POPULATION DYNAMICS OF LESSER GRAIN BORER, RUSTY GRAIN BEETLE, AND *CEPHALONOMIA WATERSTONI* IN COMMERCIAL ELEVATORS

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CHAPTER I

LITERATURE REVIEW

Commercial Facility Background

Over 500 million dollars are lost annually in the United States due to stored grain insect infestations and molds (Harein & Meronuck 1991). These losses result from reductions in test weight, decreases in germination rate, decreases in nutritional value, and discounts applied directly (Reed et al. 1989, Barak & Harein 1981a) as a result of the presence of insect parts, frass, and objectionable odors (Barak & Harein 1981a, Harein & Meronuck 1991). The impact on exported wheat is shown in surveys by Storey et al. (1982). In samples from 79 exporting ports in the United States surveyed during 1977-78, insect infestations were found in 17.9% of wheat samples having one or more live insects. A total of 5.6 and 7.5% of samples contained lesser grain borer and rusty grain beetle, respectively.

Oklahoma ranks third in the United States in wheat production and stores more than 250 million bushels annually of hard red winter wheat, *Triticum aestivum* (L.) (Cuperus et al. 1990, Kenkel et al. 1994). In Oklahoma, 36% of all wheat is stored on-farm and the remaining 64% is stored commercially (Anderson 1988).

Commercial elevator managers in Oklahoma ranked insects as the primary cause of grain damage, followed by molds, temperature, and moisture (Kenkel et al. 1993). Molds, temperature, moisture, storage time, and management practices interact to influence insect

populations in stored grain. During harvest in Oklahoma, wheat typically is placed in storage at 30-40°C and 11-12% moisture (Cuperus et al. 1990) . Harvest conditions, coupled with a long storage period and the later onset of cooler ambient temperatures (Storey et al. 1979, Hagstrum & Heid 1988) places Oklahoma in a high-risk zone in terms of insect infestations (Cuperus et al. 1990).

Oklahoma commercial storage facilities average 883,197 bushel capacities using three types of structures: steel (round), concrete, and steel (flat). Round steel bins are most prevalent in Oklahoma with 80.7% used at elevators followed by flat steel warehouses (73.3%) and concrete (38.5%). Steel structures have gained popularity due to lower construction costs than concrete and the ability to aerate. However, grain in steel structures is more difficult to turn and fumigate. Flat steel warehouses are the most difficult to fumigate due to the high surface area-to-volume ratio and the challenge of achieving an adequate seal, which results in increased control failure rates (Cuperus et al. 1990).

Stored Grain Insects

In a survey of elevator managers in Oklahoma (Kenkel et al. 1993), 39% ranked insects as their primary management concern in post-harvest grain storage. They ranked specific insects in the following order: granary weevil (*Sitophilus granarius* (L.)), lesser grain borer *(Rhyzopertha dominica* (F.)), Indianmeal moth (*Plodia interpunctella* (Hubner)), and rusty and flat grain beetles (*Cryptolestes* spp.). However, in grain samples taken from 30 on-farm and commercial bins per storage year 1982-88, no granary weevils

were detected (Cuperus et al. 1986, Cuperus et al. 1990). The main pest species revealed was *R. dominica*, followed by *Cryptolestes* spp., *Tribolium* spp., and *P. interpunctella*, even though *Cryptolestes* spp. were first in abundance.

R. dominica is a primary pest of stored wheat. This feeding site is probably a secondary adaptation because its original diet is dead wood (Potter 1935). This insect has also been documented in ant and rodent burrows feeding on stockpiled grain (Khare & Agrawal 1966). Its ability to survive on fruits and seeds found in woodrat nests is recorded by Wright et al. (1990). *R. dominica* is a destructive and voracious consumer in both the larval and adult stages because it can chew through the hulls of sound kernels to feed internally on the endosperm. Often, only a hollowed-out shell remains after feeding by this insect.

Potter (1935) determined that the average developmental time from egg to adult at 26°C and 65% RH was 58 days. This time is inversely proportional to temperature as it took only 30-40d to complete one generation at 30°C and 30% RH. The female usually lays 300-400 eggs over several weeks. Eggs are laid in groups, or singly, among the kernels. Emergence occurs in 12-18d at 26°C, but this time decreases at 30°C. Newly emerged larvae bore into the grain where they feed for the remainder of their lives. The larvae pupate after 4-5 molts, and the adults emerge, mate, and continue feeding.

C. ferrugineus is a secondary pest of stored wheat usually found feeding under bark in nature (Linsley 1944). This cosmopolitan pest feeds in both the larval and adult stages. It consumes both the germ and endosperm (Rilett 1949a) of broken or cracked kernels, but cannot damage whole, sound grain. This beetle can also survive well on molds, dust, and

fines (Rilett 1949a, Loschiavo & Sinha 1966, Dolinski & Loschiavo 1973). Molds, in particular, reduce mortality and developmental time of *C. ferrugineus* (Rilett 1949a). Fungi growing on kernels may provide nutritional supplements as well as exposing germ and endosperm for feeding (Rilett 1949a, Dolinski & Loschiavo 1973).

Female *C. ferrugineus* deposit eggs in small cracks and crevices in the wheat kernels, or intergranular spaces by means of an extensible ovipositor (Rilett 1949a). One mated female lays an average of 2.54 eggs per day and the eggs hatch in 3-4 days. The larvae emerge and begin to search for food. The first through third instars feed on broken or damaged kernels, while the fourth is quite mobile as it searches for a pupation site (Rilett 1949a, Smith 1972). The adults also have high locomotory abilities (Watters 1969).

Adults mate 1-2 days after emergence and oviposition ensues soon after. The adults eat broken kernels and dust but occasionally return to larval burrows to consume previously exposed endosperm and germ (Rilett 1949a). The optimum conditions for the development of *C. ferrugineus*, as well as most other stored grain insects, are 25-33°C (Fields 1992) and ≥75% RH. However, as with *R. dominica*, *C. ferrugineus* displays decreased developmental time and mortality with increased temperature and moisture (within the optimal range) (Rilett 1949a).

R. dominica and *C. ferrugineus* are consistent inhabitants of commercially stored grain in Oklahoma (Cuperus et al. 1990). A parasitoid of *C. ferrugineus*, *Cephalonomia waterstoni* (Gahan), a bethylid wasp, is also present in wheat storages in Kansas, Australia, and Oklahoma (Schwitzgebel & Walkden 1944, Sinclair 1982, Hagstrum 1987, Vela de Garza 1993).

Cephalonomia waterstoni is a parasitoid whose host specificity is larval *C. ferrugineus*. It typically parasitizes fourth instars because they are actively searching for a pupation site within the grain mass (Rilett 1949a, Smith 1972) while first through third instars feed inside the kernel, thus protected from attack. This wasp searches for larvae by following host kairomonal trails (Howard & Flinn 1990). Once a suitable host is found, the parasitoid grasps it with its mandibles and stings it into submission (Rilett 1949b, Finlayson 1950). Paralyzed, the larva is removed to a secluded oviposition site. Most commonly, one or two eggs, rarely up to four, are laid externally on the host's venter between or behind the metathoracic legs (Rilett 1949b, Finlayson 1950). At 90°F and 75% RH, a female wasp lays 1-3 eggs per day. The eggs hatch in 30 hrs. and the larvae reach full size in 23 hrs. at this temperature. Newly emerged *C. waterstoni* larvae remain affixed to the host and consume haemolymph after piercing the host's cuticle. One *C. ferrugineus* larva provides enough nourishment for the complete development of two wasp larvae.

Pest Management

Traditional methods of controlling stored product insects rely heavily on the use of pesticides. Two general types of pesticides used in storage facilities are protectants and fumigants. Protectants (e.g. malathion, chlorpyrifos-methyl) have residual activity and are often applied before binning (87%), as wheat is binned (30%), or as a top-dress (43%) following binning in Oklahoma commercial storages (Kenkel et al. 1994). Fumigants (e.g. phosphine, methyl-bromide) are preferred by elevator managers due to insect population

elimination properties and are applied during storage in most Oklahoma elevators (Kenkel et al. 1994).

The preventative use of protectants and fumigants during or after binning is perceived as insurance against insects brought in with the harvest, or to reduce insect population development. Old, infested farm-stored grain may be mixed with newly harvested wheat by the producer. This practice increases the chance of insect infestations reaching the commercial facility (Sinclair & Adler 1984). The low cost and ease of protectant application reinforces liberal use.

Monitoring incoming loads with sampling techniques could decrease the extensive, prophylactic use of pesticides. However, of commercial elevator managers surveyed, 57, 24, 18, and 1% stated that they took 1, 2, 3, and 4 samples per incoming load, respectively (Kenkel et al. 1993). Sampling grain can be more costly and time-consuming than protectant treatments (Kenkel et al. 1993), and it is not practical to extensively sample the huge volume of wheat brought in during harvest. Hagstrum et al. (1991) predicted a <50% probability of accurately detecting the presence of low insect population levels with the above sampling scheme. To determine if insects were present in newly harvested grain, Cuperus (unpublished data 1992) took ~5,000 samples from incoming grain loads during harvest. ~40 trucks per day over a 15 day period had 10 samples removed per truck. No insects were detected. This reinforced the concept that field infestations do not exist in hard red winter wheat. If any insects did infest the grain in the field or in uncleaned combine heads before harvest, they would suffer considerable mortality in the harvesting and grain-handling process (Greening 1973, Bryan & Elvidge 1977, Watters &

Bickis 1978, Sinclair & White 1980, Rees et al. 1994). Also, the generation time of insects in the field is significantly longer than the kernel maturity to harvest interval. Most insect infestations in commercial facilities occur after harvest and may originate on-site (Coombs & Freeman 1964, Barker & Smith 1987), from milling operations, seed plants, or uncleaned grain spillage (Sinclair & Adler 1984). Migration appears to be very important to insect infestations which arise in a facility. Most stored-product insects are good fliers (Dowdy 1994, Aslam et al. 1994), and storages have easy access points such as eaves and aeration fans.

Managers, using common protectants such as malathion, often do not know which insects they are attempting to control. Surveys by Cuperus et al. (1990) and Kenkel et al. (1993) revealed that elevator managers felt the major insect pest was the granary weevil. However, none were found during a sampling survey of on-farm and commercial storages during 1985-89 (Cuperus et al. 1990). Typical target insects included "bran bugs", "weevils", and "unknown" (Cuperus et al. 1986, Kenkel et al. 1993).

Fumigants such as phosphine kill only insect populations present at the time of fumigation. They are extremely volatile and possess no residual activity. A total of 73.1% of Oklahoma elevators fumigate their facilities after receipt of on-farm stored wheat (Kenkel et al. 1994). The commercial use of fumigants exceeds that of protectants in high-risk states like Oklahoma. Phosphine is by far the most widely used fumigant in all grain storages at 72.2% throughout the US and 82.1% in Oklahoma (Kenkel et al. 1993). Commercial operators utilize phosphine almost exclusively at 94% (Cuperus et al. 1990). Fumigations performed in September through November, when

insect populations peak, allow the lowest chance of reinfestation or damage as the grain begins to cool with the onset of winter (Cuperus et al. 1986, Epperly et al. 1987)

Only 87 of 1,020 respondents nationwide used trapping to detect insect infestations (Kenkel et al. 1994). Typical probe style traps are placed in the grain, left in place for a certain period of time, and removed to assess the number and type of insects present. Sticky flight traps are useful in detecting airborne insects migrating into a structure (Throne & Cline 1989, Dowdy & McGaughey 1994, Hagstrum et al. 1994).

Other pest management tools are used regularly in commercial facilities. Sanitation (sweeping and washing) and empty bin treatments reduce initial pest populations, protectants slow the immigration of insects into the structure, temperature management, grain cleaning, and aeration slow the population growth rate, and fumigants reduce insect populations to near zero. Essentially, the aim of non-chemical management tools is to reduce insect population development, thereby decreasing insect populations, losses, and the number of fumigations required.

Limited work on stored grain insect population dynamics has been done in commercial facilities (Reed et al. 1988, Reed et al. 1989). These facilities have been neglected, largely in favor of smaller on-farm and research structures. Non-commercial bins are generally easier to access and to control. Because effective management of stored grain insects requires thorough knowledge of their biologies and habitats (Hagstrum & Heid 1988), it may be inaccurate to extrapolate results of on-farm studies to larger commercial facilities.

