the distribution was greatly aggregated. Bliss and Owen (1958) and Harcourt (1965) reported that k of NBD for many contagious insects fell in the range of two. The reason for this could be that oviposition sites in the fields were largely governed by soil type, as observed by Dominique (1983). These results are in general agreement with Matin (1983) who reported that the value of k of NBD for NCR spring egg population at the Pike River cornfield varied from 0.34 to 1.32.

The highly significant reduction (*ca.* 78 per cent) in egg population at St. Antoine Abbe' over the winter of 1984-1985 was similar to that observed by Matin and Yule (1984b) at Pike River. They noted a 63 to 87 per cent reduction in spring egg population from that observed before fall plowing. However, Chiang (1965) in Wisconsin observed a 10 to 40 per cent reduction in NCR egg population over the winter. He noted that the main reason for higher overwintering mortality was due to either direct destruction of the eggs, or to adverse physiological effects caused by low temperatures. Patel and Apple (1967) observed that NCR egg hatchability was reduced to zero at a temperature of -23^{O}C when the eggs were exposed for 1.5 or more months. Even at -2^{O}C, there was a gradual reduction in hatching as the duration of the chill period increased. Dominique (1983) confirmed the findings of Patel and Apple (1967) by observing that NCR eggs lost their viability as the temperature dropped from 5^{O}C and the duration of the chill period extended over 120 days.

ii. LARVAL POPULATION ESTIMATES, ECONOMIC INJURY LEVEL, AND ECONOMIC THRESHOLD

Population Estimates. The data in Table 14 shows that the average larval plus pupal population varied from 8.9 to 13.8 per plant at Pike River, St. Antoine Abbe', Ormstown and St. Jean cornfields during the 1984-85 season. Duncan's multiple range test (Table 16) indicates that there were no significant differences of population means at any of the locations, except at St. Jean.

Reduction of the larval and pupal populations from the spring egg population ranged from 47.3 to 69.5 per cent, whereas both Matin and Yule (1984b) in Quebec and Patel and Apple (1967) in Wisconsin reported 81 to

TABLE 14

MEAN, STANDARD ERROR OF THE MEAN, VARIANCE, MEAN CROWDING, K OF NEGATIVE BINOMIAL DISTRIBUTION AND MORISITA'S INDEX FOR NCR LARVAL AND PUPAL POPULATIONS IN SOUTHWEST QUEBEC

Location	No. of samples	Mean ±S.E. (larvae/plant)	Variance (S^2)	Mean crowding (x^*)	k of NBD	$x^*/\bar{x} = I^*$
(1984) SAA[1]	48	a 13.7±1.8	156.5	24.1	1.3	1.76
(1985) Ormstown	80	a 13.1±1.2	106.8	20.2	1.84	1.54
Pike River	80	a 13.8±1.1	102.6	20.2	2.12	1.47
St. Jean	80	b 8.9±1.0	79.8	16.9	1.11	1.90

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

* Morisita's Index

1 St. Antoine Abbe'

97 and 81 per cent reduction. This difference in mortality rates could be attributed mainly to the effect of prolonged low winter and spring temperatures on the hatchability of NCR eggs at the time of testing, as explained above by Chiang (1965), Patel and Apple (1967) and Dominique and Yule (1983a). However, Matin and Yule (1984) suggested that the high mortality of larval and pupal populations could be attributed to the high mortality of newly hatched larvae before they are able to encounter corn roots (Britton 1937), or else to predation, eg. by ground beetles (Tyler and Ellis 1980).

The larval population at Pike River was almost doubled (13.8) in the six years from 1979, when Matin and Yule (1984b) observed 6.7 larvae/plant. However, this population increase has not continued further due perhaps to below-average temperatures in June and July 1986 (Appendix 2) severely affecting the NCR population in southwest Quebec.

Economic Injury levels and Economic Thresholds. Data obtained from Ormstown and Pike River cornfields relating root damage rating with larval density and corn yield, are illustrated respectively in Figs. 18 and 19. EIL (Tables 15 and 16) was calculated by solving the regression equations given in Figs. 18 and 19 using the formula of Ogunlana and Pedigo (1974), as described, in page 153. ET for NCR larvae (Tables 15 and 16) were calculated by solving the following formula (Michaud 1987; G. Boivin, Pers. comm. 1987) as follows:

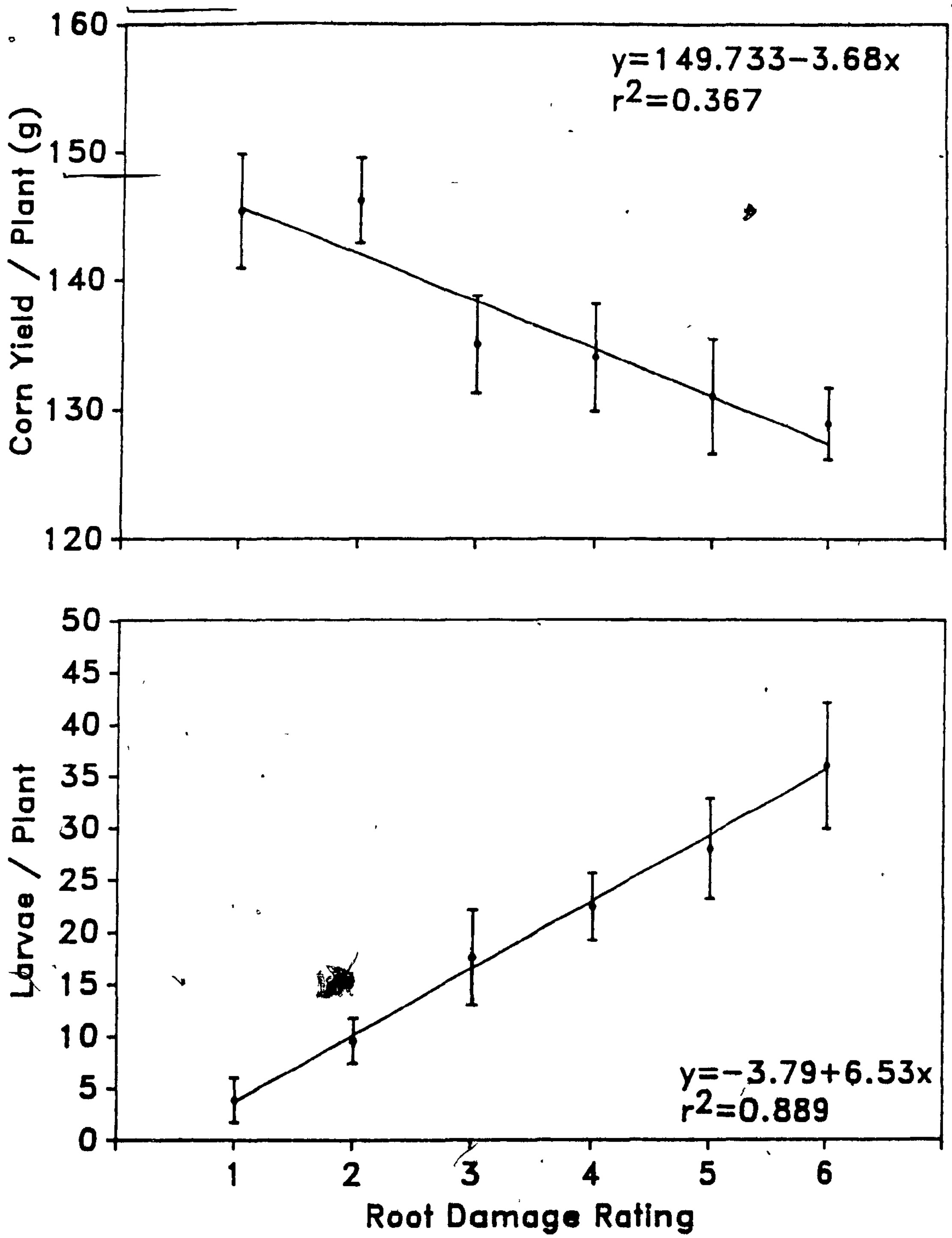
ET = EIL x Efficiency of chemical control

The efficiency of insecticides in controlling NCR larvae (Tables 15 and 16) was obtained from insecticide trials at Ormstown and Pike River

Figure 18, Data from Ormstown cornfield ; df = 78.

a. Regression for corn yield per plant Vs. root damage rating.

b. Regression for number of larvae per plant Vs. root damage rating.

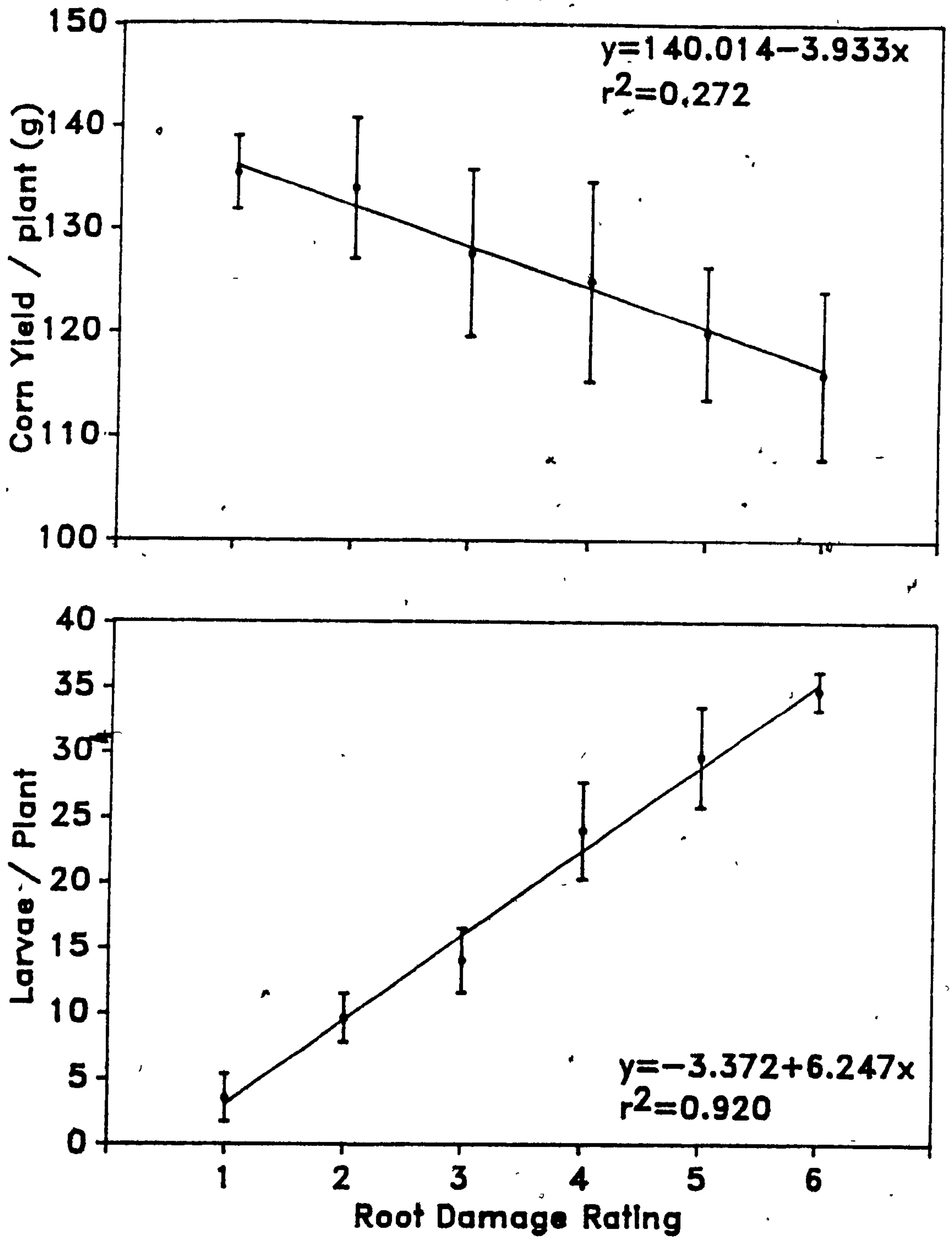


y=149.733−3.68x
r2=0.367
Corn Yield / Plant (g)
160
150
140
130
120
y=−3.79+6.53x
r2=0.889
Larvae / Plant
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
Root Damage Rating