Biological Control

Traditional methods of controlling insect pests in stored grain involve protectants and fumigants. Reliance on pesticides is favored for a variety of reasons: low cost, ease of application, difficulty of monitoring large bulks for insects, risk reduction, and the susceptibility of the commodity early in storage (Arthur 1994). Protectants, such as malathion, provide inexpensive, residual protection as the grain is binned or as a top dressing. Fumigants like the widely-used phosphine reduce existing insect populations to near zero and have no residual activity.

Recent trends toward an integrated pest management (IPM) approach in stored grain pest management has resulted from several factors. The increasing number of control failures due to insect resistance caused by the constant use or misuse of many pesticides coupled with insect exposure to sublethal doses (Arthur 1994, Collins 1994). Also, regulatory requirements of the EPA have caused cancellations of pesticides and decreased the ability of a registrant to recover developmental cost.

The development of insecticide resistance is not a recent occurrence. Many pesticides used against stored-product insects have lost or are losing their effectiveness. These insects acquire pesticide resistance from the selection pressure of high chemical application rates, number of applications, and high dosages. Multiple generations per year allow the most tolerant insects to survive to rapidly pass their resistance genes on to subsequent generations, resulting in increased control failure rates in grain storages. However, control failures, particularly with fumigants, may be partially caused by inadequate sealing of the structure prior to treatment. Zettler et al. (1989) concluded that

control failures of the common fumigant phosphine resulted from inefficient fumigation practices rather than resistance itself. Many elevator managers may overcompensate for the inability to seal a structure by overdosing (Zettler & Cuperus 1990). This practice may also contribute to insect resistance by exposing the insects to sublethal doses.

Insect resistance to the protectant malathion is widely documented (Haliscak & Beeman 1983, Herron 1990, Zettler & Cuperus 1990, Arthur & Zettler 1991). Newer, related protectants like chlorpyrifos-methyl and pirimphos-methyl are also showing early stage insect resistance (Beeman & Wright 1990, Arthur 1992). Resistance to phosphine has been detected in six stored grain insects, including *R. dominica* (Zettler et al. 1989, Herron 1990). In the United States, phosphine resistance is not yet widespread and resistance levels are low, however, it is only a matter of time until phosphine loses its effectiveness. Zettler & Cuperus (1990) screened 8 and 21 strains of *Tribolium castaneum* (Herbst) and *R. dominica* respectively collected from 61 storages in western Oklahoma. They found that one *T. castaneum* and 8 of 12 *R. dominica* strains were resistant to phosphine, with some having survival frequencies as high as 92% to discriminating doses. In addition to insect resistance, protectants in the organophosphate family tend to degrade upon exposure to high commodity temperature and moisture (Watters 1959, Strong & Subr 1960, Quinlan et al. 1979, Arthur et al. 1992, Collins 1994). In high-risk storage areas like Oklahoma, these conditions limit the effectiveness of these compounds particularly when coupled with the extended storage period before winter temperatures (Cuperus et al. 1986, Epperly et al. 1987).

Increasingly stringent EPA requirements for chemical controls is limiting the type

and number of pesticides available on the market mainly because developers cannot recoup costs if elevator managers are not purchasing a costlier, compliant product. Furthermore, many once widely used pesticides have or will be removed for sale. Methyl bromide, a common fumigant, will be phased out by the year 2001. Malathion will not be re-registered as a grain protectant in the US in its liquid formula (Arthur 1994) and it is possible that phosphine may ultimately be removed. The removal of phosphine from the market would have far-reaching effects. Elevator managers surveyed in 1992 by Kenkel et al. (1993) stated that there were no alternatives to phosphine. Modified atmospheres might be the next best "fumigation style" alternative. This technique utilizes gases such as carbon dioxide or nitrogen to kill insects. However, facility modifications needed in order to use this method are costly, which may prohibit smaller operations from using it. Managers would be more likely to use empty bin treatments, protectants, and temperature control to reduce insect populations. They could increase sampling at time of receipt or substantially discount infested grain. Increased use of aeration would help control insect problems, but again, installing an aeration system in facilities that do not have them is costly. A viable, non-toxic alternative to pesticides is biological control in the context of a well-balanced IPM program.

Many scientists are advocating multi-faceted IPM programs that emphasize alternative controls and reduced pesticide inputs. Sanitation, grain cleaning, aeration, monitoring, and biological control are all components of a complete IPM program. One aspect of this research is the determination of natural parasitoid populations and its relationship with its host.

Biological control involves the use of natural enemies, including parasitoids, predators, or pathogens to reduce an insect infestation to tolerable levels. The insect orders Hymenoptera, Coleoptera, and Hemiptera contain species which possess potential and actual abilities to decrease pest insect populations.

Biological control in the stored-product ecosystem is advantageous because no dangerous residues are left on the product. Biological control agents are harmless to humans and require no special knowledge or certification to apply. Additionally, they have great reproductive potential and may provide continued control with later generations (Brower et al. 1991).

Parasitic biocontrol agents usually have high host-specificities and might be ineffective if many pest species are present. Coupling a host-specific parasitoid with a polyphagous predator, or with other parasitoids having different host specificities can enhance pest suppression (Press et al. 1982, Brower & Press 1990, Brower et al. 1991). Biocontrol agents are slow-acting and do not provide the rapid, dramatic reductions in pest populations like pesticides. Frequent, massive releases of biocontrol agents may be required for effective control and can be expensive. However, as more commercial suppliers of biocontrol agents perfect mass-rearing techniques, prices are likely to decrease (Brower et al. 1991, Parker & Nilakhe 1990).

The FDA still has contamination of the product by parasitoid and predator insect parts labeled as "filth", which may impede their use in manufactured food products at milling plants, etc. Bulk-stored products can be cleaned to eliminate this contamination prior to any consequent processing (Brower et al. 1991).

Many species of beneficials naturally colonize grain storages, yet they seldom occur in numbers sufficient for effective control of a pest (Nilakhe & Parker 1990). Augmentation of naturally-occurring beneficial populations with lab-reared insects provides an increased probability of success partly due to the enclosed nature of the storage structure containing the beneficials.

Predators are effective in controlling various stored grain pests in laboratory and commercial experiments. They are limited in comparison to parasitoids because they are general feeders and attack a wide range of insects. A study by Press et al. (1982) compared the suppression abilities of two parasitoids and a predator. Wasps achieved 97% and 92.2% control while the predator had significantly less control at 78.3%. Although combined use of both has been successful (Keever et al. 1986), they can also be antagonistic as the predator may consume the parasitoid eggs (Parajulee & Philips 1994) as well as cannibalizing their own nymphs (Arbogast 1979). The relatively larger size of predators may limit their degree of penetration within the product. Press et al. (1978) found that *Xylocoris flavipes* (Reuter) did not penetrate into finely cracked material or dust. Pest insects occurring deeper in a compacted grain mass or in an area high in fines may be safe from predator attack.

Parasitoids are usually very host-specific and can forage deep within a grain mass. Most parasitoids in the order Hymenoptera are very small (1-2mm). Their host specificity is typically a narrow range within a certain genus or species. Most parasitoids attack the egg or larval stage in a one-to-one relationship. Parasitized pests ultimately die without damaging the commodity or the amount of damage is reduced considerably.

Two classifications of parasitoids exist: endoparasitoids and ectoparasitoids. This is based on where their eggs are deposited on the host. Endoparasitoids oviposit internally on a host, while ectoparasitoids affix their eggs externally. Parasitization occurs once an egg is laid on or in the host's egg or larva. Parasitoid larvae emerge and consume a portion of the host until their development is complete. The host does not develop and therefore does not damage the grain or reproduce.

Parasitoids alone have shown tremendous potential in studies on both the commercial and laboratory level. Brower (1988) released 3,000 *Trichogramma pretiosum* Riley weekly for 14 weeks into metal storages containing 200 kg of peanuts naturally infested with *P. interpunctella*. An average of 92.8 *P. interpunctella* per kg were found in the control bin while only 39.6 per kg remained in the bin treated with the parasitoid. Synergistic effects of two species of parasitoid were achieved when introduced together to control *P. interpunctella* than each alone (Brower & Press 1990). Flinn et al. (1994) effectively suppressed *R. dominica* in wheat with *Choetospila elegans* Westwood. After 198 d of storage, wheat in the control and treated bins averaged 2.06 and 0.05 *R. dominica* per kg.

Sampling/Monitoring

A complete and consistent monitoring program using trapping and sampling methods provides an early indication of potential stored grain insect infestations. Once detected, the developing population can be effectively managed in a timely fashion.

Many techniques are available for monitoring insects in bulk grain.

Conventionally, grain is sampled with a grain trier, deep cup probe, or vacuum probe upon receipt or after binning. These methods are useful in detecting population densities > 1 insect per kg (Wilkin 1990). Nevertheless, such densities pose potential risks to grain quality during storage and to grain acceptance during selling (Johnson 1979). Reliable monitoring systems for low-density insect populations would increase management options and reduce prophylactic grain treatment with pesticides. The grain trier, deep cup probe, and vacuum probe methods of sampling are all labor-intensive, increase costs (man-hours, equipment costs), and diminish the acceptance of a sampling program. These sampling methods have several problems associated with them: 1) they sample a small, statistically non-representative grain sample, 2) they are not left in the grain long enough (instantaneous sampling does not detect wandering insects) and, 3) the probes are not escape-proof (Loschiavo 1975, Loschiavo & Smith 1986, White & Loschiavo 1986). Sampling with this type of equipment may underestimate insect populations (Barak & Harein 1982). Pitfall traps, however, are more effective (at least 10x more so than sampling (Cogan & Wakefield 1987)) in detecting insect populations, particularly at low densities.

Initially, pitfall traps designed and tested by Loschiavo & Atkinson (1967, 1969, 1973) were perforated metal cylinders placed vertically into the grain into which the insects blundered. Their latest version (Loschiavo & Atkinson 1973) was modified by Barak & Harein (1982) with a threaded tip and downward-sloping perforations. This latest variant was marketed by Trécé, Inc. (Salinas, CA) as Storgard®. The current model, Storgard® WB Probe II™ (Trécé, Inc.; Salinas, CA), is an economical plastic

trap with larger perforations and a screw-tip collection reservoir.

Pitfall traps are more efficient for active insects because they are left in the grain and accumulate captured insects as opposed to traditional sampling devices. They are sensitive to low densities and detect wandering insects. The insects, once caught, die or are removed from the trap during inspection which may aid in regulating the size of the insect population and result in decreased grain damage (White & Loschiavo 1986).

Many factors influence insect catch in traps: insect species, trapping duration, grain temperature, grain type and condition, and trap location (Cuperus et al. 1990). Location of traps and insect density (Wright & Mills 1984, White & Loschiavo 1986), as well as type of storage structure, management practices, and areas with high fines (broken kernels, stems, dust, etc.) (White et al. 1990) act to govern insect populations. The non-uniform distribution of insects within grain bulks also affects trapping efficiency (Loschiavo 1975, Wright & Mills 1984, 1985; Loschiavo & Smith 1986).

Trapping efficiency varies for different insect species based on their biologies. For example, *C. ferrugineus* is a very active insect (Watters 1969, Smith 1972). Its wandering habits make it more catchable than *R. dominica* which tends to remain in one location (Subramanyam & Harein 1989)

Fargo et al. (1989) showed that the total number of insect species caught in pitfall traps increases significantly ($p \leq 0.05$) with trapping duration. However, this response varies with species. Catches of *C. ferrugineus* increased significantly with duration, while *R. dominica* did not. Thus, when all insect species are analyzed together, the net effect is an increase in trapping efficiency with trapping duration. This is because the positive

increase of *C. ferrugineus* catch overshadows the lack of increase of *R. dominica* catch with respect to trapping duration. It is thought that trapped insects release aggregation and sex pheromones that elevate trap attractiveness (Loschiavo 1974, Barak & Harein 1982), but the data of Fargo et al. (1989) do not support this hypothesis. Fargo et al. (1994) also showed the limited effectiveness of attractants and pheromones in influencing trap catch within a small wheat bulk.

Grain temperature, generally, is directly proportional to trap catch, although less active species like *R. dominica* do not fit this trend. Fargo et al. (1989) found that increased temperature resulted in significantly greater trap catch of mobile species like *C. ferrugineus*, but not for more stationary species such as *R. dominica*.