Figure 19. Data from Pike River cornfield ; df = 78.

a. Regression for corn yield per plant Vs. root damage rating.

b. Regression for number of larvae per plant Vs. root damage rating.



y=140.014-3.933x
r2=0.272
Corn Yield / plant (g)
150
140
130
120
110
100
y=-3.372+6.247x
r2=0.920
Larvae / Plant
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
Root Damage Rating

TABLE 15

COST OF CHEMICAL CONTROL, EFFICIENCY OF INSECTICIDE, ECONOMIC DAMAGE, ECONOMIC INJURY LEVEL (EIL) AND ECONOMIC THRESHOLD (ET) OF ORMSTOWN CORNFIELD NCR LARVAL POPULATION EXPERIMENT (1985)

Insecticide	Cost of chemical control ($/ha)	Insecticide efficiency (%)	Economic damage (kg/ha;grain loss)		E I L				E T (Larvae/plant)	
			1980-85	1986/87	1980-85		1986/87		1980-85	1986/87
					Larvae /plant	RDR*	Larvae /plant	RDR*		
PP993 (1G)	50.0	76	327	435	13.1	2.6	16.5	3.1	10.0	12.5
fonofos (Dyfonate[r] 20G)	39.7	70	259	345	10.8	2.2	13.7	2.9	7.7	9.7
chlorpyrifos (Lorsban[r] 15G)	49.0	55	320	426	12.9	2.6	16.0	3.1	7.1	8.8

*Root damage rating.

TABLE 16

COST OF CHEMICAL CONTROL, EFFICIENCY OF INSECTICIDE, ECONOMIC DAMAGE, ECONOMIC INJURY LEVEL (EIL) AND ECONOMIC THRESHOLD (ET) OF PIKE RIVER CORNFIELD NCR LARVAL POPULATION EXPERIMENT (1985)

Insecticide	Cost of chemical control ($/ha)	Insecticide efficiency (%)	Economic damage (kg/ha;grain loss)		E I L				E T (Larvae/plant)	
			1980-85	1986/87	1980-85 Larvae /plant	RDR*	1986/87 Larvae /plant	RDR*	1980-85	1986/87
PP993 (1G)	50.0	76	327	435	12.0	2.5	15.1	2.9	9.1	11.4
fonofos (Dyfonate[r] 20G)	39.7	70	259	345	9.7	2.1	12.6	2.5	7.1	8.8
chlorpyrifos (Lorsban[r] 15G)	49.0	55	320	426	11.8	2.4	14.7	2.9	6.5	8.2

*Root damage rating.

cornfields (page 156).

The data in Tables 15 and 16 show that the EIL for the larval stage was greatly affected by the cost of chemical control/corn price ratio. Based on this ratio, EIL at Ormstown and Pike River cornfields vary respectively from either 10.8 to 13.2 and 9.7 to 12 or 13.7 to 16.5 and 12.6 to 15.1 NCR larvae / plant for the 1980-85 and the 1986-87 periods, respectively. Also in Tables 15 and 16, the ET levels were greatly affected by the efficiency of the insecticide in controlling NCR larvae. Based on these factors, the ET for NCR larvae at Ormstown and Pike River (Tables 15 and 16), respectively varies from either 7.1 to 10.0 and 6.5 to 9.1 or 8.8 to 12.5 and 8.2 to 11.4 NCR larvae / plant for the 1980-85 and the 1986-87 periods, respectively. In the literature, an ET of 10 NCR larvae/plant has been accepted by most researchers in Iowa (Peters 1963). However, since this level was established in 1963, when corn prices as well as control costs probably differed greatly from present prices, no valid comparison can be made.

Based on the observed EIL (Tables 15 and 16), calculated on the bases of 1986/87 corn prices ($ 115/t; Fultan 1986; Irvine 1986) one would suggest that NCR population (Table 12) observed during 1986 season at St. Antoine Abbe', Ormstown and Pike River, were far below the real EIL and therefore one would recommend that no control of any type should be applied until the population approached that EIL. It should also be noted that corn prices are expected to decline further than the 1986/87 prices, to ca. $ 90/t by the end of 1987 (Fultan 1986; Irvine 1986).

iii. ADULT POPULATION ESTIMATES

The data in Table 17 show that the adult population at Pike River and Ormstown remained unchanged from 1984 to 1985. There was no significant difference between adult population means except for the St. Jean cornfield. In 1986, adult populations were reduced by 63 and 74 per cent from the 1985 peak adult populations at Ormstown and Pike River, respectively. Reductions between peak larval population and peak adult population varied from 43 to 49 per cent during the course of this study (Table 14 and 17).

The k of NBD and Morisita's (1967) index (Table 17) varied from 12 to 62 and 1.02 to 1.08, respectively. This indicates that the distribution of the adult population was random during the sampling period. Variation in the degree of randomness between fields could be attributed to the low population in 1986, which to some extent was determined by the emergence sites of adults as well as any differences in sowing dates. However, these results were generally in agreement with Matin and Yule (1984a) who observed K of NBD of 67.22 when more than 50 per cent of corn silks had dried up.

The adult population (Table 17) at Pike River was increased in 1984 and 1985 by 38 per cent since Matin and Yule (1984b) observed a steady average of 5.5 adults/plant during the 1979-82 period at the same field. On the other hand, in 1986, the peak adult population in all

TABLE 17

MEAN, STANDARD ERROR OF THE MEAN, VARIANCE, MEAN CROWDING, K OF THE NEGATIVE BINOMIAL DISTRIBUTION, AND MORISITA'S INDEX, FOR ADULT POPULATION ESTIMATES IN SOUTHWEST QUEBEC

Location	No. of samples		Mean±S.E. (adults/plant)	Variance (s^2)	Mean crowding (x^*)	k of NBD	$x^*/x = I^*$
(1984)							
SAA[1]	84	a	7.0±0.31	7.92	7.13	53.3	1.02
Pike River	84	a	7.7±0.35	10.26	8.03	23.2	1.04
(1985)							
Ormstown	60	a	6.9±0.36	7.69	7.0	62.6	1.02
Pike River	60	a	7.8±0.40	9.45	8.01	36.9	1.03
St. Jean	60	b	4.8±0.32	6.29	5.11	15.4	1.07
(1986)							
SAA[1]	80	d	0.85±0.11	0.91	0.92	12	1.08
Ormstown	80	c	2.50±0.18	2.61	2.54	51.6	1.02
Pike River	80	c	1.98±0.17	2.22	2.10	17.8	1.06

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

* Morisita's index
[1] St. Antoine Abbe'

fields was reduced drastically by 74.4 per cent from the 1985 adult population. This steep decline in adult population could be attributed mainly to the below-normal temperatures prevailing during June and July 1986. Dominique and Yule (1983b) mentioned that, based on air temperature, 421 to 431 degree days (DD) above the threshold level (9.7°C) are required for the first eclosion of NCR eggs in southwest Quebec. They noted that, under normal weather conditions, the thermal requirements for hatching were usually met by the first week of June. In 1986, the thermal requirements for the eclosion of eggs were met only on 5 July 1986 (Appendix 2). From the weather data collected at Ste. Clotilde (an agricultural research station situated between the study fields) one might expect that either the prolonged chill period affected the hatchability of the eggs (Chiang 1965; Patel and Apple 1967; Dominique and Yule 1983b), or by the time larvae started to hatch (5 July 1986), the corn plants were old enough to resist their attack or to provide adequate nutrition for them.

Adult population trends during the study period are combined with those observed earlier by Matin and Yule (1984b) at Pike River in Fig. 20.

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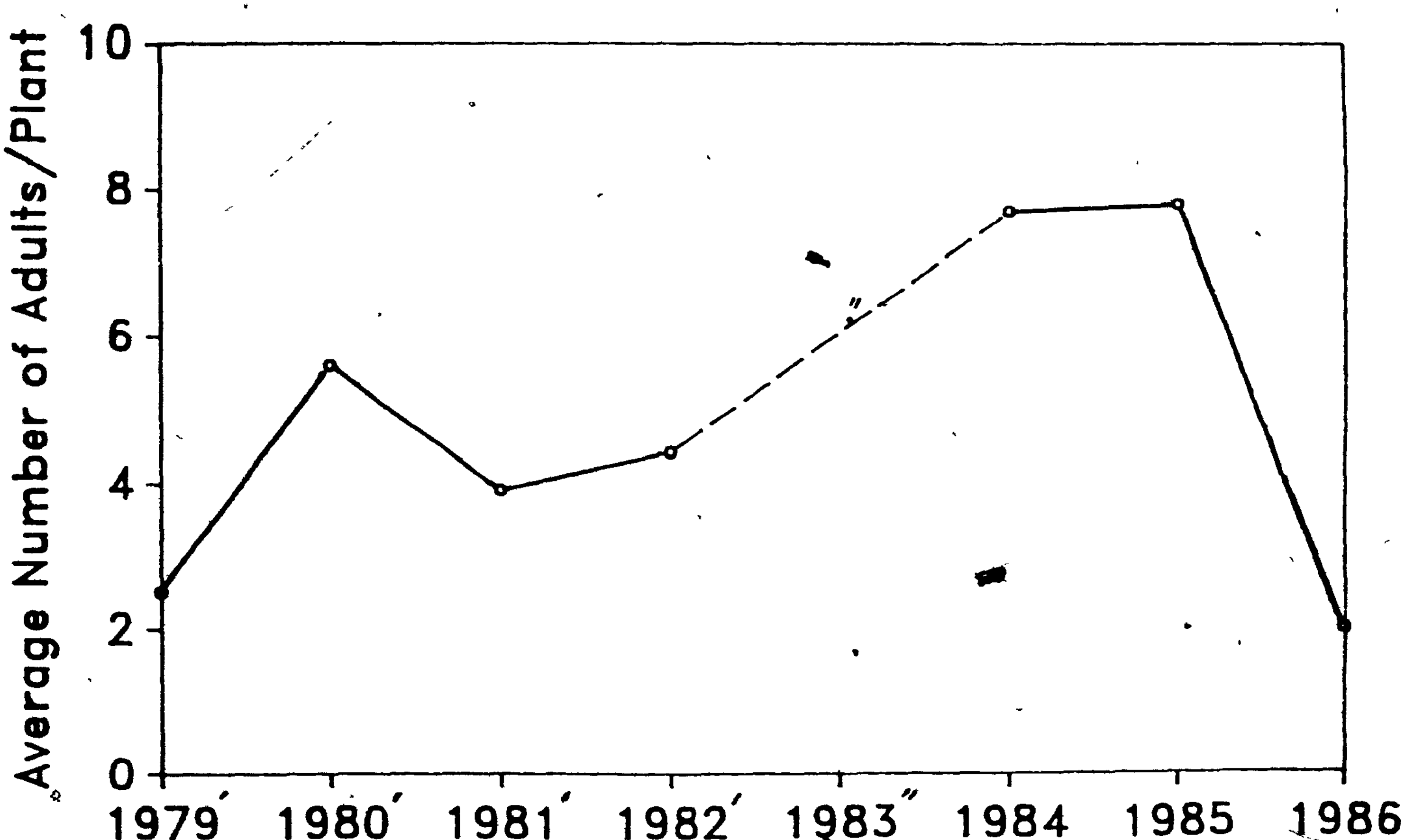
FIGURE 20. NORTHERN CORN ROOTWORM ADULT POPULATION TRENDS AT PIKE RIVER DURING 1979–1986



'After Matin and Yule (1984b)
"No observation

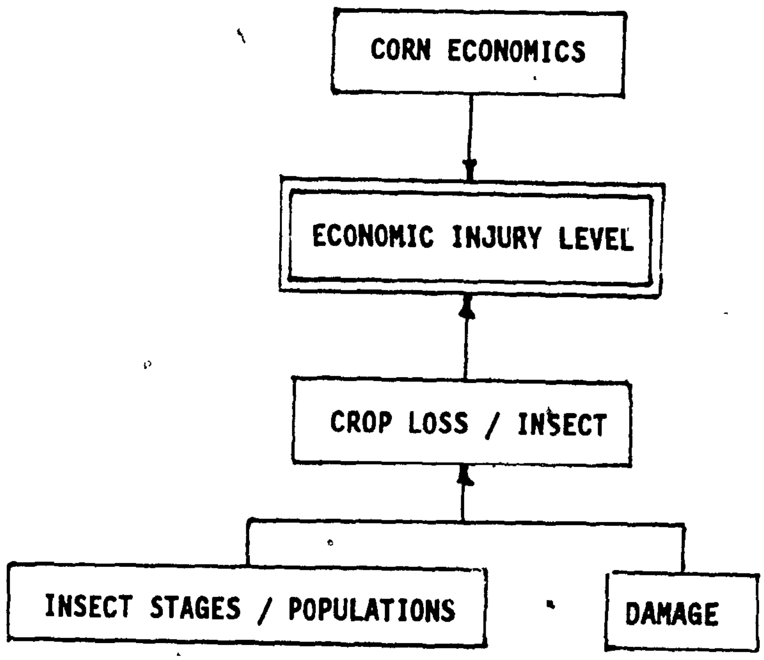
iv. MODEL FOR FACTORS AFFECTING ECONOMIC INJURY LEVEL

An appropriate analysis of all factors affecting NCR population, crop yield, ecosystem and marketing standards leads to the establishing of practical EIL and ET, considered to be basic in any pest management program. Two main components affect the EIL and ET parameters: (a) corn economics (corn prices and management cost), and (b) crop loss per insect. Although these components are expressed through a simple formula (Section III.A.3.ib; page 69), they depend on a number of complex interacting factors (Fig. 21).

a). Corn Economics

Corn Prices. The market value of corn is one of the major components of EIL and ET. For this reason, market forces should be analysed to estimate expected returns from corn so that marginal revenue exceeds marginal cost (break-even analysis). During the six years between 1980-85, Canadian corn prices averaged $153/t (Anonymous 1986). However, during the 1986/87 period, corn prices declined to an average of $115/t and the 1987 prices are expected to drop even further to an average of $90/t (Fulton 1986; Irvine 1986). The main reasons for this decline in corn prices are: economic policies (exports, imports and loans) and world competition, especially from the U.S., the E.E.C. and Argentina (Fulton 1986; Irvine 1986). Tables 16 and 17 shows the effects of corn prices on the EIL and ET. An updated analysis of corn prices should be made before any control decision is undertaken.

Figure 21. Model for factors affecting economic injury level.


CORN ECONOMICS
ECONOMIC INJURY LEVEL
CROP LOSS / INSECT
INSECT STAGES / POPULATIONS
DAMAGE

Management Cost. Because chemical control of NCR is undertaken as a prophylactic measure during planting time, with the same equipment as that used for seeding, the cost of control varies mainly according to the type of insecticide employed. Tables 16 and 17 outlines the effect of control cost on the EIL and ET. Another factor affecting ET is the efficiency of the insecticide (Tables 16 and 17). Therefore, in pest control decision-making, consideration must be given not only to the cost of insecticide but also to the proper analysis (normative approach; Mumford and Norton 1984) of pesticide resistance, pest resurgence, effect on non-target organisms and the adaptation of micro-organisms for the rapid breakdown of insecticides, necessitating the rotation of these insecticides.

b). Crop Loss Per Insect

The density-damage relationship is the most complex factor in the determination of the EIL and ET. This relationship depends on interactions among a number of variables. Cold winter temperature is considered the key factor in the reduction of overwintering egg populations. Table 12 and previous observations by Matin (1983) indicate that winter temperatures in Quebec reduce egg populations by 78 and 63-87 per cent respectively. Moreover, Chiang *et al.* (1972) and Dominique (1983) report that overwintering eggs lost their viability as temperatures decreased and duration of chill period increased. Degree days (DD) required for egg development are adversely affected by low spring temperature. It was observed in 1986 (Appendix 1, 2) that the DD requirement for egg development, was fulfilled one month late, early July rather than early June (Dominique 1983). On the other hand, low spring temperature and excessive rain can delay the corn sowing date. Pendleton (1979) reported that, in temperate corn-growing areas, early planting is a key cultural practice. It provides higher yields, shorter plants, longer days during the grain-filling period and a greater economic return from a given increment of nitrogen fertilizer than would occur with corn planted later. Moreover, larval feeding has greater effect on more succulent roots, the result of late planting, as opposed to well-established roots from earlier planting. Another adverse effect of late planting is poor pollination due to adult feeding on fresher silks (Fig. 22), resulting in partially barren ears (Fig. 23). Varietal resistance and population intensity of insects and plants should also be considered in any evaluation of insect density-damage relationship.

Severe infestation of NCR causes corn plants to lodge in strong winds and storms (Palmer 1968). However, heavy rains, plowing and soil structure are other factors that affect plant lodging. Another factor that may result in lodging is a deficiency of potassium (Mohr and Dickinson 1979). For these reasons, lodging should not always be attributed solely to larval feeding without these other factors being analysed as possible contributors. Whatever the reasons, plant lodging itself contributes to delayed growth, thus causing the plants to be out of cycle and resulting in incomplete pollination (Palmer 1968).

Figure 22. Northern corn rootworm adult feeding on silks.

Figure 23. Partially barren ears, resulted from incomplete pollination, due to adult feeding on silks.

IV. CHEMICAL CONTROL

1. INTRODUCTION

Despite the problems of resistance, effects on non target organisms and environmental pollution, pesticide use remains the main management strategy for pest control on corn in North America (Chiang 1978). Chemical insecticides are normally applied to corn in granular or liquid formulations. Granular insecticides are generally applied as a narrow band (15-18 cm) on the row at planting time with light incorporation into the soil. Liquid formulations can be applied at cultivation time, near the base of the corn plant and covered lightly with soil.

In this particular study, susceptibility of NCR larvae to several insecticides was assessed by direct contact, and in-soil bioassay. The efficacy of PP993 (a new soil pyrethroid insecticide), fonofos, and chlorpyrifos, were further tested in corn fields at different application times, placements and dosage (for pyrethroid only). Liquid formulations of fonofos MS (micro-encapsulated), and disulfoton LC were tested for their efficacy against NCR larvae at cultivation time. Residues of PP993, fonofos, and chlorpyrifos, applied as granules at planting time, were determined throughout the growing season.

2. MATERIALS AND METHODS

i. INSECTICIDE BIOASSAY

Direct contact toxicity. Susceptibilities of first-instar NCR larvae to eight soil insecticides were assessed using a Potter spray tower and the procedure described by Harris and Mazurek (1961). Insecticides used were technical grade with a minimum of 92 per cent purity. The solvent used was a mixture of olive oil and acetone in a ratio of 1:19. Concentrations of 0.0001, 0.001, 0.01 and 0.1 per cent solution (w/v) were prepared for each insecticide. Three replicates of 10 larvae were used for each concentration. Larvae were placed on moist filter paper in 9 cm petri dishes and sprayed with 5 mL of each concentration. Checks were sprayed with solvent only. Roots of sprouting corn were added to each dish to serve as food for the larvae. Dishes were then sealed and placed in a dark incubator held at $23 \pm 2^{o}C$. Mortality counts, using reflex response to a probe, were made at 24 and 48 hours after treatment.

Soil bioassay. Second instar NCR larvae were used as the test stage for this study. The rearing technique was slightly modified from that used by Dominique (1983). Approximately 2500 NCR eggs were incubated in Limbro^{R} multi-well plates filled with distilled, sterilized water and held in a dark incubator at $23 \pm 2^{o}C$ until hatching occurred. Newly-hatched larvae were transferred to rootlets of sprouting corn in 9 cm plastic petri dishes lined with moist filter paper. Fresh rootlets were added as required. The dishes were sealed tightly and placed in a dark incubator held at 23$\pm$2^{o}C. Seven-day-old second instar larvae were used in this assay.

Assays were conducted using sieved (No. 1 mesh) clay-loam soil collected from an Ormstown cornfield. The procedure for the soil bioassay has been described by Harris and Mazurek (1966) and Sutter (1982). Five concentrations (0, 1, 2, 4 and 8 ppm) of six insecticides were prepared in soil for each bioassay. The solvent used was a mixture of pentane and acetone in a ratio of 1:1. The insecticides were pipetted on to the surface of 50 g of oven-dried soil held in 400 mL glass jars and tumbled for five minutes. The jars were allowed to ventilate for one hour to evaporate off the solvent mixture. The soil moisture content was adjusted to 10 per cent by weight and ten larvae were added and incorporated into the soil by shaking the jar. Each treatment was repeated a minimum of two times. Mortality counts using a reflex response to a probe were taken at 24, and 48 hours after treatment.