Many stored grain insects have aggregated distribution patterns that must be taken into account when sampling. Variation between two samples from the same location can be similar to samples from different bins with respect to insect numbers sampled (Hagstrum et al. 1985). Subramanyam & Harein (1990) obtained corresponding results with traps. Aggregated distributions are affected by moisture and temperature variations. *C. ferrugineus* is positively affected by temperature, moisture, and to a lesser degree by gravity (Surtees 1964, Watters 1969, Loschiavo 1983). These distribution patterns make trap catch very sensitive to trap placement. Information on species-specific dispersion patterns is required to understand how and where to sample or trap insects.

The amount of broken kernels and fines also influences insect movement and distribution. McGregor (1964) demonstrated that *T. castaneum* is attracted to fines. Moisture and fungi also affect insect distribution (Watters 1969, Dolinski & Loschiavo

1973, Storey et al. 1983). Areas of higher moisture, temperature, and molds usually occur in the center of the bin (Loschiavo 1975).

More research is needed in monitoring stored grain insect populations in order to ascertain optimal trap placement and the interpretation of insect catch to conclude if and when treatment is required.

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CHAPTER II

IMMIGRATION AND POPULATION DYNAMICS OF STORED GRAIN INSECTS

Abstract

This study focuses on the immigration and population dynamics of stored-wheat insects during the 1993-94 storage seasons in two commercial facilities in North Central Oklahoma. The objectives of this study were to determine the immigration patterns and population distributions of insect pests found in stored commercially-stored wheat in Oklahoma. Several key insects emerged: *Rhyzopertha dominica* (F.), *Cryptolestes* spp., *Typhaea stercorea* (L.) (Coleoptera: Bostrichidae, Cucujidae, Mycetophagidae) and *Cephalonomia waterstoni* (Gahan) (Hymenoptera: Bethylidae). Sticky flight traps placed internally and externally on each bin indicated that insects enter after harvest through the eaves and vents and congregate in the center of the grain mass. Insects caught in pitfall traps and deep cup probe samples supported this tendency of insect accumulation. Generally, insect population densities increased from the time of binning until peaking in August - September. Differences were found in grain moisture and temperature between different regions that may explain insect clustering in the center. More insects were caught in surface samples than at depths of 1 and 2m. Vacuum samples taken monthly at 3, 6 and 9m demonstrated that insects did not enter the structure from the bottom. The migration of insects into grain storages after binning is an important source of infestation at the commercial level because these facilities contain large quantities of grain, use less protectants, and are much larger then on-farm storages.

Introduction

The stored grain pests *Rhyzopertha dominica* (F.), *Typhaea stercorea* (L.), *Cryptolestes ferrugineus* (Stephens), and its parasitoid *Cephalonomia waterstoni* (Gahan) are known to occur in both farm and commercial level grain storages, but studies involving these insects usually take place in smaller on-farm or research storage structures. Although some experiments at the commercial level have been conducted, information is limited. Because the potential for commercial losses is great, the efficacious and timely management of pest populations is essential. A comprehensive trapping and/or sampling system to monitor insect population fluctuations is crucial. By sampling incoming grain, the facility manager can determine if insects arrive from infested on-farm storages and discount accordingly. The use of aerial traps coupled with probe traps in the grain mass provides an indication of when and what types of insects are immigrating into the structure and how they distribute themselves in the grain. These techniques can furnish the facility manager with adequate information to use in pest control decisions.

Oklahoma ranks third in the United States in wheat production and stores more than 250 million bushels annually of hard red winter wheat, *Triticum aestivum* (L.) (Cuperus et al. 1990, Kenkel et al. 1994). In Oklahoma, 36% of all wheat is stored on-farm and the remaining 64% is stored commercially (Anderson 1988).

Commercial elevator managers in Oklahoma ranked insects as the primary cause of grain damage, followed by molds, temperature, and moisture (Kenkel et al. 1993). Molds, temperature, moisture, storage time, and management practices interact to determine insect populations in stored grain. During harvest in Oklahoma, wheat

typically enters the bin at 30-40°C and 11-12% moisture (Cuperus et al. 1990) . This, coupled with a long storage period and the later onset of cooler ambient temperatures (Storey et al. 1979, Hagstrum & Heid 1988) places Oklahoma in a high-risk zone for potential insect infestations (Cuperus et al. 1990).

Oklahoma commercial storage facilities average 883,197 bushel capacities using three types of structures: steel (round), concrete, and steel (flat). Round steel bins are most prevalent in Oklahoma with 80.7% used at elevators followed by flat steel warehouses (73.3%) and concrete (38.5%). Steel structures, in general, have gained popularity due to lower construction costs and the ability to aerate. However, grain in steel structures is more difficult to turn and fumigate. Flat steel warehouses are the most difficult to fumigate due to the high surface area-to-volume ratio and the challenge of achieving an adequate seal, which results in increased control failure rates (Cuperus et al. 1990). Additionally, commercial facilities use less protectants than do on-farm storages.

In a survey of elevator managers in Oklahoma (Kenkel et al. 1993), 39% ranked insects as their primary management concern in post-harvest grain storage. They ranked specific insects in the following order: granary weevil (*Sitophilus granarius* (L.)), lesser grain borer *(Rhyzopertha dominica* (F.)), Indianmeal moth (*Plodia interpunctella* (Hubner)), and *Cryptolestes* spp. However, in grain samples taken from 30 on-farm and commercial bins per storage year 1982-88, no granary weevils occurred (Cuperus et al. 1986, Cuperus et al. 1990). The main pest species revealed was *R. dominica*, followed by *Cryptolestes* spp., *Tribolium* spp., and *P. interpunctella*, in order of potential destructiveness, though *Cryptolestes* spp. were first in abundance.

Insect infestations in stored grain originate not only from natural reservoirs (Linsley 1944) and rodent middens (Khare & Agrawal 1966), but also from on-site infestations in uncleaned grain spills (Sinclair & Adler 1984), seed mills, or empty granaries (Coombs & Freeman 1964, Barker & Smith 1987). We initially detected insects with flight traps well before harvest. After grain binning the numbers captured in flight traps increased due to the insect's attraction to volatiles emanating from the grain mass (Barrer 1983, Dowdy et al. 1993, Sedlacek & Weston 1995).

This study focuses on the population dynamics of *R. dominica* (lesser grain borer), *Cryptolestes* spp., and *Cephalonomia waterstoni* found in two commercial facilities in Oklahoma. *R. dominica* is a primary pest of stored wheat. This food source is probably a secondary adaptation because its original diet is dead wood (Potter 1935). This insect occurs in ant and rodent burrows feeding on stockpiled grain (Khare & Agrawal 1966). It can survive on fruits and seeds found in woodrat nests as recorded by Wright et al. (1990). *R. dominica* is a destructive and voracious consumer in both the larval and adult stages because it can chew through the hulls of sound kernels to feed internally on the endosperm. Often, only a hollowed-out shell remains after feeding by this insect. This initial feeding exposes more kernel surfaces to air, thus releasing more grain volatiles and serving to attract other primary and secondary grain pests (Sedlacek & Weston 1995).

Potter (1935) determined that the average developmental time from egg to adult at 26°C and 65% RH was 58 days. This time is inversely proportional to temperature as it took only 30-40d to complete one generation at 30°C and 30% RH. The female usually

lays 300-400 eggs over several weeks, typically in groups, or singly, among the kernels. Emergence occurs in 12-18d at 26°C, but this time decreases at 30°C. Newly emerged larvae bore into the grain where they feed for the remainder of their lives. The larvae pupate after 4-5 molts, and the adults emerge, mate, and continue feeding.

C. ferrugineus is a secondary pest of stored wheat that is usually found feeding under tree bark in nature (Linsley 1944). This cosmopolitan pest feeds in both the larval and adult stages. It consumes both the germ and endosperm (Rilett 1949a) of broken or cracked kernels, but cannot damage whole, sound grain. This beetle can also survive well on molds (Rilett 1949a, Loschiavo & Sinha 1966, Dolinski & Loschiavo 1973), dust, and fines (Sedlacek & Weston 1995). Molds, in particular, reduce mortality and developmental time of *C. ferrugineus* (Rilett 1949a). Fungi growing on kernels may provide nutritional supplements and expose germ and endosperm for feeding (Rilett 1949a, Dolinski & Loschiavo 1973).

Female *C. ferrugineus* deposit eggs in small cracks and crevices in the wheat kernels, or intergranular spaces by means of an extensible ovipositor (Rilett 1949a). One mated female lays an average of 2.54 eggs per day and the eggs hatch in 3-4 days. The larvae emerge and begin to search for food. The first through third instars feed internally on broken or damaged kernels, while the fourth is quite mobile as it searches for a pupation site (Rilett 1949a, Smith 1972). *C. ferrugineus* adults also have high locomotory abilities (Watters 1969).

Adults mate 1-2 days after emergence and oviposition ensues shortly after copulation. The adults consume broken kernels and dust but occasionally return to larval

burrows to consume previously exposed endosperm and germ (Rilett 1949a). The optimum developmental conditions for *C. ferrugineus,* and most other stored grain insects, are 25-33°C (Fields 1992) and ≥75% RH. However, as with *R. dominica*, *C. ferrugineus* displays decreased developmental time and mortality with increased temperature and moisture (within the optimal range) (Rilett 1949a).

R. dominica and *C. ferrugineus* are consistent infesters of commercially stored grain in Oklahoma (Cuperus et al. 1990). A parasitoid of *C. ferrugineus*, *Cephalonomia waterstoni* (Gahan), a bethylid wasp, is also present in wheat storages in Kansas, Australia, and Oklahoma (Schwitzgebel 1944, Sinclair 1982, Hagstrum 1987, Vela de Garza et al. 1993). The term parasitoid refers to a parasitic insect that belongs to the same taxonomic class as its host, typically has a 1:1 relationship with the host, and ultimately kills the host.

Cephalonomia waterstoni is a parasitoid whose host specificity is larval *C. ferrugineus*. It typically parasitizes fourth instars because they are actively search for a pupation site within the grain mass (Rilett 1949b, Smith 1972). First through third instars feed inside the kernel and are protected from attack. This wasp searches for larvae by following host kairomonal trails (Howard & Flinn 1990). Once a suitable host is found, the parasitoid grasps it with its mandibles and stings it into submission (Rilett 1949b, Finlayson 1950). Paralyzed, the larva is removed to a secluded oviposition site. Most commonly, one or two eggs, rarely up to four, are laid externally on the host's venter between or behind the metathoracic legs (Rilett 1949b, Finlayson 1950). At 90°F and 75% RH, a female wasp lays 1-3 eggs per day. The eggs hatch in 30 hrs. and the larvae

reach full size in 23 hrs. at this temperature. Newly emerged *C. waterstoni* larvae remain affixed to the host and consume haemolymph after piercing the host's cuticle. One *C. ferrugineus* larva provides enough nourishment for the complete development of two wasp larvae.

The objectives of this study are to: 1) determine the time and location of insect immigration into commercial grain storages and, 2) characterize the population dynamics of insects within these storages. Understanding these insects' biologies and population dynamics in commercial facilities provides a foundation from which to perform further experimentation. Knowledge of the manner in which stored grain insects immigrate into and distribute themselves within commercial storages can provide a basis for implementing an effective monitoring program.

Materials and Methods

Two commercial, steel bins located in Crescent and Kingfisher, Oklahoma, with capacities of ≈ 4,500 and 6,000 metric tons (total height of ≈ 18.4m and ≈ 21.5m) respectively and filled with hard red winter wheat, *Triticum aestivum* (L.), were used for this study. The bins were sampled during the storage years of 1993 and 1994. Before grain binning (Crescent: July 6, 1993 and June 28, 1994; Kingfisher: June 21, 1993 & 94), the bins were swept clean and the empty bins were fumigated with chloropicrin at recommended rates. During the 1993 storage year, the Crescent facility was only half-full.

Before the start of wheat harvest (June 9, 1993 and June 10, 1994), 20 unbaited flight traps (Phercon II; Trécé Inc., Salinas, CA) were attached to ropes exteriorly on the

bins in the cardinal directions. Each rope held five traps at the following heights: ground level, one-quarter bin height, one-half bin height, three-quarters bin height and outside eaves. The ropes ran through pulleys bolted through the roof eaves, for efficient trap replacement. After wheat binning (June 21 1993, June 21 1994), additional traps were placed inside the bins. In 1993, four traps per height, positioned in the cardinal directions, were placed both in the inner eaves and cap. In 1994, four traps per height were placed at the following heights: inner eave, vents at one-half bin radius, and in the cap. Inner eave and vent flight traps were affixed with magnetic clips. Cap traps were positioned beneath the center of the bin roof with a ≈ 6.0m length of 5cm diameter PVC pipe. The lower ≈ 3.0m of this pipe was inserted into the peak of the grain mass, while the upper end held a 1.2m square PVC pipe "X" (one trap placed distally on each "arm" of this "X").

Twelve plastic pitfall traps (Storgard WB II Probe traps; Trécé Inc., Salinas, CA) were placed in each bin after grain binning (July 6, June 21, 1993; June 28, 21, 1994). Three traps were placed in each cardinal direction at ≈1.5m from the bin wall, one-half bin radius and in the center of the bin. The four center traps formed the corners of a 1.5m x 1.5m square.

Removal of grain samples required a 2.0m deep cup probe with a brass cup (250 g capacity; Seedburo Equipment Co., Chicago, IL) at the 12 trap locations. Samples were removed at each trap location at three depths: two, one and zero meters from the surface. Two samples (≈500 g each), taken at each depth at each sampling site, resulted in 72 samples per bin per sampling date.

Vacuum probe samples occurred monthly (June 21, July 26, and September 13

(August 16 at Crescent) each year) at five locations in each bin: one in each cardinal direction (one-half bin radius) and one in the center. Two samples of ≈ 1-2 kg each were removed at 3.0, 6.0 and 9.0m below the grain surface at each sampling site in the grain mass, for a total of 30 samples per bin for each sampling date.

Sampling and collection of trap catch was completed weekly. Flight traps, deep cup probe samples, and pitfall trap catches were placed in labeled plastic bags and taken to the laboratory for processing. All insects caught in flight and pitfall traps were identified and counted. Deep cup and vacuum probe samples were processed over a modified incline sieve (White 1983) three times per sample to remove the insects from the grain. Insects were then identified and counted. All of the 1993 samples were weighed and moisture contents determined using an electronic balance (Ohaus Lume-O-Gram balance; Ohaus scale corp., Florham Park, NJ) and an hygrometer (Agromatic WK II; ASIDIC Ltd., Clear Lake, IA). All of the 1994 samples were weighed with an electronic balance (Fisher Scientific XD-8KD; Denver Instruments, Inc.; Denver, CO) and reweighed after baking for 24 hrs at 105°C in an oven (Fisher Isotemp® Oven, Model 438F; Fisher Scientific; Indiana, PA) to determine moisture content.

Twelve thermocouples, placed in the grain at the beginning of each sampling year and left for the duration of the sampling period, were used to record grain temperature at the time of sample collection. Temperatures were taken at the four cardinal directions and depths corresponding to the deep cup probe samples.

The Crescent facility was fumigated (≈ August 25, 1993 and ≈ August 30, 1994) due to high insect populations. However, the Kingfisher facility was sampled until

September of both years. At Crescent in 1994, the unforeseen removal of six truckloads of grain at the end of July resulted in an inverted cone rather than a peaked grain mass in our study bin. All of the center traps and thermocouples were irretrievably pulled into the grain mass, effectively disrupting established insect populations in this region. Sampling/trapping in the center was discontinued for the remainder of the 1994 season.

Insects captured in each of the trapping/sampling devices were analyzed using SAS Categorical Modeling (CATMOD) (SAS Institute, 1988) which employed a log-linear model to determine the causes of insect catch variation and to partition it into various sources. The SAS General Linear Models (GLM) (SAS Institute, 1988) was used to determine the sources of variation of the temperature and moistures readings taken throughout the grain mass.

Pearson product-moment correlations were calculated using the SAS correlation procedure (CORR) (SAS Institute, 1988) to determine the relationship between the number of insects captured and temperature and moisture content.

Results

Insect species captured: A variety of species representing five insect orders were detected: Coleoptera, Lepidoptera, Hymenoptera, Hemiptera, and Psocoptera. The Coleoptera were by far the most numerous: *Cryptolestes* spp. (Cucujidae: *C. ferrugineus*, rusty grain beetle; *C. pusillus* (Schönherr), flat grain beetle); *R. dominica*, lesser grain borer (Bostrichidae); *Tribolium castaneum*, red flour beetle (Herbst) (Tenebrionidae); *Typhaea stercorea* (L.), hairy fungus beetle (Mycetophagidae); *Ahasverus advena* (Waltl), foreign grain beetle (Cucujidae); *Cynaeus angustus* (Le Conte), larger black flour beetle

(Tenebrionidae); *Sitophilus oryzae* (L.), rice weevil (Curculionidae); *Tenebroides mauritanicus* (L.), cadelle (Trogossitidae); *Oryzaephilus surinamensis* (L.), sawtoothed grain beetle (Cucujidae); *Corticaria* spp. (Lathridiidae); and unidentified species of the family Anthicidae (Table 1). Occasionally, *Plodia interpunctella* (Hübner), Indianmeal moth (Lepidoptera: Pyralidae); *Xylocoris flavipes* (Reuter), warehouse pirate bug (Hemiptera: Anthocoridae); and *Liposcelis* spp. , booklice (Psocoptera: Liposcelidae) were detected. The most abundant beneficial was *Cephalonomia waterstoni* (Hymenoptera: Bethylidae).

The total and average capture rates, and the number of times detected of the most abundant of these insects are outlined in Table 1. The most abundant species captured in flight traps at both locations in 1993 and 1994 was *C. ferrugineus*, followed by *C. waterstoni* and *T. stercorea*. At both locations and years, *C. ferrugineus* and *T. stercorea* were caught in the highest numbers in the pitfall probe traps. The most abundant species sampled with the deep cup probes were *C. ferrugineus, R. dominica,* and *Tribolium* spp. at Kingfisher and *C. ferrugineus, C. waterstoni, O. surinamensis*, and *Tribolium* spp. at Crescent. *O. surinamensis*, and *Tribolium* spp. are secondary grain pests that do not damage whole, sound kernels, while *T. stercorea* is an incidental insect species that is not considered a problematic stored grain pest because it does not damage whole grain and is typically a fungivore. *S. oryzae*, the rice weevil, is a destructive primary pest but was only detected at low levels.

Temperature and Moisture Content: The temperatures measured in 1993 were analyzed with the PROC GLM procedure (SAS Institute, 1988) . The average

temperature at Kingfisher was 29.01 ± 7.59 °C and at Crescent 33.60 ± 6.24 °C (Fig. 1). Due to the large amount of variation in the temperature readings, the data were analyzed by location and julian date in order to obtain a model that fit well and to partition some of the variability caused by location and julian date in the original model. Generally, the main sources of variation in temperature were distance from wall and depth, indicating that temperatures are different at each level of each factor. The temperature data from 1994 were analyzed similarly. The average temperature at Kingfisher was 27.58 ± 4.75 °C and 19.18 ± 11.39 °C at Crescent (Fig. 2). Trends similar to the 1993 temperatures were evident with distance from wall and depth significant contributors to temperature variation.

The grain moisture data taken in 1993 were analyzed with the PROC GLM procedure (SAS Institute, 1988). The mean moisture content from deep cup probe samples in 1993 was 11.36 ± 1.24% at Kingfisher and 12.97 ± 1.19% at Crescent. Due to the large amount of variation in the moisture readings, the data were analyzed by location and julian date in order to obtain a model that fit well and to partition some of the variability caused by location and julian date in the original model. Moisture variations originated from many sources over the course of the sampling period. No single main effect or interaction stands out consistently during the storage period, although most sources responsible for moisture variation were significant. The mean moisture content from deep cup probe samples in 1994 was 8.78 ± 3.02% at Kingfisher and 10.02 ± 2.65% at Crescent. Like 1993, no single main effect or interaction stands out consistently during the storage period.

We used several trapping and sampling techniques in order to obtain our information on insect populations. The unbaited, sticky flight traps provided an early indication of which insects occurred in the vicinity of the storages prior to grain binning as well as immigration into the facility after harvest. The pitfall probe traps detected insect populations in the grain mass early in the storage season because of their sensitivity to low population levels. The deep cup probes provided an instantaneous measure of insect density in the grain, but did not detect insects until population levels rose. The vacuum samples that we removed enabled us to determine if insects entered the structure from the bottom plus the depth and extent of insect penetration into the grain mass.

Flight Traps: Flight traps provided the earliest indication of insect populations well before grain binning for both storage years and locations. During bin filling (began on ≈ June 9, 1993 and June 10, 1994), the overall flight trap catch increased, particularly in the outer eave traps and those located interiorly near the cap. During both storage years, insects caught in flight traps was greatest in the cap (Figs. 5, 6). *C. ferrugineus* was captured in the highest numbers at each location for both years with the exception of Kingfisher in 1993 where *Cephalonomia waterstoni* was most prevalent. *R. dominica* was captured the least of the three species (Figs. 3-5, 7).

R. dominica was the first insect captured each year (except at Kingfisher in 1993), usually well before the onset of harvest (Figs. 5, 7). *R. dominica* trap counts usually rose slightly as the storage year progressed and these insects most often appeared in exterior flight traps as well. This indicates that *R. dominica* immigrate into the structure, but few we detected flying inside the bin. This appears to demonstrate that this insect goes inside

the bin and immediately moves into the grain.

C. ferrugineus was initially detected on July 12, 1993 and June 14, 1994 at Kingfisher and June 21, 1993 and June 28, 1994 at Crescent. *C. waterstoni,* detected on July 12, 1993 and June 5, 1994 at Kingfisher and July 19, 1993 and July 5, 1994 at Crescent was generally caught after the first detection of its host, *C. ferrugineus* (Figs. 3, 4). Both *C. ferrugineus* and *C. waterstoni* numbers caught increased for both locations into mid to late August and decreased thereafter. The number of *R. dominica* caught stayed fairly constant throughout the sampling periods or increasing only marginally.

Most *T. stercorea* were captured exteriorly at both locations in 1993. More of these insects were detected in 1994 interiorly compared with the 1993 trap catches (Figs. 6, 8).

For both years and sampling locations, trap height had a highly significant effect with respect to trap catch for all species. The only exception is *R. dominica* caught in 1993 (df=6, χ^2=10.38, p=0.1097) (Table 2), most likely due to the fact that this insect immigrates into the structure and does not fly around inside the bin.

There were no significant directional effects on insect capture for any of the insects in 1994, but direction did affect flight trap catch in 1993 for *C. waterstoni* (df=3, χ^2=13.08, p=0.0045) as did trap height (df=6, χ^2= 25.09, p=0.0003) (Table 3) and *C. ferrugineus* (Table 4). This is probably the result of the random flight vectors of the insects toward the grain mass as well as fluctuations in trap catch based on wind speed and direction. *C. ferrugineus* was analyzed by height due to a highly significant trap height effect in the original analysis.

Location and trap height were the significant main effects influencing the capture of *R. dominica* in 1994 (Table 5). Most of these insects were captured in the exterior traps as they moved into the bin, but few appeared in the traps inside the bin. Again, *R. dominica* establishes residency rapidly after entering the structure.

Trap height and location also had a significant effect on *Cephalonomia waterstoni* in 1994 (Table 6), and *C. ferrugineus* capture rates in 1994 (Table 7). More of these insects were captured inside (highest trap heights) because they are mobile and fly within the bin after immigrating.

Pitfall Traps: Pitfall traps did not detect any insects during the first week of trapping in 1993 at Kingfisher (June 21) or Crescent (July 6). However, traps detected *C. ferrugineus* in small numbers at both locations during the first week of sampling in 1994: Kingfisher (June 21), Crescent (June 28) (Figs. 9, 10).