Corrections for natural mortality were calculated using Abbott's formula (Abbott 1925). LD50, fiducial limits and Chi-square values were calculated for each insecticide. Significance of difference between probit lines were determined using the analysis of covariance as reported by Zar (1984). A chi-square test (Finney 1971; Hubert 1984) was used to test the fitness of the probit lines.

ii. FIELD TESTS OF INSECTICIDES AGAINST NCR IN SOUTHWEST QUEBEC CORNFIELDS

a). Insecticide Trials At Planting Time

Field tests were carried out in cornfields at Pike River and Ormstown in the summer of 1985 to evaluate the efficacy of PP993 (2, 3, 5, 6-tetrafluoro-4-methylbenzyl cis-3-[Z,2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-carboxylate) a new soil pyrethroid insecticide, fonofos and chlorpyrifos against NCR larvae. The study fields were mostly clay loams and had a history of high NCR infestation (ca. seven adults/plant in 1984). Carbofuran had been applied at Pike River in 1977, but since that time neither field had been treated with insecticide.

Granular formulations of PP993 (1G) and fonofos (as Dayfonate® 20G) were applied, respectively, at the rate of 11.2 g/10 m row and 5.6 g/10 m row at Pike River. Chlorpyrifos (as Lorsban® 15G), applied at the rate of 7.5 g/10 m was included in the experiment at Ormstown. Insecticides were applied using a hand-held applicator. This device was constructed of a 100 ml plastic bottle with a lower valve fitted to the top of a metal household dust pan designed to spread insecticide granules over an 18 cm-wide band of soil.

Corn hybrids Pioneer® 3994 and 3925 were planted at Pike River and

Ormstown respectively. Each test plot consisted of one row of corn 10 m long collectively arranged in a RCBD. An untreated row planted with corn was included between each plot. Each block, consisting of 12 and 16 treatment combinations, included a check (without insecticide) repeated three and four times respectively at Pike River and Ormstown. Insecticides were applied in the furrow at two depths: at seed level (7 cm) and above seed level (3 cm). A shovel was used to make a 20 cm wide furrow at the designated depths to allow for insecticide application in an 18 cm band. The check plot was treated similarly but no insecticide was applied. The first set of treatments was applied at the usual planting time on 10 and 13 May; the second set at NCR egg hatching time on 2 and 3 June (Dominique 1983), at Pike River and Ormstown respectively.

An assessment was made of the efficacy of various insecticides and methods of application by larval counting from plant root samples, root damage rating, and grain yield. Three corn plants from each subplot were selected at random on 21 and 23 July for larval counts. The plants were cut down at ground level and a soil sample of 20 x 20 cm, with the base of the plant at its centre and 10 cm deep, was dug out. Soil samples were brought to the laboratory in plastic bags and were stored in a cold room at 5^{o}C pending examination. Samples were examined visually for NCR larvae following the method described in page 101, and damage to plant roots was rated using the Hills and Peters (1971) method. Forty plants from each subplot were hand-harvested, dried at 65^{o}C until a constant weight was obtained, shelled and grain weight recorded.

The percentage larval control resulting from each insecticide treatment was determined. Economic thresholds for larval stages of NCR were calculated using information obtained from this experiment. The data were analysed using the analysis of variance procedure (ANOVA) and the general linear model procedure (GLM) of the Statistical Analysis System (SAS Institute 1979). Duncan's multiple range test was used to determine significance of differences between treatment means.

b). Field Dosage Tests of Insecticides

A field test was undertaken at Pike River to evaluate the efficacy of PP993 (1G) applied at different dosages, fonofos (as Dyfonate® 20G) and fonofos MS (micro-encapsulated), applied at manufacturers recommended dosage, to control NCR larvae. The test field was mostly clay loam and the farmer reported a high NCR infestation during the previous summer. The test field was planted with Pioneer® 3994 corn hybrid on 4 May, 1986.

One day after seeding at a depth of 7 cm, granular formulations were applied in an 18 cm-wide band at 3 cm deep with the custom hand applicator (Fig. 26). PP993 (1G) was applied in three dosages rates, 8, 11.2 and 14 g/10 m row, and fonofos (as Dyfonate® 20G) at the rate of 5.6 g/10 m row. Fonofos MS (micro-encapsulated) was sprayed with a hand garden sprayer at the rate of 2.5 mL/10 m of row. This was done on 3 June, 1985, which was the beginning of the egg hatching period. The fonofos MS was sprayed around the base of the young corn plants in a band approximately 30 cm wide. A shovel and rake were used respectively to incorporate both granular and liquid formulations of insecticides into the soil.

A randomized complete block design with 10 replications and six treatment combinations, including a non-treated check, was used for this experiment. Each subplot consisted of two rows 10 m long; with a buffer zone made up of two untreated rows left between each subplot.

c). Insecticide Trial at Cultivation Time

An experiment was conducted at Pike River to assess the efficacy of liquid formulations of insecticide to control NCR larvae, when applied during the egg-hatching period. The test field had been in continuous corn since 1973 (ie. no rotation) and had a history of high NCR infestation during the summer of 1985. Hybrid grain corn Pioneer^{R} 3994 was planted at 75 cm row spacings on 1 May and cultivated 1 June, 1986. Fonofos MS (micro-encapsulated) and disulfoton LC were sprayed one day after cultivation, using a hand garden sprayer, at rates of 2.5 mL/10 m of row and 1.5 mL/ 10 m of row, respectively, in a 30 cm wide band at the base of the plants. A rake was used to incorporate the insecticide into the soil. The time of insecticide application was chosen to coincide with the period of egg eclosion of NCR in southwest Quebec cornfields (Dominique 1983). The subplots consisted of two rows 10 m long. Two buffer rows were planted to corn between each subplot. The two insecticides and the untreated check were arranged in a randomized complete block design with eight replications.

The efficacy of the insecticides was assessed through larval counting, root damage rating, and determination of plant height, stem circumference and grain yield. On 8 July, 1986, three plants were selected at random for larval counts and root damage rating. The plants were cut down at ground level and quadrat soil samples of 20 x 20 cm with the plant base at its centre and 15 cm deep were dug out. Soil samples were examined visually as described in section 111.B.2.ii, for larval presence, and root system damage was rated (Hills and Peters 1971). On 21 and 26 September, 1986, 25 randomly-selected plants were hand harvested after plant height and stem circumference at the first base node above ground level were measured. The ears were dried at 65^0 C until a constant weight was obtained, then shelled and kernel weight recorded.

The data were analysed by ANOVA and GLM procedures of the Statistical Analysis System (SAS Institute 1979). Duncan's multiple range test was used to determine significance of differences between the treatment means.

iii. INSECTICIDE RESIDUES INVESTIGATIONS

Residue levels of various granular insecticides in soils were studied in the summer of 1985 at the Ormstown cornfield to determine if chemicals applied at seeding time persisted through the period when NCR larvae were active in the field. The study field had been in continuous corn since 1972 and, from that time, no insecticide had been used. The soil was clay loam type and had a pH of 5.8.

PP993 (1G), fonofos (as Dyfonate® 20G) and chlorpyrifos (as Lorsban® 15G) were mixed into the soil at planting time with a hand applicator, as described in page 153. The application was made in an 18 cm band at 3 cm deep and at an average rate of 11.2, 5.6 and 7.5 g/ 10 m of row, respectively. The experimental area consisted of two blocks, with each block divided into three subplots. The treatment insecticides were randomized within each block. Each subplot consisted of a 10 m row planted with Pioneer® 3994 corn hybrid on 10 May, 1985. An untreated row was planted to corn between each subplot.

<u>Soil Sampling.</u> Six randomly-selected soil cores, 10 cm deep and 5 cm in diameter, were removed with a golf cup cutter from each treatment plot and mixed together in groups. Sampling was done immediately after application then at 4, 8, 12 and 23 weeks later. Composite samples from each treatment were brought to the laboratory in plastic bags and stored in a deep freeze at -20°C pending analysis. Samples were then thawed

and mixed thoroughly in a home cement mixer and passed through a No.15 sieve for chemical analysis and moisture determination. Soil moisture for each subsample was determined by oven-drying of 10 g at 105°C until a constant weight was obtained (Mathur *et al.* 1975).

<u>Extraction of soils</u>. A slight modification to the procedure of Belanger and Hamilton (1979) for extracting insecticides from soils was used in this experiment. That is, samples were processed in their 'as sampled' field-moisture state rather than after oven-drying. Three moist subsample equivalent to 10 g of oven-dry soil from each insecticide treatment, taken at every sampling date, were weighed into 50 mL flasks fitted with a teflon-lined stopper. Thirty mL of a mixture of 1:1 acetone:hexane (v/v) of high purity chromatography grade was added to the soil sample, which was then agitated vigorously on a mechanical shaker for two hours. The flask contents were then transferred to a 40 x 150 mm centrifuge tube fitted with a teflon-lined screw cap. The soil suspension was centrifuged in a Sorvall® laboratory centrifuge , at 2000 rpm for 5 min. to separate the organic solution from the soil residue. Each soil sample was re-extracted three more times with 25 mL of the same solvent mixture. The combined supernatants were washed with 150 mL distilled water in a 500 mL separatory funnel to remove the acetone. The hexane solution remaining was dried over sodium sulfate in a 22 i.d. x 400 mm long (234 mL) Chromaflex® column. The dried extract solution was collected in a 50 mL calibrated flask and made up to the mark with hexane.

Extraction efficiencies of the methods were measured by adding 10 ppm of each insecticide in granular formulation to an untreated soil sample obtained from the same field and allowing it to stand at room temperature for one hour before extraction. The samples were then processed as described above and the per cent recovery of the insecticide added was calculated.

<u>Residue Analysis</u>. A Varian® model 3700 gas chromatograph fitted with a Ni^{63} electron capture detector and a Hewlett Packard® integrator (model 3390A) were used for analyzing insecticide residues. The glass column, 1.22 m long x 2 mm i.d., was packed with Chromosorb W, 100-120 mesh coated with three per cent OV-17. Operating conditions are given in Table 18. Under these conditions, retention times for fonōfos, PP993 and chlorpyrifos were 4.1, 3.5 and 3.9 min., respectively.

The recovery of insecticide residue in a particular sample was determined by comparing peak heights and areas with those of reference standards of known concentration. All samples were analysed three times and average values based on oven-dry soil weights were reported. The results obtained from soil samples were not corrected for recovery. Residues found on each sampling date are presented in graph form, and the data were analysed statistically to determine means and their standard errors.

TABLE 18

Operating conditions for gas chromatographic analysis of PP993, fonofos and chlorpyrifos.

Column	Glass, 1.22 m x 2mm i.d.
Column packing material	3 per cent OV-17 on Chromosorb W, 100-120 mesh
Column Temp. for:	
fonofos and PP993	250°C
chlorpyrifos	270°C
Injector Temp.	250°C
Detector Temp.	300°C
Nitrogen carrier gas flow-rate	50 mL/min.
Volume injected	1 uL

3. RESULTS AND DISCUSSION

i. INSECTICIDE BIOASSAY

Direct-Contact Toxicity. Mortalities observed 48 hours post-treatment were too high to allow calculation of LD50's, so that analysis of the results was restricted to 24-hour mortalities. The responses of first-instar NCR larvae to eight contact insecticides are given in Table 19. Chi-square analysis (Finney 1971; Hubert 1984) indicated that the calculated probit lines of all insecticides adequately fit the data. An analysis of covariance (Zar 1984) on the probit regression lines indicated no significant difference ($p > 0.05$) between slopes. However, the LD50 value of PP993 was significantly different ($p = 0.05$) from the LD50's of isofenphos, carbofuran, chlorpyrifos, and disulfoton as evaluated by the non-overlapping 95 per cent fiducial limits (Table 19).

Comparison of LD50's showed mortality responses of first-instar NCR larvae varied by a factor of 4 between the most toxic insecticide, PP993, and the least toxic, isofenphos. Terbufos was the second most toxic compound, less toxic than PP993 by a factor of 1.5. The approximate order of effectiveness based on LD50 values is as follows: PP993, terbufos, fensulfothion, fonofos, chlorpyrifos, carbofuran, disulfoton, and isofenphos.

Soil Bioassay. The responses of second-instar NCR larvae to a range of

TABLE 19

RESULTS OF TOPICAL APPLICATION OF EIGHT INSECTICIDES TO FIRST-INSTAR NCR LARVAE USING A POTTER SPRAY TOWER

Insecticide	LD50 (ppm)	95% Fiducial Limits (ppm) Lower	Upper	Slope	χ^2
isofenphos	14.200 b	7.700 -	25.970	1.121	1.479
carbofuran	11.005 b	6.759 -	17.919	1.609	0.223
chlorpyrifos	10.335 b	6.229 -	17.146	1.491	0.037
fensulfothion	5.965 ab	3.400 -	10.422	1.306	0.419
disulfoton	11.944 b	6.835 -	20.872	1.266	0.499
fonofos	6.563 ab	3.368 -	12.879	0.993	0.327
PP993	3.350 a	1.940 -	5.797	1.412	0.382
terbufos	4.780 ab	2.800 -	8.135	1.450	0.639

LD50's followed by the same letter are not significantly different ($p > 0.05$), based on non-overlapping 95% fiducial limits.

insecticide concentrations in soil (ppm) are presented in Table 20. There is no significant difference ($p = 0.05$) between the slopes of the probit regression lines as determined by the analysis of covariance (Zar 1984). Chi-square analyses (Finney 1971, Hubert 1984) indicates that the probit regression lines of all insecticides adequately fit the data. The LD50 values of the test insecticides were not significantly different ($p > 0.05$) as evaluated by the non-overlapping fiducial limits (Table 20).

Based on LD50 values (Table 20), PP993 was the most toxic compound and fensulfothion the least. Terbufos was the second-most toxic insecticide, followed by chlorpyrifos. Fonofos ranked number four in performance against second- instar larvae.

Both PP993 and terbufos were very effective contact insecticides and perhaps fumigants. Fensulfothion was slightly less toxic than terbufos as a contact insecticide, whereas, when tested in soil, it gave the poorest performance. Fonofos was found to be slightly more effective than carbofuran both as a contact insecticide and as a fumigant. Lew and Sutter (1985) reported 0.04 ppm as LD50 for terbufos against third-instar NCR larvae, whereas in this test 0.5 ppm was observed as LD50 for terbufos against second-instar NCR larvae. Harris (1966), using several insecticides in different types of soils, concluded that the inherent activity of most insecticides increased in soils containing a reduced amount of clay and organic matter in proportion to sand content. This

TABLE 20

LD50'S OF SIX INSECTICIDES TO SECONED-INSTAR NCR LARVAE, EXPRESSED AS CONCENTRATIONS IN SOIL (PPM)

Insecticide	LD50 (ppm)	95% fiducial limits (ppm) lower - upper	Slope	χ^2
fonofos	0.883 ab	0.696 - 1.120	3.446	0.406
carbofuran	0.920 ab	0.689 - 1.227	2.337	0.677
fensulfothion	1.253 b	1.018 - 1.541	2.716	1.367
terbufos	0.497 a	0.289 - 0.855	2.397	0.282
chlorpyrifos	0.661 a	0.431 - 1.015	1.962	0.532
PP993	0.197 a	0.036 - 0.969	1.658	0.849

LD50's followed by the same letter are not significantly different ($p > 0.05$), based on non-overlapping 95% fiducial limits.

might be one of the reasons for the discrepancy between the LD50 values of terbufos observed in this test and that reported by Lew and Sutter (1985). In these two tests terbufos was the most toxic compound among the selection of organophosphorus and carbamate insecticides used. A similar result for terbufos effectiveness was reported by Sutter (1982); Lew and Sutter (1985); Ontario Ministry of Agriculture (1985).

From a practical point of view, it is important to relate the toxicity observed in this laboratory bioassay to the residues apparently present during the peak larval hatch in cornfields. As shown in page 179, residues of 0.27, 3.43 and 2.65 ppm were observed 12 weeks after application for PP993, fonofos and chlorpyrifos respectively. Ahmad *et al.* (1979) reported residues in cornfields during larval hatch as follows (in ppm): 5 for carbofuran; 3 for fonofos; 2.5 for chlorpyrifos; 0.8 for phorate; and 0.4 for terbufos. These residues are far greater than the LD50 values observed in the present bioassay. Our results suggested that application rates of chemicals such as carbofuran, fonofos and chlorpyrifos could be reduced to levels that yielded residues capable of causing *ca.* 95 per cent larval mortality. However, other factors that might reduce the potential toxicity of these chemicals, such as moisture, soil type, micro-organisms and developing resistance, as reported by Harris (1972), should be considered in optimizing the rate of application.

ii. FIELD TESTS OF INSECTICIDES AGAINST NCR IN SOUTHWEST QUEBEC CORNFIELDS

a). Insecticide Trials at Planting Time

The results given in Table 21 summarize the analysis of variance procedure for the dependent variable, corn yield. The results given in Table 21 show that yield remains unaffected by insecticide placement. The table also indicates that there ~~was~~ no significant interaction between either treatment * placement, treatment * time, or placement * time. However, time of application greatly affected corn yield at both locations (F value = 748.74 and 204.15, respectively, at Ormstown and Pike River cornfields). This effect resulted in highly significant (p = 0.0035) yield reduction between different treatments. For this reason the treatments were further analysed separately at each time of application (Table 22). Analysis of the data at each time of application showed no significant difference in grain yield between treatments at both fields. However, both root damage ratings and larval density were highly affected by the insecticide treatments.

The results of Duncan's multiple range test are given in Tables 23 and 24, respectively for Ormstown and Pike River cornfield trials in 1985. There was no significant difference in yield between different treatments and the check plot at the Ormstown cornfield, whereas PP993

TABLE 21

ANALYSIS OF VARIANCE PROCEDURE FOR THE DEPENDENT VARIABLE, YIELD, OBTAINED FROM INSECTICIDE TRIALS EXPERIMENT IN 1985

(a) Ormstown Field

Source	DF	F Value	PR > F	C.V.
Model	15	53.01	0.0001**	6.2348
Treatment	3	4.95	0.0045**	
Placement	1	0.21	0.6511	
Time	1	748.74	0.0001**	
Blocks	3	10.08	0.0001**	
Treatment*Placement	3	0.07	0.9775	
Treatment*Time	3	0.21	0.8904	
Placement*Time	1	0.20	0.6600	

(b) Pike River Field

Source	DF	F Value	PR > F	C.V.
Model	11	20.91	0.0001**	5.1211
Treatment	2	5.67	0.0097**	
Placement	1	0.47	0.4990	
Time	1	204.15	0.0001**	
Blocks	2	6.41	0.0059**	
Treatment*Placement	2	0.48	0.6263	
Treatment*Time	2	0.01	0.9935	
Placement*Time	1	0.32	0.5794	

** Significant at p = 0.01

TABLE 22

ANALYSIS OF VARIANCE PROCEDURE FOR THE DEPENDENT VARIABLES, YIELD, LARVAE AND ROOT DAMAGE RATINGS, FOR FIELD INSECTICIDE TRIALS (1985)

(a) Ormstown field

Insecticide appl. date	Dependent variable	Source	DF	F Value	PR > F
13 May 1985	Yield	Treatment	7	1.64	0.1709
	Larvae	"	7	10.36	0.0001**
	Root D.R.^	"	7	10.81	0.0001**
3 June 1985	Yield	Treatment	7	0.31	0.9401
	Larvae	"	7	10.71	0.0001**
	Root D.R.^	"	7	3.59	0.0026**

(b) Pike River field

Insecticide appl. date	Dependent variable	Source	DF	F Value	PR > F
10 May 1985	Yield	Treatment	5	2.48	0.0918
	Larvae	"	5	10.89	0.0001**
	Root D.R.^	"	5	5.22	0.0011**
2 June 1985	Yield	Treatment	5	0.58	0.7163
	Larvae	"	5	5.90	0.0004**
	Root D.R.^	"	5	8.61	0.0001**

** Significant at p = 0.01
^ Root damage rating

TABLE 23

MEAN YIELD, LARVAL POPULATION AND ROOT DAMAGE RATINGS FOR ORMSTOWN INSECTICIDE TRIALS (1985)

Treatment	Date	10 May 1985			21 May 1985		
Granular insecticide	Depth of application	Yield/ plot (cm)	Lar[1]/ plant (g)	Root D.R.^	Yield/ plot	Lar[1]/ plant (g)	Root D.R.^
PP993 (1G)	3	6056a	3.4a	1.6a	3902a	3.8a	1.9a
	7	5937a	3.7a	1.6a	3865a	3.9a	1.8a
fonofos (Dyfonate 20G)	3	5973a	4.7a	1.7a	3864a	3.0a	1.7a
	7	5972a	4.3a	1.8a	3894a	3.1a	1.8a
chlorpyrifos (Lorsban 15G)	3	5891a	7.0a	2.3a	3746a	4.3a	2.0a
	7	5743a	6.2a	2.2a	3808a	4.2a	2.0a
Control	-	5560a	14.8b	3.3b	3599a	13.6b	3.1b

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

1 Larvae
^ Root damage rating

TABLE 24

MEAN YIELD, LARVAL POPULATION AND ROOT DAMAGE RATINGS FOR PIKE RIVER INSECTICIDE TRIALS (1985)

Treatment date		10 May 1985			21 May 1985		
Granular insect-icide	Depth of appl-cation (cm)	Yield /plot (g)	Larvae /plant	Root D.R.^	Yield /plot (g)	Larvae /plant	Root D.R.^
PP993 (1G)	3	5475a	3.8a	1.6a	4281a	4.4a	1.7a
	7	5407ab	3.6a	1.7a	4256a	4.9a	1.8a
fonofos (Dyfonate 20G)	3	5394ab	4.0a	1.9a	4238a	3.8a	1.7a
	7	5455a	3.8a	1.9a	4311a	3.6a	1.6a
Control	-	5141b	13.0b	3.1b	3984a	13.7b	[illegible].4b

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

^ Root damage rating

(1G) and fonofos (as Dyfonate® 20G), applied during planting time at Pike River, at 3 and 7 cm deep, respectively, showed a significant difference in yield from the nontreated check plots. At the normal application time, PP993 increased corn yield by 7.8 and 5.8 per cent, respectively, at Ormstown and Pike River cornfields, whereas fonofos increased corn yield by 7.4 and 5.5 per cent, respectively. Chlorpyrifos increased corn yield by 4.6 per cent.