C. ferrugineus and *Cephalonomia waterstoni* were found in pitfall traps from August 2-16, 1993 at Crescent and increased steadily. On August 23 (the last sampling date), trap catch dropped sharply (Fig. 10), possibly due in part to decreasing grain temperatures after August 2. Only two *R. dominica* were trapped during the sampling period, one on August 2 and the other on August 23. At Kingfisher in 1993, all three insect species' trap counts increased from August 2 through September 7, at which point the trap counts decreased until the final sampling date on September 20 (Fig. 9). At Crescent in 1994, *C. ferrugineus* trap catch rose steadily from June 28 to peak on August 2 and gradually declined thereafter until August 16 (last sampling date) (Fig. 10). The Crescent *C. waterstoni* counts in 1994 were sporadic throughout the season until

peaking sharply on August 16 (Fig. 10). After initial detection of *R. dominica* on July 5, 1994, its trap counts experienced two moderate peaks on August 2 and August 16 (Fig. 10). At Kingfisher, both *C. ferrugineus* and *C. waterstoni* trap counts escalated until cresting on August 30 (Fig. 9). *R. dominica* counts peaked on September 6 and decreased thereafter. *C. ferrugineus* was the most abundant insect followed by *C. waterstoni*, and *R. dominica*.

Large populations of *T. stercorea* were detected with pitfall traps at both locations during both sampling years. They appeared to cluster either near the bin wall or the center of the bin (Figs. 11, 12) and the populations fluctuated greatly during the sampling period. These growth spikes usually occurred after precipitation, which may account for the erratic population trends.

The 1993 *R. dominica* data was analyzed only for Kingfisher. Kingfisher had significant directional, distance from wall, and direction by distance from wall effects and tended to aggregate in the center of the bin at both locations (Figs. 13, 14).

For the pitfall counts of *C. ferrugineus* and *C. waterstoni* in 1993, the data was analyzed by location and distance from wall in order to attempt to separate the variation. There was a highly significant directional effect on trap catch at every level of location and trap distance from the wall (Tables 8, 10). Frequency tables calculated (Tables 9, 11) show the inconsistent nature of the counts with respect to direction at each level of distance from wall between locations. Both of these insects seemed to accumulate in areas of the grain near the bin's center (Figs. 15-18).

R. dominica displayed a distance-from-wall effect in addition to location by

distance-from-wall and direction by distance-from-wall interactive effects on the variation seen in the trap counts in 1994 (Table 12). The location and distance from wall effects are separated in Figs. 9 and 10.

The data for *C. waterstoni* from 1994 a strong locational effect (df=1, χ^2= 6.72, p=0.0096) (Table 13) and this strong effect may be partially responsible for the significant location by direction and location by distance from wall interactive effects on trap catch. *C. waterstoni* was captured most often in the center (Figs. 17, 18) where the most *C. ferrugineus* were caught as well (Fig. 15, 16).

The pitfall counts of *C. ferrugineus* in 1994, were analyzed by location and distance from wall in order to attempt to elucidate causes of variation. There was a highly significant directional effect on trap catch at every level of location and trap distance from the wall (Table 14). The insects preferred the center of the bin at Kingfisher (Fig. 15).

Deep Cup Probes: The deep cup probe samples detected insects much later than did the pitfall probe traps. They are not as sensitive as pitfalls and began to detect insects after the populations increased sufficiently to raise the probability of discovery. *C. ferrugineus* was usually captured first because it reached higher population densities faster than did the other insects and it has significant locomotory abilities (Figs. 19, 20). Approximately 1-4 weeks later we began capturing more *R. dominica* and *C. waterstoni*.

The analysis of *R. dominica* captured in deep cup probes in 1993 indicates significant ($p<0.05$) directional and distance from wall effects (Table 15). A significant ($p<0.05$) location by temperature interactive effect exhibits the sample variation

differences between the locations for each level of temperature meaning that temperatures differ by location.

C. waterstoni captured in deep cup probes in 1993 showed significant ($p<0.05$) depth and temperature effects on insect populations as well as a location by direction interactive effect, probably due mainly to the differences between the locations rather than direction alone (Table 16).

Because of the differences seen in the *C. ferrugineus* populations between sampling locations, the data for Kingfisher and Crescent were analyzed separately for deep cups in 1993. The Crescent data did not show any significant effects by the independent variables (Table 17), although the insects tended to congregate in the center of the bin (Fig. 18). The Kingfisher data only showed temperature to have a highly significant ($p=0.0004$) effect and a significant ($p=0.0437$) three-way interaction among direction, distance from wall, and depth (Table 18). The early morning moderate temperatures probably do not provide an indication of insect temperature preference with respect to maximum daily temperatures in the region. The three-way interaction tells us that *C. ferrugineus* populations sampled vary at each level of depth and distance from wall in all cardinal directions, most likely due to large, variable *C. ferrugineus* populations. Figures 23 and 24 show the tendencies of these populations with respect to location and distance from wall.

The analysis of *R. dominica* captured in deep cup probes in 1994 indicates strong main effects of location, distance from wall, and depth ($p=0.0000$ for all) (Table 19). The significant interactive effects of location by temperature and location by distance from wall

may be due to the strong location and distance from wall main effects creating significance in the interaction. *R. dominica* displayed a tendency to aggregate near the center at each location (Figs. 21, 22).

C. waterstoni captured in deep cup probes in 1994 showed significant depth ($p=0.0000$) and distance from wall ($p=0.0103$) main effects on insect populations as well as a location by temperature interactive effect($p=0.0067$) (Table 20). The occurrence of more *C. waterstoni* at the center of the bins is detailed in Figures 25 and 26. However, most of the variation is probably due to the disparate numbers of *C. waterstoni* captured at each location.

The *C. ferrugineus* deep cup catch in 1994 showed no significant effects of any type in the analysis (Table 21). The sample capture by location and distance from wall showed that the populations tended to clump in the center of the bin at Kingfisher (Fig. 25).

The expected trend of insects migrating deeper into the grain mass over time only occurred consistently in samples removed from Kingfisher in 1993 (Fig. 27). Other sampling locations and years displayed this trend, but not clearly, which may be due to the instantaneous sampling nature of the deep cup coupled with the locomotory abilities inherent in each species of insect.

The *T. stercorea* populations detected with deep cup probes tended to be near the surface of the grain mass (Fig. 28). Whenever we sampled these insects, we found them in the uppermost regions of the grain.

Vacuum Probes: During the entire two-year study, we removed approximately 180

vacuum probe samples of ≈1-2 kg. each in which we found 173 insects total, usually in the samples at 3.0 and 6.0m (Table 22). Clearly, this is strong evidence that no insects are entering the structure through the bottom of the bin. Any insects found at this depth are most likely emigrants of the existing populations on the grains' surface that have migrated deeper into the grain mass. This data reinforces the concept that stored grain insects generally confine their activities to the upper regions of large bulks of grain.

Correlation coefficients associating temperature, moisture content, and insects captured by trap type with one another are shown in Tables 23-26. There are no obvious trends, so only highlights will be elucidated. The largest positive coefficient of 0.44669 related *R. dominica* capture in deep cup probes to pitfall traps and the largest negative coefficient of -0.43387 related *R. dominica* capture in pitfall traps to temperature and both values were significantly ($p < 0.05$) different from zero. Generally, there was no consistent correlation trends (positive or negative) with respect to a particular insect capture frequency in one trap type versus another or with insect capture frequency correlated with moisture or temperature. All correlation coefficients were typically weakly positive or weakly negative.

Discussion

Cuperus et al. (1986), using grain trier and deep cup probe samples, found the most abundant grain insects in stored wheat in Oklahoma were the lesser grain borer, rice weevil, *Cryptolestes* spp., *Tribolium* spp., and the sawtoothed grain beetle. In contrast, this study demonstrates that *Cryptolestes* spp. were the most numerous, followed by *T. stercorea*, *Tribolium* spp., *C. waterstoni*, *O. surinamensis*, and *R. dominica*. This may be

because the *Cryptolestes* spp. are more mobile and have a shorter generation time than the other insects. They also may prefer the conditions found in the commercial storages during the course of this study. Also, the studies by Cuperus et al. (1986, 1990) used only standard sampling methods (deep cup probes and grain triers) and did not use trapping devices. The hairy fungus beetles, although numerous, prefer moister conditions conducive to mold growth and their populations increased and decreased in a dramatic fashion, possibly in response to precipitation. As fungivores, they were most likely incidentals that existed transiently in the grain mass. The parasitoid *C. waterstoni* was most abundant in flight traps and was not captured in large numbers in pitfall traps or deep cup probe samples. This could be due to the fact that they follow larval *C. ferrugineus* through the grain mass and are not attracted to adults trapped in the pitfall probes. The *R. dominica*, were clumped in distribution and do not move much through the grain mass, thus we did not detect many with pitfall probes. They were detected with deep cup probes also, particularly if the sample was removed near a region of *R. dominica* aggregation. The *Tribolium* spp. and occurred in large numbers in pitfall probes at Kingfisher and were the most abundant non-focus insect captured in deep cup probes there as well. *O. surinamensis* was most abundant non-focus insect captured in pitfall traps and deep cup probes at Crescent .

Flight traps placed in the outer eaves, inner eaves, vents, and cap typically caught more insects because the top of the bin is accessible to immigrating insects. Insects were detected in small numbers before grain was binned, indicating their presence in the area, probably due to random interception of flying insects or insects being carried by the wind.

Flight traps were placed interiorly in each bin after harvest and immediately began detecting greater numbers of insects, demonstrating the rapid immigration of insects into the facility after binning (July 6, June 21, 1993; June 28, 21, 1994 for Crescent and Kingfisher, respectively).

Different insect species exhibited dissimilar trapping frequenices based on trap location. Because the flight traps were unbaited, the insects captured were not responding to the trap attractiveness. The factors affecting trap catch were probably the orientation of the insects toward the grain mass, distance of insect populations from the facility, characteristic flight behavior of each species, wind speed and direction, and weather conditions. More *R. dominica* were captured in exterior flight traps. Once inside the structure, the *R. dominica* populations seemed to settle quickly into the grain mass and did not fly extensively within the bin. In contrast, *C. ferrugineus* and *C. waterstoni* immigration was detected in the exterior traps and greater numbers were caught inside the structure. These insects have a higher locomotory behavior than does *R. dominica*, and appeared to continually redistribute themselves within the bin during the course of the trapping period each year. Perhaps they were constantly moving within the bin as they searched for a more favorable food source or less crowded area to inhabit. Additionally, the confined space within the bins is likely to have a more homogeneous density of insects in flight than open areas outside the bin (Leos-Martínez et al. 1986).

Pitfall traps detected insects during the first week of placement in the grain mass at Crescent on August 2, 1993 and June 28, 1994 and at Kingfisher on June 28, 1993 and June 21, 1994. Usually, *C. ferrugineus* was captured first, followed by either *R. dominica*

or *C. waterstoni*. As time progressed, the numbers of insects captured increased until peaking in August or September, depending on the facility. Definite trends are discernible with respect to the insects trapped at different trap distances from the bin wall, although these trends aren't consistent for each insect species (with the exception of *R. dominica*) for each bin location and trapping year. *R. dominica* were captured most in the center, followed by ½ bin radius and the bin wall at both locations in 1993 and at Kingfisher in 1994. This may be due to the assumed accumulation of a higher density of easily consumable broken and cracked kernels along the spout line in the center of the bin. Temperatures and moistures did vary by distance from wall, which may aid in explaining insect aggregation in the center of the bin , which is attractive to the insects (Surtees 1965, Loschiavo 1983, Fargo et al. 1989). On average, the temperatures in the center of the bin were not or were only slightly greater than other locations in the bin. However, initial surface temperature averages were minimally larger than those at other depths, typically early in the storage year after which they undergo a leveling. This, coupled with more "trash" along the spout line may account for the higher insect populations.

C. ferrugineus and *C. waterstoni* trap catch varied considerably with respect to trap location. At Crescent in 1993 and at Kingfisher in 1994, *C. ferrugineus* populations were most abundant in the center . At Kingfisher in 1993, the traps near the bin wall captured the most insects. Again, the removal of grain at Crescent in 1994 radically altered insect population, so caution must be used in interpreting these results. *C. waterstoni* displayed consistent trends both years at both locations, with the majority being captured in the center of the bin.

Commonly, the trap catch of *C. ferrugineus* and *C. waterstoni* exceeded that of *R. dominica* at each level of trap distance from wall by a large margin. This is due to the shorter developmental time and greater fecundity of these two insects compared to *R. dominica*. When examining the trap catch of these insects by direction, no consistent trends are evident.

Evidence indicates that insect infestation of stored grain occurs after grain binning and initial infestation occurs in the top layer of grain and that the insects gradually move downward into the grain mass over time (Vela de Garza 1993). Hagstrum (1989) documented this trend with *C. ferrugineus* infesting newly stored wheat. During the first several weeks of sampling with deep cup probes, we caught very few or no insects. In mid to late July of both years we began detecting *C. ferrugineus* and, shortly thereafter, *C. waterstoni*.