Larval density and root damage ratings at plots treated with insecticides were significantly different from the non-treated checks at both application times (Tables 23 and 24). When insecticides were applied at the normal application time at Ormstown and Pike River cornfields, PP993 caused a 76 and 71.5 per cent reduction, respectively, in larval population, whereas fonofos and chlorpyrifos caused 70 and 67 per cent reduction, respectively.

The highly significant difference in yield between the two application times could be attributed mainly to unconnected biological factors rather than being a result of insecticide application dates. The main reason for yield reduction when application time occurred later was the adverse effect on pollination caused by adult feeding on the fresher silks. The other biological reason for lower yield might be the fact that, as reported by Pendelton (1979), early planting is a key cultural practice in temperate corn growing areas. It provides higher yields, shorter plants, stronger plants, earlier shading of the soil to help reduce evaporation, longer days during the grain-filling period, and a greater economic return from a given increment of nitrogen fertilizer than would occur with corn planted later.

The lack of interaction between placement and insecticide treatments (F value = 0.07 - 0.48; Table 21) indicates that it made no difference where the PP993, fonofos or chlorpyrifos was applied, whether at the seed level or above the seed level, i.e. in front of the planter press wheel or behind it. However, Erbach and Tollefson (1983) reported that granular insecticides applied in front of the planter press wheel provide the greatest amount of incorporation.

PP993 was very competitive with fonofos and chlorpyrifos in its effectiveness against NCR larvae. These results were in general agreement with Oleson and Tollefson (1985) who found that PP993 worked as well as terbufos and fonofos and both are slightly more effective than chlorpyrifos. Ostlie (1985) also confirmed that PP993 performed as well as terbufos and both ranked ahead of fonofos and chlorpyrifos. An Ontario Ministry of Agriculture report (1985) stated that fonofos performed better than chlorpyrifos in controlling rootworms. The poorer performance of chlorpyrifos might be attributed to the findings of Tashiro and Kuhr (1978) that, as the moisture increases, the volatility of chlorpyrifos is reduced, resulting in less toxicity to insects.

All insecticide treatments were superior to the untreated controls for every measurement of efficacy except yield. Among these measurements of efficacy, larval density and root damage ratings were the best means for evaluating insecticide performance. These results agreed with those of Mayo (1986) who reported that yield differences must exceed 30 to 62.5 bushels per ha before before statistically significant differences can be detected. For this reason, he reported that root damage ratings or root-pull resistance measurements are the best criteria for comparing insecticide efficacy.

The results of this investigation suggest the feasibility of using PP993 for NCR control. It could be used as a novel class of insecticide (pyrethroid),to be rotated with other commonly used soil insecticides, and in conjunction with crop rotation, to help manage resistance problems. However, many more tests would be needed to meet the registration requirements of Agriculture Canada before becoming available for operational use.

b). **Field Dosage Tests of Insecticides**

The results of the analysis of variance procedure for these tests are given in Table 25. Larval density and root damage ratings were highly affected by the treatment (F value= 13.42 and 5.61 respectively). None of the other measurement criteria were affected by the treatment. Plant height was the only measurement criterion affected by blocks. The results of Duncan's multiple range test of the means of all variables are given in Table 26. The table indicates that, except for larval population, there was no significant difference in measurement criteria between plots treated with insecticides and the untreated controls. There was no significant difference in measurement criteria between the three dosages of PP993 (Table 25). However, a slightly larger number of larvae and higher root damage rating were observed with the lower dosage (8 g/10 m of row). Fonofos MS performed almost as well as fonofos as Dyfonate^R 20G. In terms of reducing the larval population, the insecticides were ranked in descending order of effectiveness as follows: PP993 1G (14 g/10 m of row); PP993 1G (11.2 g/10 m of row) and fonofos as Dyfonate^{R}20G; (5.6 g/10 m of row); PP993 1G (8 g/10 m of row) and fonofos MS (2.5 mL/10 m of row).

The poor performance of the insecticide treatments over the untreated controls, especially in grain yield, may be attributed to the small larval infestation that occured perhaps as a result of low temperatures during June and July 1986 (Appendix 2). Dominique and Yule (1983a) observed that 1 June usually coincides with the required degree days (431) needed for the first eclosion of NCR eggs. However, in 1986, the required number of degree days for the first eclosion of eggs was only met during the first week of July (Appendix 2). Moreover, the prolonged period of chill that occurred in 1986 before egg hatching began is likely to have affected the viablity of the eggs (Chiang 1965; Patel and Apple 1967; and Dominique and Yule 1983b).

Larval density was apparently the most sensitive criterion of treatment effects (F value = 13.42). This suggested that at low larval density, larval counts from plant roots are superior to root damage ratings as a measurement of insecticide efficacy. Root damage ratings were less sensitive than larval counts because extensive root damage was not exerted by low larval population density.

The results of this investigation (Table 26) did not indicate any significant difference between dosages of PP993 or any of the other treatments. However, as reported by Metcalf (1980), low rates of pesticide application are regarded as one of the main principles of pesticide management. Lower rates of pesticides are more ecologically sound in that they have less effect on the pests' natural enemies, thus helping to delay pest or secondary pest resurgence. Moreover, low rates reduce control cost and help delay the establishment of pest resistance by reducing the genetically selective pressure for the resistance. The use of low rates conforms to the "dirty field" or "pest residue" concept of pest management. This stresses the importance of leaving substantial numbers of living target pest species as host material for conserving or increasing the natural enemy population.

TABLE 25

ANALYSIS OF VARIANCE PROCEDURE FOR INSECTICIDE DOSAGE EXPERIMENT AT PIKE RIVER (1986)

Dependent variable	Source	DF	F Value	PR > F
Larvae	Treatment	5	13.42	0.0001**
	block	9	0.90	0.5258
Plant height	Treatment	5	1.46	0.2135
	block	9	14.46	0.0001**
Stem circumference	Treatment	5	0.33	0.8571
	block	9	1.21	0.2852
Grain yield	Treatment	5	1.01	0.4254
	block	9	1.33	0.2499
Root damage rating	Treatment	5	5.61	0.0001**
	block	9	0.85	0.5683

** significant at p = 0.01

TABLE 26

MEAN LARVAL DENSITY, PLANT HEIGHT, STEM CIRCUMFERENCE, YIELD, AND ROOT DAMAGE RATINGS, OF INSECTICIDES DOSAGE EXPERIMENT AT PIKE RIVER (1986)

Treatment	Larvae/ Sample	Height (cm)	Circumfer- ece (cm)	Yield/ plot(g)	Root D.R^
PP993 1G (8g)*	0.7a	215a	7.3a	2842a	1.10a
PP993 1G (11.2g)*	0.4a	214a	7.4a	2880a	1.03a
PP993 1G (14g)*	0.3a	217a	7.4a	2824a	1.03a
fonofos (Dyfonate 20G; 5.6g)*	0.4a	216a	7.5a	2955a	1.03a
fonofos MS (2.5 mL)*	0.8a	217a	7.3a	2797a	1.07a
Control	2.1b	217a	7.5a	2877a	1.5a

Means followed by the same letter in the same column are not significantly different ($p > 0.05$; Duncan's multiple range test).

* Dosage of granular insecticide per 10 m row
Root damage rating

^Root damage rating

c). Insecticide Trials at Cultivation Time

The data in Table 27 summarize the results of the analysis of variance procedure of fonofos MS and disulfoton LC applied at cultivation time. The results indicate that larval counts from plant roots and root damage ratings were greatly affected by the insecticide treatment. Stem circumference was significantly affected ($p = 0.0271$) by the treatment. Plant height and grain yield remained unaffected by the treatment.

The results given in Table 28 show that plants treated with fonofos MS and disulfoton LC did not significantly differ from each other in larval density or root damage ratings, but both measurements differ significantly from untreated controls. Fonofos MS caused a 61 per cent reduction in larval population, whereas disulfoton LC caused a 45 per cent reduction. Stem circumference for disulfoton-treated plots was significantly less than either fonofos treated plots or control plots without insecticide. Neither plant hight nor grain yield showed any significant difference among the different treatments. However, fonofos MS was apparently superior to disulfoton LC in all efficacy measurements. The superiority of fonofos to disulfoton might be attributed to the longer persistance of fonofos and/or the possible phytotoxicity of disulfoton, as shown by the significantly thicker stem circumference and slightly shorter plant it produced (Oleson and Tollefson 1985).

As calculated by the degree days observed by Dominique (1983).

TABLE 27

ANALYSIS OF VARIANCE PROCEDURE FOR FONOFOS MS AND DISULFOTON LC APPLIED AT CULTIVATION TIME AT PIKE RIVER (1986)

Dependent variable	Source	DF	F Value	PR > F
Larvae	Treatment	2	15.56	0.0001**
	block	7	0.72	0.6592
Plant height	Treatment	2	0.69	0.5053
	block	7	7.43	0.0001**
Stem circumference	Treatment	2	3.71	0.0271*
	block	7	2.72	0.0115*
Grain yield	Treatment	2	0.52	0.6186
	block	7	3.25	0.0289*
Root damage rating	Treatment	2	6.36	0.0035**
	block	7	0.76	0.6248

** Significant at p = 0.01

* Significant at p = 0.05

TABLE 28

MEAN LARVAL DENSITY PER PLANT, PLANT HEIGHT, STEM CIRCUMFERENCE, YIELD AND ROOT DAMAGE RATINGS OF INSECTICIDE TRIALS AT CULTIVATION TIME (1986)

Treatment	Larvae/ sample	Height (cm)	Stem circumferece (cm)	Yield/ plot(g)	Root D.R.^
fonofos MS (2.5mL/10m row)	1.3a	234a	7.72a	2412a	1.21a
disulfoton LC (1.5mL/10m row)	1.8a	231a	7.36b	2322a	1.41a
Control	3.3b	232a	7.66a	2428a	1.92b

Means follwed by the same letter in the same column are not significantly different (p = 0.05; Duncan's multible range test.

^ Root damage rating

(Appendix 2), it appears that adverse weather conditions in 1986 affected larval population by delaying egg eclosion until the first week of July. One might expect that, if normal hatching had occured in the first week of June as reported by Dominique (1983), the performance of both fonofos MS and disulfoton LC in reducing larval population might have been better than that observed in this experiment.

iii. INSECTICIDE RESIDUE INVESTIGATIONS

Analysis of extracts from 10 g of soil samples fortified with 10 ppm of PP993, fonofos and chlorpyrifos in the laboratory gave average recoveries of 89.6±0.43, 91.0±0.36, and 89.5±0.71 per cent, respectively.

Theoretically, granular application of PP993 (1G), fonofos (20G) and chlorpyrifos (15G), respectively, at the rate of 11.2, 5.6 and 7.5 g (granules) per 10 m of row (18 cm band) would result in 0.62, 6.20 and 6.25 ppm in the upper 10 cm layer of soil. The concentrations of parent insecticides in soil and percentage decline at each sampling date from the parent amount, applied during sowing time, are given in Tables 29 and 30 respectively. Gas chromatograms (on 3% OV-17 column) of extracts of PP993, fonofos and chlorpyrifos treated soil are given in Fig. 25. Fig. 24 shows the comparative decline rate of PP993, fonofos and chlorpyrifos as percentage of the initial amount measured at application time. The initial concentrations of PP993, fonofos and chlorpyrifos detected in the soil at 10 cm depth were 0.62, 7.16 and 5.44 ppm respectively (Table 29). Fig. 24 shows that chlorpyrifos decreased to *ca.* 65 per cent by four weeks after application, whereas both PP993 and fonofos decreased to *ca.* 75 per cent. Residue levels of all insecticides dissipated at a faster rate during the first four weeks, followed by a slower rate during the rest of the growing lseason. Fig. 24 shows that 50 per cent of the parent PP993, fonofos and chlorpyrifos in the soil had disappeared in *ca.* 9, 12 and 11 weeks respectively. Residues of

TABLE 29

PERSISTENCE OF PP993, FONOFOS, AND CHLORPYRIFOS IN ORMSTOWN CORNFIELD SOIL (1985)

Weeks after insecticide application	PP993 (1G) 11.2 g/10 m of row (*)	fonofos[1] 5.6 g/10 m of row (*)	chlorpyrifos[2] 7.5 g/10 m of row (*)
0	0.62 ± 0.05	7.16 ± 1.07	5.44 ± 0.42
4	0.46 ± 0.06	5.41 ± 0.25	3.53 ± 0.61
8	0.34 ± 0.03	4.32 ± 0.23	3.22 ± 0.79
12	0.27 ± 0.02	3.43 ± 0.41	2.65 ± 0.10
23	0.13 ± 0.01	2.21 ± 0.03	1.30 ± 0.14

1 As Dyfonate 20 G
2 As Lorsban 15 G
* Values in ppm±S.D.

TABLE 30

PP993, FONOFOS AND CHLORPYRIFOS RESIDUES IN THE SOIL AS PERCENTAGE OF INITIAL CONCENTRATIONS

Weeks after insecticide application	PP993 (1G) 11.2 g/10m of row (%)	fonofos[1] 5.6 g/10m of row (%)	chlorpyrifos[2] 7.5 g/10m of row (%)
0	100	100	100
4	74	76	65
8	55	60	59
12	44	48	49
23	21	31	24

1 Applied as Dyfonate 20G
2 Applied as Lorsban 15G

FIGURE 24. COMPARATIVE DECLINE RATE OF PP993,FONOFOS AND CHLORPYRIFOS AS PERCENTAGE OF THE INITIAL AMOUNT MEASURED AT APPLCATION TIME

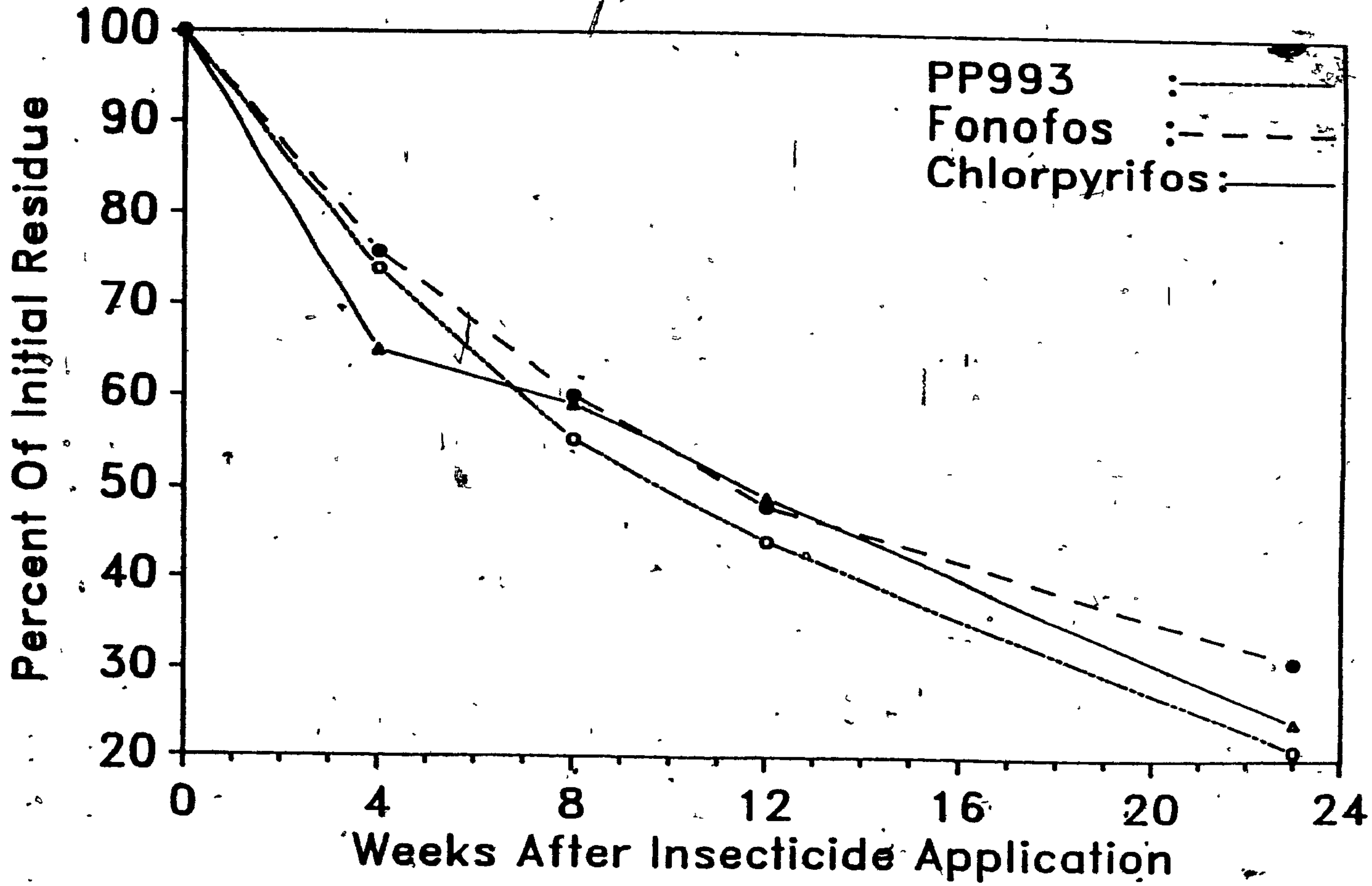
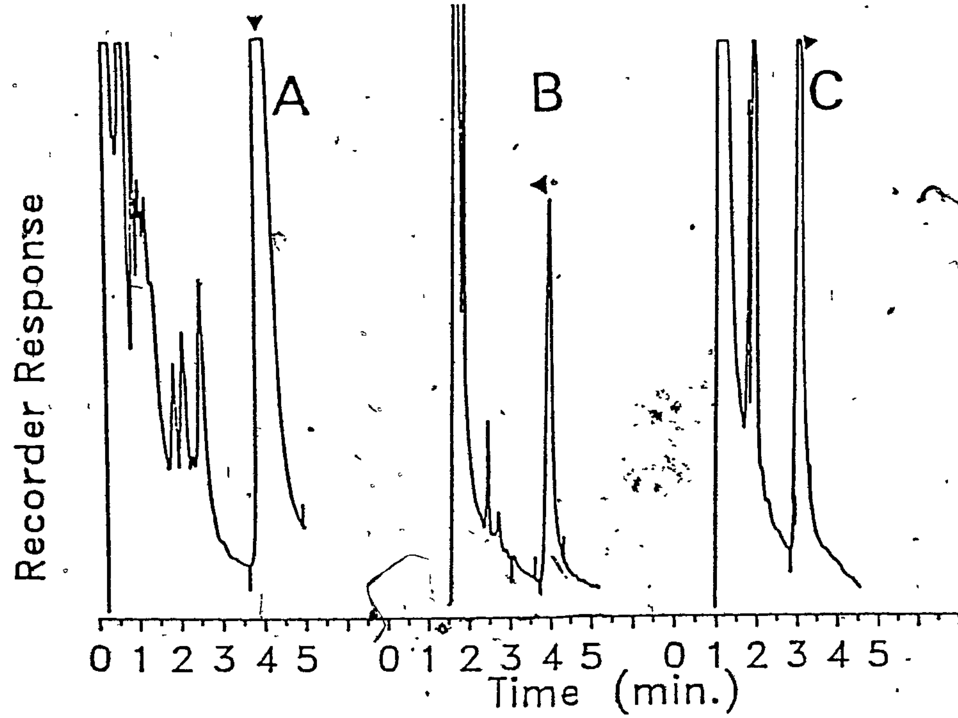


FIGURE 25. GAS CHROMATOGRAMS (ON 3% OV−17 COLUMN) OF EXTRACTS OF CHLORPYRIFOS (A), FONOFOS (B), AND PP993 (C)−TREATED SOIL AT APPLICATION TIME



both fonofos and chlorpyrifos were greater than 2.65 ppm during the critical 4 to 12 week period which coincides with the presence of the NCR larvae in the field, whereas PP993 remained above the 0.27 ppm level. Approximately 30 per cent of the applied fonofos remained at the end of the growing season, whereas *ca*. 20 per cent of PP993 and chlorpyrifos remained.

The relatively substantial amount of PP993, fonofos and chlorpyrifos (Table 27) detected from 4 to 12 weeks after application provides an estimate of their effectiveness against NCR. In this study residues of 0.27, 3.43 and 2.65 ppm were detected for PP993, fonofos and chlorpyrifos 12 weeks after application. These amounts are mostly far in excess of the LD50 values of 0.197, 0.883 and 0.661 ppm respectively observed for PP993, fonofos and chlorpyrifos in soil bioassays (Table 29). Ahmad *et. al.*(1979) reported residue levels of 3 ppm and 2.5 ppm respectively for fonofos and chlorpyrifos during the peak larval hatch, which is slightly less than that observed in this study. Only half the amount of fonofos initially applied was found 12 weeks after application. This is similar to what was observed by Suett (1971) who found that 50 per cent of fonofos applied to mineral soil had disappeared in 11 weeks. In another study, Mathur *et. al.*(1976) noted about a 60 per cent decrease in fonofos after 125 days. In contrast, Ahmad *et. al.* (1979) reported 46 days as the 'half life' for fonofos. At the end of the growing season, *ca*. 30 per cent of the initial amount of fonofos was detected. This result was very close to that of Saha *et. al.* (1974) and Suett (1971), who found, respectively, that 33-35 per cent and 20-30 per cent of fonofos persisted through the end of the growing season. In organic soils, fonofos persisted longer than in mineral soils, as observed by Belanger *et al.* (1982), who found that 40-48 per cent of the initial fonofos was retained by the soil through to the end of the growing season.