The expected trend of insects migrating deeper into the grain mass over time was conspicuous at Kingfisher in 1993 for all insect species. The insects captured in deep cup samples on the grain surface contained more insects than those taken at 1 or 2m in mid August (initial detection of insects with deep cups). Near the end of the sampling, we observed a slight decrease (except with *C. waterstoni*) in the surface samples, while insects captured in samples at 1 and 2m increased steadily during this time. However, this trend was inconsistent, most likely due to the instantaneous sampling nature of the deep cup probe itself. The deep cup is not sensitive to lower population densities and would require more samples per bin in order to attempt to discern any trend.

We captured the majority of *T. stercorea* near the surface of the grain mass (Fig.

28) at various distances from the bin wall. These insects are slightly larger than any other insect we detected, thus may have decreased ability to successfully move down into the grain mass. Also, the fungus and detritus that this insects feeds on are most easily found and consumed at the surface of the grain.

Insect counts for both pitfall probe traps and deep cup probe samples indicate that insects tend to congregate in the center of the grain mass and usually restrict themselves to the surface of the grain mass, at least initially. Temperature and moisture are influential in insect distribution (Surtees 1965) and affect insect capture (Loschiavo 1983, Fargo et al. 1989). The temperature and moistures did differ from other regions in the grain in our investigation. The temperature usually varied slightly, but consistently, by distance from wall and depth over the course of time, with the warmer temperature occurring on the surface initially. Near the end of the sampling periods the average temperatures inverted and the deeper regions were warmer. The moistures varied at virtually every level of depth, direction, and distance from wall during the course of the study.

Most correlation coefficients relating deep cup catch with pitfall trap catch were positive, and many were significantly different from zero. This provides evidence that the number of insects caught in deep cups and pitfall traps are related. One consistent trend appeared when correlating deep cup or pitfall trap catch with flight trap capture during both years at both locations - *R. dominica* did not appear related, while both *C. ferrugineus* and *C. waterstoni* had positive coefficients. This demonstrates that flight trap catch appeared to be an indicator of the relative population level of these two insects within the grain mass as shown by the deep cup and pitfall captures. Though *R. dominica*

is picked up by flight traps as it immigrates into the bin, it is more difficult to detect in the grain because it is relatively stationary and aggregates, which may partially explain the non-significant negative correlation coefficients.

In conclusion, immigration by stored grain insects into bins after harvest is probably the most important source of infestation in commercial facilities. These insects are present in the area well before grain harvest, either in natural reservoirs or in on-site infestations in uncleaned grain spillage, seed plants, etc. Once the grain is binned, these insects are attracted by the aromatic volatiles of the grain and/or aggregation pheromones exuded by insects that arrived very early in the grain storage process. We found the sticky flight traps useful in detecting insects as they immigrated into the structure and for monitoring redistribution inside the bin. The pitfall probes traps provided an early indication of insect populations in the grain mass because they are sensitive to low insect densities. The deep cup probe was useful because, although not responsive to low insect populations, it provided a measure of actual density which allowed us to determine relative infestation levels.

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Table 1 . Total and average number of insects captured by trap type for Kingfisher and Crescent in 1993-1994

Species	Flight traps			Pitfall traps			Deep cup probes		
	N[a]	Avg.[b]	Total[c]	N	Avg.	Total	N	Avg.	Total
Kingfisher 1993									
C. ferrugineus	130	212.4	3398	95	2240.7	29129	103	13.4	187
R. dominica	11	1.1	18	27	16.9	220	47	6.1	85
C. waterstoni	160	96.2	1539	23	125.6	1633	53	8.3	116
T. stercorea	66	14.1	268	79	328.6	4600	5	0	0
Tribolium spp.	0	0	0	89	189.5	2653	35	3.3	46
O. surinamensis	0	0	0	81	33.4	467	1	0.1	2
A. advena	15	2.1	32	13	5.3	74	3	0.4	5
Anthicidae	1	0.07	1	18	2.9	40	0	0	0
C. angustus	0	0	0	8	1.7	24	0	0	0
Corticaria spp.	0	0	0	0	0	0	0	0	0
S. oryzae	1	0.07	1	1	0.07	1	0	0	0
Kingfisher 1994									
C. ferrugineus	80	9.8	176	155	532.9	6928	26	2.6	37
R. dominica	32	3.3	59	9	1.2	16	24	3.2	45
C. waterstoni	90	9.2	166	23	5.0	65	6	0.6	9
T. stercorea	111	14.1	253	153	1163.8	15129	5	0.4	6
Tribolium spp.	20	1.5	25	130	460.8	5990	43	4.5	63
O. surinamensis	1	0.06	1	47	13.8	179	1	0.07	1
A. advena	0	0	0	6	1.0	13	0	0	0
Anthicidae	6	0.4	6	53	32.7	425	1	0.07	1

Table 1. Total and average number of insects captured by trap type for Kingfisher and Crescent in 1993-1994

C. angustus	0	0	0	21	3.9	50	0	0	0
Corticaria spp.	10	1.4	24	21	6.2	80	0	0	0
S. oryzae	4	0.18	4	6	0.5	7	4	0.3	4
Crescent 1993									
C. ferrugineus	60	58.7	704	48	6532.3	45761	145	43.6	349
R. dominica	12	1.1	13	2	0.3	2	1	0.3	2
C. waterstoni	40	12.6	151	25	55.9	391	31	8.4	67
T. stercorea	47	42.3	694	46	539.3	4854	11	1.9	15
Tribolium spp.	0	0	0	5	36.8	331	1	0.13	1
O. surinamensis	4	0.5	5	32	75.4	679	14	1.9	15
A. advena	18	3.7	41	6	1.4	13	0	0	0
Anthicidae	2	0.7	8	42	57.3	516	0	0	0
C. angustus	0	0	0	19	11.1	100	0	0	0
Corticaria spp.	7	1.2	13	24	29.1	262	0	0	0
S. oryzae	0	0	0	1	0.1	1	1	0.13	1
Crescent 1994									
C. ferrugineus	67	3.5	451	80	2728.4	21827	52	11	99
R. dominica	14	1.4	19	21	8.8	70	17	4.6	41
C. waterstoni	41	7.2	101	10	5.5	44	23	0.02	26
T. stercorea	43	6.4	89	80	4216.3	33730	13	1.4	13
Tribolium spp.	2	0.15	2	44	40.5	324	4	0.3	4
O. surinamensis	3	0.2	3	47	33.5	269	11	1.4	13
A. advena	0	0	0	9	6.1	49	2	0.3	3

Table 1. Total and average number of insects captured by trap type for Kingfisher and Crescent in 1993-1994

Anthicidae	0	0	0	32	13.8	110	1	0.1	1
C. angustus	0	0	0	55	129.3	1034	1	0.1	1
Corticaria spp.	1	0.1	1	6	1.0	8	0	0	0
S. oryzae	3	0.2	3	45	27.5	220	2	0.3	3

[a] Number of times each species was detected

[b] Average number of insects captured per sampling date

[c] Total number of insects captured during the sampling period

Table 2. Maximum likelihood analysis of variance of *R. dominica* captured in flight traps at Kingfisher and Crescent in 1993.

Source	df	χ^2	*P*
Location	1	0.29	0.5905
Direction	3	0.18	0.9808
Height	6	10.38	0.1097
Location * Direction	3	7.40	0.0603
Likelihood ratio	42	9.52	1.0000

Table 3. Maximum likelihood analysis of variance of *C. waterstoni* captured in flight traps at Kingfisher and Crescent in 1993

Source	df	χ^2	*P*
Location	1	22.59	0.0000
Direction	3	13.08	0.0045
Location * Direction	3	2.84	0.4167
Height	6	25.09	0.0003
Location * Height	6	11.11	0.0849
Direction * Height	18	66.73	0.0000
Loc * Dir * Height	12	60.85	0.0000
Likelihood ratio	0	.	.

Table 4. Maximum likelihood analysis of variance of *C. ferrugineus* captured in flight traps at Kingfisher and Crescent in 1993

	Source								
	Location			Direction			Location * Direction		
Height	df	χ^2	*P*	df	χ^2	*P*	df	χ^2	*P*
Base	1	5.05	0.025	3	32.70	0.0000	3	11.29	0.0103
¼ bin	1	2.69	0.1011	3	51.95	0.0000	3	1.99	0.5749
½ bin	1	5.62	0.0000	3	29.63	0.0000	3	28.47	0.0000
¾ bin	1	15.67	0.0001	3	69.91	0.0000	3	20.64	0.0001
O. eave	1	4.44	0.035	3	80.55	0.0000	3	11.84	0.0079
I. eave	1	3.69	0.0548	3	4.03	0.2579	3	3.23	0.3571
Cap	1	155.9	0.0000	3	27.85	0.0000	3	83.5	0.0000

Table 5. Maximum likelihood analysis of variance of *R. dominica* captured in flight traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	4.33	0.0374
Direction	3	0.15	0.9856
Height	7	16.02	0.0249
Loc * Dir	3	7.34	0.0617
Loc * Height	7	9.94	0.1922
Dir * Height	21	20.06	0.5175
Likelihood ratio	21	17.95	0.6520

Table 6. Maximum likelihood analysis of variance of *C. waterstoni* captured in flight traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	8.03	0.0046
Direction	3	5.38	0.1458
Height	7	111.76	0.0000
Loc * Dir	3	5.60	0.1329
Loc * Height	7	9.42	0.2242
Dir * Height	21	33.38	0.0422
Likelihood ratio	21	24.21	0.2832

Table 7. Maximum likelihood analysis of variance of *C. ferrugineus* captured in flight traps at Kingfisher and Crescent in 1994

Source	df	$\chi 2$	*P*
Location	1	0.00	0.9828
Direction	3	5.32	0.1497
Height	7	367.88	0.0000
Loc * Dir	3	2.90	0.4076
Loc * Height	7	61.37	0.0000
Dir * Height	21	34.14	0.035
Likelihood ratio	21	26.78	0.1784

Table 8. Maximum likelihood analysis of variance of *C. waterstoni* captured in pitfall traps at Kingfisher and Crescent in 1993

By group	Source	df	χ^2	*P*
DFW1-K	Direction	3	58.24	0.0000
DFW2-K	Direction	3	117.21	0.0000
DFW3-K	Direction	3	240.08	0.0000
DFW1-C	Direction	3	14.18	0.0027
DFW2-C	Direction	3	64.02	0.0000
DFW3-C	Direction	3	102.52	0.0000

Table 9. ***C. waterstoni*** **capture frequencies by direction and distance from wall in pitfall traps at Kingfisher and Crescent in 1993**

Location	Bin wall	½ Bin radius	Center
Kingfisher			
North	110	35	69
East	51	52	92
South	129	169	348
West	169	151	257
Crescent			
North	28	8	105
East	30	55	10
South	18	73	30
West	7	5	21

Table 10. Maximum likelihood analysis of variance of *C. ferrugineus* captured in pitfall traps at Kingfisher and Crescent in 1993

By group	Source	df	$\chi 2$	*P*
DFW1-K	Direction	3	158.02	0.0000
DFW2-K	Direction	3	63.74	0.0000
DFW3-K	Direction	3	122.41	0.0000
DFW1-C	Direction	3	535.27	0.0000
DFW2-C	Direction	3	240.05	0.0000
DFW3-C	Direction	3	32.81	0.0000

Table 11. ***C. ferrugineus*** **capture frequencies by direction and distance from wall in pitfall traps at Kingfisher and Crescent in 1993**

Location	Bin wall	½ Bin radius	Center
Kingfisher			
North	3046	1382	2024
East	3515	997	2333
South	3290	1260	2753
West	4051	1248	2570
Crescent			
North	2569	1784	4769
East	2042	2539	4708
South	1174	1618	4273
West	2362	2006	4514

Table 12. Maximum likelihood analysis of variance of *R. dominica* captured in pitfall traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	1.27	0.2589
Direction	3	7.55	0.0563
Loc * Dir	3	5.01	0.1707
Dist. from Wall	2	6.80	0.0335
Loc * DFW	2	21.87	0.0000
Dir * DFW	6	32.12	0.0000
Likelihood ratio	6	6.24	0.3964

Table 13. Maximum likelihood analysis of variance of *C. waterstoni* captured in pitfall traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	6.72	0.0096
Direction	3	5.68	0.128
Loc * Dir	3	14.97	0.0018
Dist. from Wall	2	3.74	0.1543
Loc * DFW	2	17.42	0.0002
Dir * DFW	6	12.35	0.0546
Likelihood ratio	6	5.83	0.442

Table 14. Maximum likelihood analysis of variance of *C. ferrugineus* captured in pitfall traps at Kingfisher and Crescent in 1994

By group	Source	df	χ^2	*P*
DFW1-K	Direction	3	232.91	0.0000
DFW2-K	Direction	3	163.68	0.0000
DFW3-K	Direction	3	490.94	0.0000
DFW1-C	Direction	3	536.1	0.0000
DFW2-C	Direction	3	313.22	0.0000
DFW3-C	Direction	3	54.11	0.0000

Table 15. Maximum likelihood analysis of variance for *R. dominica* captured in deep cup probes at Kingfisher and Crescent in 1993

Source	df	χ^2	*P*
Location	1	0.81	0.3677
Direction	3	9.86	0.0198
Dist. from wall	1	4.84	0.0278
Temperature	2	3.02	0.2207
Loc * Temp	2	6.92	0.0314
Likelihood ratio	97	26.41	1.0000

Table 16. Maximum likelihood analysis of variance for *C. waterstoni* captured in deep cup probes at Kingfisher and Crescent in 1993

Source	df	χ^2	*P*
Location	1	1.09	0.2973
Direction	3	3.29	0.3493
Dist. from wall	1	3.68	0.0550
Depth	2	7.19	0.0274
Temperature	2	22.25	0.0000
Loc * Dir	3	14.98	0.0018
Loc * Temp	2	5.06	0.0795
DFW * Depth	2	4.89	0.0869
Likelihood ratio	90	59.65	0.9943

Table 17. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Crescent, 1993

Source	df	χ^2	*P*
Dist. from wall	1	3.34	0.0675
Depth	2	3.62	0.1633
Temperature	2	3.45	0.0633
Temp * Depth	2	2.44	0.2945
Likelihood ratio	39	24.85	0.9620

Table 18. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Kingfisher, 1993

Source	df	χ^2	*P*
Temperature	2	15.89	0.0004
Direction	3	4.65	0.1996
Temp * Dir	4	5.90	0.2065
Dist. from wall	1	0.88	0.3493
Temp * DFW	2	2.17	0.3385
Dir * DFW	3	4.27	0.2338
Temp*Dir*DFW	3	4.90	0.1795
Depth	2	3.66	0.1601
Temp*Dir*Depth	12	13.57	0.3291
DFW * Depth	2	4.24	0.1198
Dir*DFW*Depth	6	12.96	0.0437
Likelihood ratio	12	3.64	0.9891

Table 19. Maximum likelihood analysis of variance for *R. dominica* captured in deep cup probes at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	107.84	0.0000
Dist. from wall	2	142.09	0.0000
Depth	2	42.22	0.0000
Temperature	1	3.28	0.1942
Loc * Temp	1	62.38	0.0000
Loc * DFW	2	50.27	0.0000
Temp * Depth	2	0.19	0.9114
Likelihood ratio	111	8.25	1.0000

Table 20. Maximum likelihood analysis of variance for *C. waterstoni* captured in deep cup probes at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	0.23	0.6288
Dist. from wall	2	9.15	0.0103
Depth	2	41.60	0.0000
Temperature	1	1.04	0.3076
Loc * Temp	1	17.60	0.0000
Temp * Dir	3	12.20	0.0067
Temp * DFW	2	9.21	0.0100
Dir * DFW	6	12.87	0.0451
Likelihood ratio	106	41.72	1.0000

Table 21. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	1.83	0.1758
Temperature	1	2.85	0.0913
Loc * Temp	1	1.40	0.2361
Loc * DFW	2	5.47	0.065
Temp * DFW	2	4.16	0.1247
Likelihood ratio	117	54.24	1.0000

Table 22. Total and average insect capture by sample depth in vacuum probes at Kingfisher and Crescent in 1993-1994

	Depth[a]	RGB			LGB			CEPH			SAW	
		N[b]	Avg[c]	Tot[d]	N	Avg	Tot	N	Avg	Tot	N	Avg	Tot
Kingfisher '93													
June 21	3	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0
August 9	3	1	0.5	5	0	0	0	0	0	0	0	0	0
	6	2	0.2	2	0	0	0	0	0	0	0	0	0
	9	1	0.4	4	0	0	0	0	0	0	0	0	0
September 2	3	4	0.8	8	2	0.2	2	2	0.2	2	0	0	0
	6	2	0.2	2	1	0.1	1	0	0	0	0	0	0
	9	0	0	0	0	0	0	3	0.3	3	0	0	0
Kingfisher '94													
June 21	3	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0

Table 22. Total and average insect capture by sample depth in vacuum probes at Kingfisher and Crescent in 1993-1994

July 26	3	1	0.1	1	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0
September 13	3	3	0.6	6	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0
Crescent '93													
July 6	3	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0
August 9	3	6	8.7	87	0	0	0	1	0.2	2	2	0.2	2
	6	4	0.7	7	0	0	0	0	0	0	2	0.2	2
	9	0	0	0	0	0	0	0	0	0	1	0.1	1
Crescent '94													
June 28	3	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0

Table 22. Total and average insect capture by sample depth in vacuum probes at Kingfisher and Crescent in 1993-1994

	9	0	0	0	0	0	0	0	0	0	0	0	0
July 26	3	1	0.4	4	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	9	1	0.1	1	0	0	0	0	0	0	0	0	0
August 16	3	3	0.9	9	0	0	0	1	0.3	3	0	0	0
	6	4	0.8	8	0	0	0	0	0	0	0	0	0
	9	3	0.4	4	0	0	0	0	0	0	0	0	0

[a] Depth in meters

[b] Number of times detected

[c] Average sample capture

[d] Total insects captured

Table 23. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Kingfisher, 1993

Parameters	*R. dominica*	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	-0.0138	0.13573*	0.24288*
Deep cup/pitfall trap[b]	0.44669*	0.15552*	0.24072*
Pitfall trap/flight trap[c]	-0.03067	0.22417*	0.11684
Pitfall trap/temperature[d]	-0.43387*	-0.0133	-0.22345
Deep cup/Temperature[e]	-0.22252*	-0.21043*	-0.21412*
Pitfall trap/grain moisture[f]	0.03666	0.17961*	0.06159
Deep cup/grain moisture[g]	-0.02144	0.07207	-0.01848

[a-g] df = 864, 720, 277, 69, 224, 335, 359 respectively for each set of correlation parameters

* Coefficient is significantly different from zero

Table 24. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Crescent, 1993

Parameters	*R. dominica*	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	-0.00898	0.37695*	0.08736
Deep cup/pitfall trap[b]	0.28038*	0.21934*	0.05044
Pitfall trap/flight trap[c]	-0.02518	0.12376	0.3393*
Pitfall trap/temperature[d]	0.10697	-0.38266*	-0.38851*
Deep cup/Temperature[e]	0.37481*	0.1909	-0.17169
Pitfall trap/grain moisture[f]	-0.17099*	0.00622	-0.28438*
Deep cup/grain moisture[g]	0.20100	-0.2286	-0.1922

[a-g] df = 432, 282, 112, 31, 46, 191, 69 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Table 25. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Kingfisher, 1994

Parameters	*R. dominica*	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	-0.01551	0.07966*	0.16748*
Deep cup/pitfall trap[b]	-0.02014	0.10337*	0.34228*
Pitfall trap/flight trap[c]	0.04696	0.22401*	0.15424*
Pitfall trap/temperature[d]	-0.10042	-0.0587	-0.22368*
Deep cup/Temperature[e]	0.0269	0.03097	-0.01271
Pitfall trap/grain moisture[f]	0.01157	0.03692	0.04468
Deep cup/grain moisture[g]	0.03375	0.09759*	0.04882

[a-g] df =936, 936, 416, 96, 647, 336, 647 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Table 26. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Crescent, 1994

Parameters	*R. dominica*	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	-0.02347	0.14571*	0.29108*
Deep cup/pitfall trap[b]	0.10843*	0.13443*	0.39051*
Pitfall trap/flight trap[c]	-0.04881	0.00902	0.19801*
Pitfall trap/temperature[d]	-0.15324	0.34016*	0.21859
Deep cup/Temperature[e]	-0.17844*	-0.12509	-0.31600*
Pitfall trap/grain moisture[f]	0.03264	0.03467	0.04761
Deep cup/grain moisture[g]	0.06446	0.15424*	0.21127*

[a-g] df = 527, 479, 157, 43, 165, 159, 191 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Fig. 1. Average grain temperature at both sampling locations from June 21 to September 20, 1993.

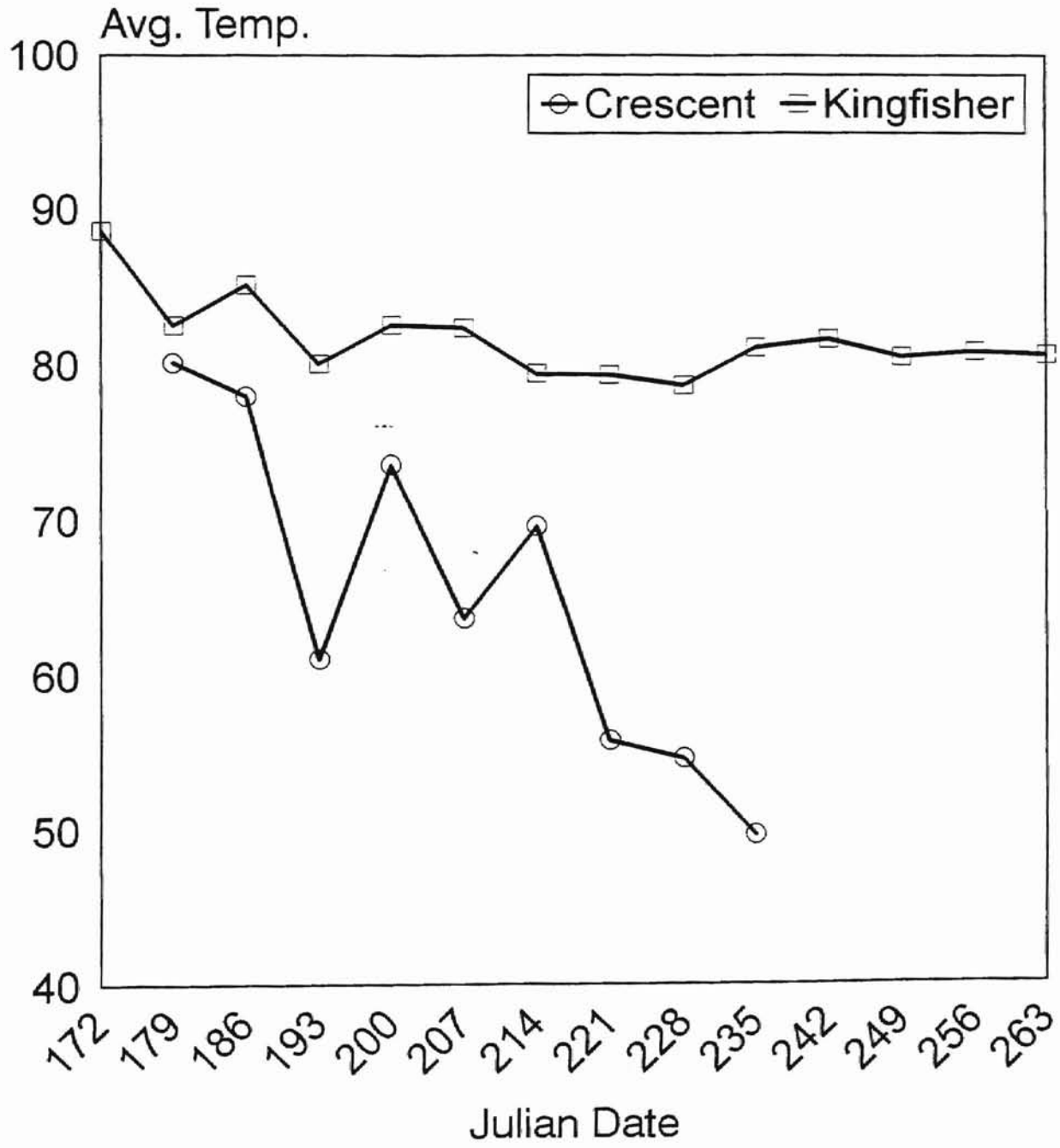

Avg. Temp.
100
90
80
70
60
50
40
Crescent
Kingfisher
172
179
186
193
200
207
214
221
228
235
242
249
256
263
Julian Date

Fig. 2. Average grain temperature at both sampling locations from June 21 to September 20, 1994.