Fig. 24 shows that 50 per cent of the chlorpyrifos had dissipated 11 weeks after application. Tashiro and Kuhr (1978), using different formulations of chlorpyrifos (0.88 G and 0.95 G), reported that 50 per cent of the insecticide was lost 9 to 11 days after application. The main reason for this discrepancy might be the difference in formulation, according to these authors. Other factors such as weather conditions, soil type and soil micro-organisms greatly influences the biodegradation of chemicals in soil, as reported by Burkhardt and Fairchild (1967); Suett (1971); Harris (1972); Belanger *et al.*(1982); De Vault (1986).

PP993 had diminished by 50 per cent nine weeks after application, and *ca.* 20 per cent was left in the soil by the end of the growing season. Because of the lack of literature on the persistence of PP993 in soil, a comparison with other results is not possible.

Table 29 shows that 20-30 per cent of the applied chemicals remained at the end of the growing season. Due to the effect of winter cold, one would anticipate no appreciable change in residues from the end of the growing season through to the following spring. However, as the spring soil temperature exceeds the critical level of 6-7^{o}C, as reported by Suett (1971, 1975), the residues start to decline again. Suett (1975) reported that the primary breakdown mechanisms of parent organophosphorus and carbamate insecticides were mainly microbiological and were inhibited while soil temperatures remained below 6-7^{o}C. Presumably therefore, under Quebec weather conditions, a small amount of fonofos would be present the following season. This assumption was fortified by Saha *et al.* (1974) who found that 3-10 per cent of fonofos was retained by the soil for 29 months in Saskatchewan.

Prolonged persistence of insecticides, particularly if they remain biologically active, may encourage the development of resistant strains of organisms. Moreover, micro-organisms could be adapted for rapid breakdown of insecticides, as reported by Belanger *et al.* (1982); De Vault (1986). However, Harris (1972) noted that many organophosphorus insecticides have positive temperature coefficients and their toxicity decreases as temperatures decline. Therefore, low temperatures during winter and early spring might be expected to reduce substantially the potential toxicity of any insecticide residues persisting into spring.

V. SUMMARY AND RECOMMENDATIONS

SUMMARY AND RECOMMENDATIONS

Studies on the effects of damage to corn roots and grain yield resulting from artificial infestation with different densities of NCR eggs, first-instar larvae, and adults, indicate that EIL's vary from *ca.* 58 to 76, 15 to 19, and 9 to 12, respectively. Under field conditions at Pike River and Ormstown, Que., EIL and ET varied from 11 to 14 and 8 to 10 larvae per plant respectively. The main factors affecting EIL and ET during this study were corn price fluctuation, differences in control costs, insecticide efficiency, spring weather conditions and NCR population density. Thus, if meaningful EIL and ET are to be established, appropriate adjustment and analysis of all factors (Fig. 21) affecting NCR population, crop yield, marketing standards and ecosystems should be carried out.

We found the most sensitive parameters for measuring density-damage relationships to be root damage rating and adult emergence from artificially-infested plants under greenhouse conditions. Although yield was the most practical measurement, it was only significantly different from the check at minimum densities of 150 eggs, 60 first-instar, larvae and 21 adults per plant. Under field conditions, larval count from plant roots was the most definitive measurement for evaluating density-damage relationships and insecticide efficacy. Plant lodging measurement should not be considered solely a result of larval damage without first analysing other factors such as rainstorms, wind, soil structure and potassium deficiency.

Field studies on NCR intra- and inter-generational population changes in Southwest Quebec cornfields indicate a 78 per cent reduction in overwintered egg population; a 64 per cent reduction from the egg to larval stage; and a 46 per cent reduction from the larval to adult stage. Below-normal spring temperatures (as well as crop rotation in St. Antoine Abbe) in 1986, decreased NCR population by 63, 74 and 88 per cent in Ormstown, Pike River and St. Antoine Abbe, respectively.

Studies on the susceptibility of NCR larvae to several insecticides, assessed by direct contact and in-soil bioassays, indicate that PP993 and terbufos were the most effective contact insecticides and possibly soil fumigants. Fonofos and chlorpyrifos performed similarly in soil bioassays, as tested by their LD50.

In laboratory bioassays, the LD50's against NCR larvae of PP993, fonofos and chlorpyrifos were 0.197, 0.883 and 0.661 ppm, respectively, and the residues detected in cornfields during larval peak were 0.27, 3.4 and 12.65 ppm, respectively. These results suggest that the application rates of these chemicals could be reduced to levels that yield residues capable of causing about 95 per cent larval mortality. However, other factors, such as moisture, soil type, micro-organisms and developing resistance, that might reduce the potential toxicity of these chemicals, must be considered in optimizing the rate of application.

Field studies on the effects of insecticide placement on NCR larval control, indicate that it makes no difference whether the PP993, fonofos or chlorpyrifos was applied at the seed level or above the seed level, i.e. in front of the planter press wheel or behind it. However, Erbach and Tollefson (1983) report that granular insecticides applied in front of the planter press wheel provide the greatest amount of incorporation.

Results of 1985 field studies showed that PP993 was very competitive with fonofos and chlorpyrifos in its effectiveness against NCR larvae. All insecticide treatments proved superior to the untreated controls for every measurement of efficacy except yield. In these studies, the overall reduction in larval density from the untreated control, of 71, 73 and 61 per cent, resulted in a yield reduction of 7.2, 6.9 and 4.8 per cent, respectively, for PP993, fonofos and chlorpyrifos. Field insecticide trials in 1986 indicate that there was no significant difference in measurement criteria between the performance of three dosages (8, 11.2 and 14 g/10m row, 1G granules) of PP993, fonofos as Dyfonate[R] 20G, and fonofos MS (microencapsulated, applied during cultivation time). Results suggest the feasibility of using PP993 for NCR control.

Insecticide trials at cultivation time indicate that fonofos MS and disulfoton LC caused a 61 and 45 per cent reduction, respectively, in larval populations from untreated controls. A significant difference in stem circumference in disulfoton- treated plots as opposed to either fonofos-treated or control plots without insecticides might indicate some phytotoxicity associated with disulfoton LC.

Initial concentrations of PP993, fonofos and chlorpyrifos detected in the soil from the Ormstown cornfield to a depth of 10 cm were 0.62, 7.16 and 5.44 ppm, respectively. Fifty per cent of the parent PP993, fonofos and chlorpyrifos in the soil had dissipated within 9, 12 and 11 weeks, respectively. Residues of both fonofos and chlorpyrifos were greater than 2.65 ppm during the critical 4 to 12 week period coinciding with the presence of NCR larvae in the field, whereas PP993 remained above the 0.27 level. Approximately 20-30 per cent of the applied chemicals persited through to the end of the growing season. Thus, the amount of insecticide residues during peak larval periods were far greater than their laboratory LD50's, and a substantial amount of insecticide (20 to 30 per cent) was left in the soil after the growing season. It is likely under Quebec winter conditions that small amounts of these chemicals would persisted to the following spring.

VI. LITERATURE CITED

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APPENDIX

APPENDIX 1

Weather data for Macdonald College area (1986).

	June, 1986			July, 1986		
Date	Min.T°	Max.T°	Rain (mm)	Min.T°	Max.T°	Rain(mm)
1	9.0	16.5	12.8	11	24.5	--
2	5.0	14.5	--	15	24	0.7
3	0.0	18	12.8	12	20	12.4
4	6.5	24.5	--	10	21	--
5	13.5	22.5	0.6	14.5	22	7.8
6	9.5	20.5	--	16	24.5	--
7	10.5	23.5	--	21.5	28.5	--
8	12.5	26.5	2.0	16.5	28	--
9	11	25.5	--	18.5	27	--
10	11	26	--	12.5	22	--
11	15.5	25.5	4.8	9.5	21	--
12	11	20	3.8	15	21	--
13	11	18	35.4	14.5	17.5	9.4
14	13.5	23	--	14.5	21	24.2
15	13.5	24.5	--	12	25	22.6
16	16	28	--	15	27	0.4
17	8.5	26.5	13	16	27.5	--
18	8.5	20.5	0.7	19	29	--
19	9	22.5	--	18.5	29	0.4
20	11	24.5	--	17.5	28	4.6
21	8	25.5	--	15	23	--
22	14.5	28	--	10.5	24.5	--
23	19	28	5	15	28	--

June, 1986

Date	Min.T°	Max.T°	Rain (mm)
24	14	27	10.2
25	7.5	16.5	1.5
26	10.5	20.5	--
27	13.5	20.5	24.4
28	16.5	25.5	5.7
29	13.5	25.5	2.0
30	12	23.5	3.2
31			

July, 1986

MinT°	Max.T°	Rain(mm)
18.5	30	--
21	31	--
19	30.5	44.7
16.5	22.5	--
16	28	--
18	28	--
16	21.5	4.8
15	18.5	2.8

PAGES 211 AND 214 (OF THE WEATHER DATA) APPEAR TO BE MISSING.

THE THESIS SHOULD NOT BE ADVERSELY AFFECTED BY THE MISSING PAGES.

PLEASE CONTACT THE UNIVERSITY OR THE AUTHOR, IF REQUIRED.

VEUILLEZ NOTER LES PAGES 211 ET 214 (WEATHER DATA) SEMBLENT MANQUER.

TOUTEFOIS LA THESE N'EN SERA PAS AFFECTEE.

VEUILLEZ CONTACTER L'UNIVERSITE OU L'AUTEUR, SI BESOIN IL Y A.

	June, 1986			July, 1986		
Date	Min.T°	Max.T°	Rain (mm)	Min.T°	Max.T°	Rain (mm)
1	10.5	17	1	11	24.5	0.6
2	8.0	14	13.5	14.5	19.5	4.8
3	6	13.5	0	11	16	12.5
4	0.5	18	0	5.5	21.5	8.8
5	5.5	25.5	0	14	21	0.8
6	13.5	1.5	0	15	26.5	0
7	6.5	22.5	0	29.5	24	0
8	12.0	23.5	11.4	18	27	0
9	17.5	26	1	19	25.5	0
10	10.0	23	0	10.5	20	0
11	11.5	26.5	8.8	9	20.5	0
12	13.5	19.5	0.4	7	19.5	0
13	11	15	29.2	14	18	13.4
14	10.5	19.5	0.2	15	22	4
15	13	23.5	0	16	25	22
16	15.0	26	0	12.5	27.5	0
17	18.0	29.5	5.4	13.5	28.5	0
18	8	15.5	0	16	28.5	0
19	7	20.5	0	18	29.5	0
20	10.5	22.5	0	20	27.5	20.4
21	12.0	22.5	0	15	22	0
22	5.5	25.0	0	9	25.5	0
23	8.0	28.0	2.8	15.5	27	0

Date	Min.T°	Max.T°	Rain (mm)	Min.T°	Max.T°	Rain (MM)
24	18.5	26.5	0	17	31	0
25	10.5	20.5	19.8	18	33	14.6
26	6	16	0	19	23	49.6
27	7.5	21	4	16.5	25.5	0
28	13.5	20	8.6	16	27	0
29	14	25.5	0	16.5	25	4.8
30	13	23	13	15.5	23	5.6
31				15.0	18.0	0

Appendix 3

NCR larval feeding into the corn roots.

Appendix 4

"Goose-necking" corn plants due to NCR larval feeding.