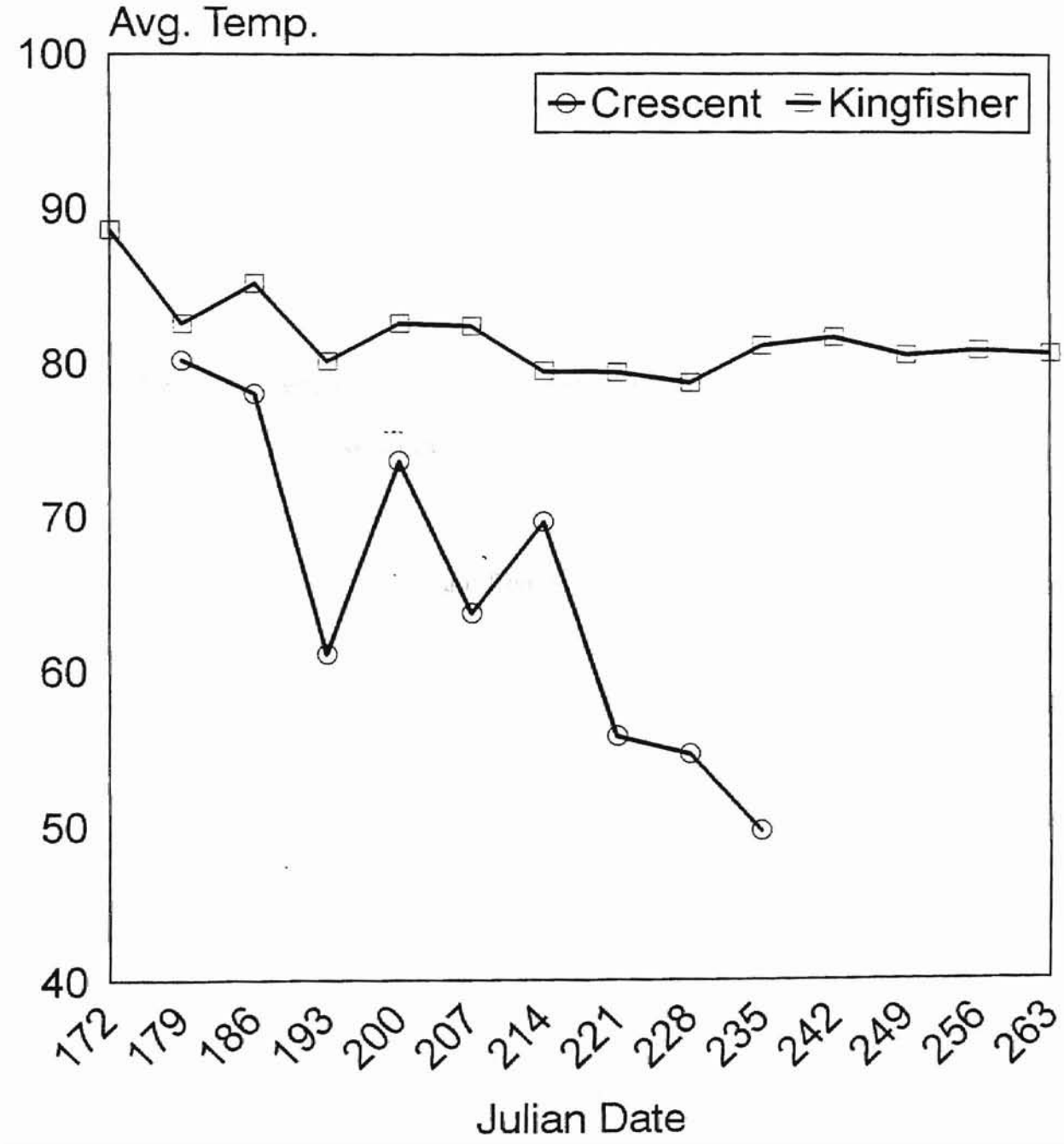
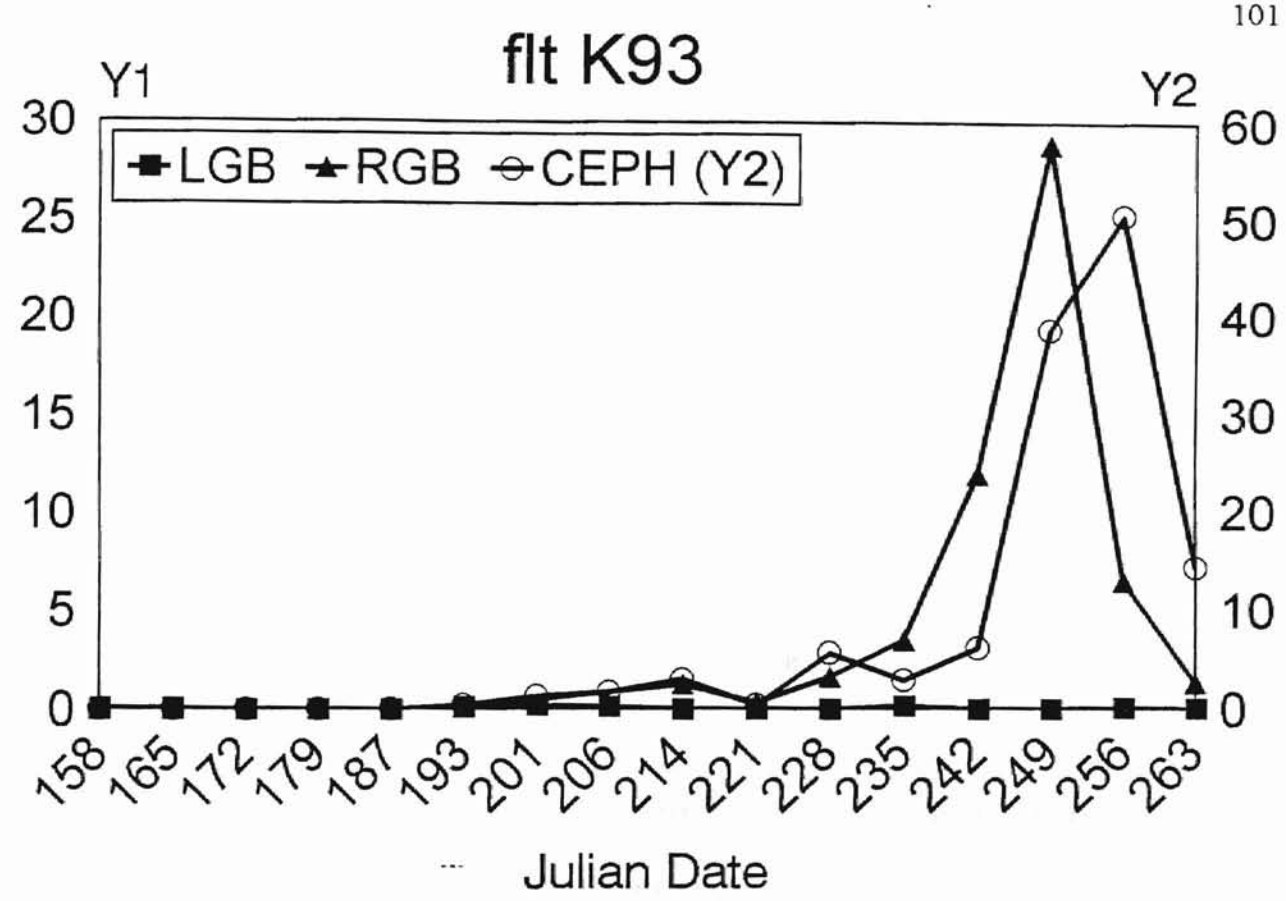

Avg. Temp.
100
90
80
70
60
50
40
Crescent
Kingfisher
172
179
186
193
200
207
214
221
228
235
242
249
256
263
Julian Date

Fig. 3. Average number of adult insects captured in flight traps at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in flight traps from June 7 to September 20 at Kingfisher in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y1); CEPH, *C. waterstoni* (Y2); B) Average number of adult insects captured in flight traps from May 17 to September 13 at Kingfisher in 1994; LGB, lesser grain borer, *R. dominica*; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni*


flt K93
Y1
Y2
LGB
RGB
CEPH (Y2)
30
25
20
15
10
5
0
60
50
40
30
20
10
0
158
165
172
179
187
193
201
206
214
221
228
235
242
249
256
263
Julian Date

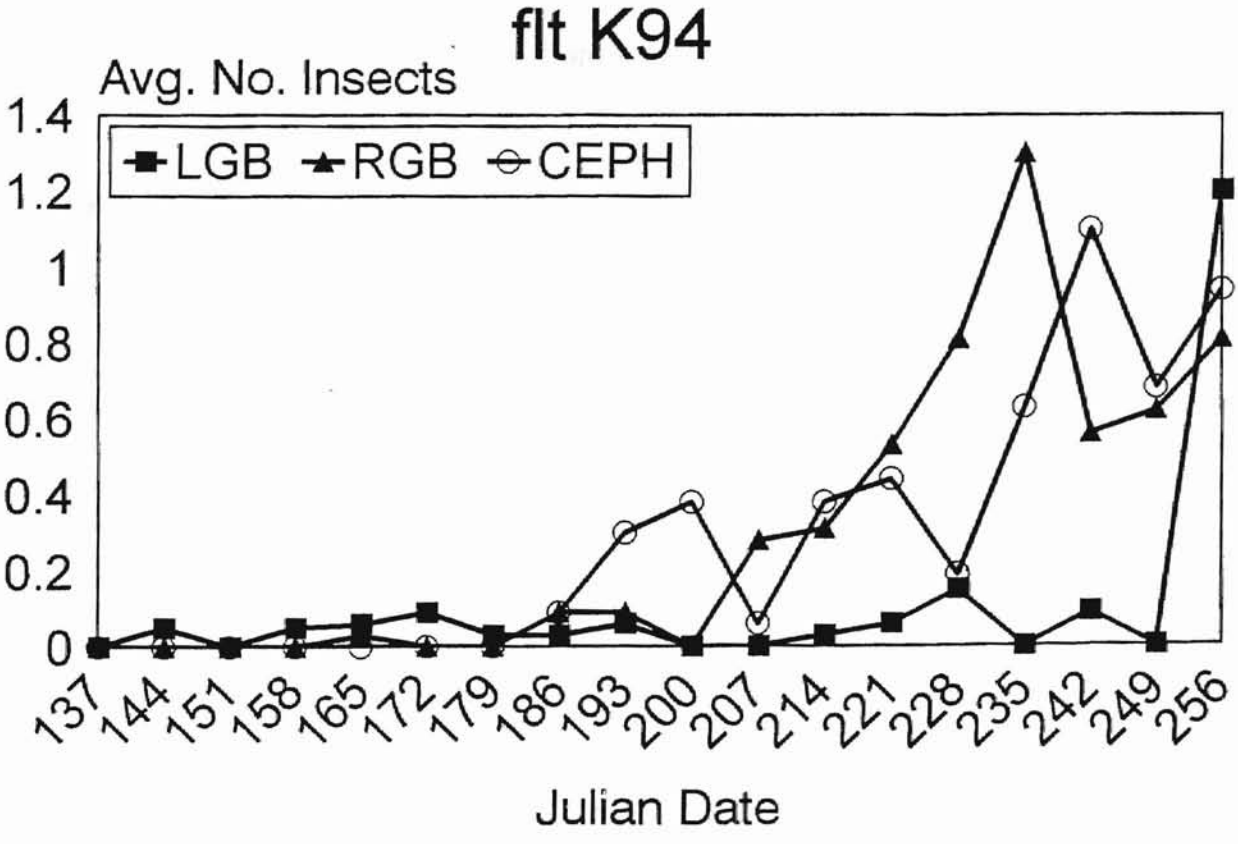
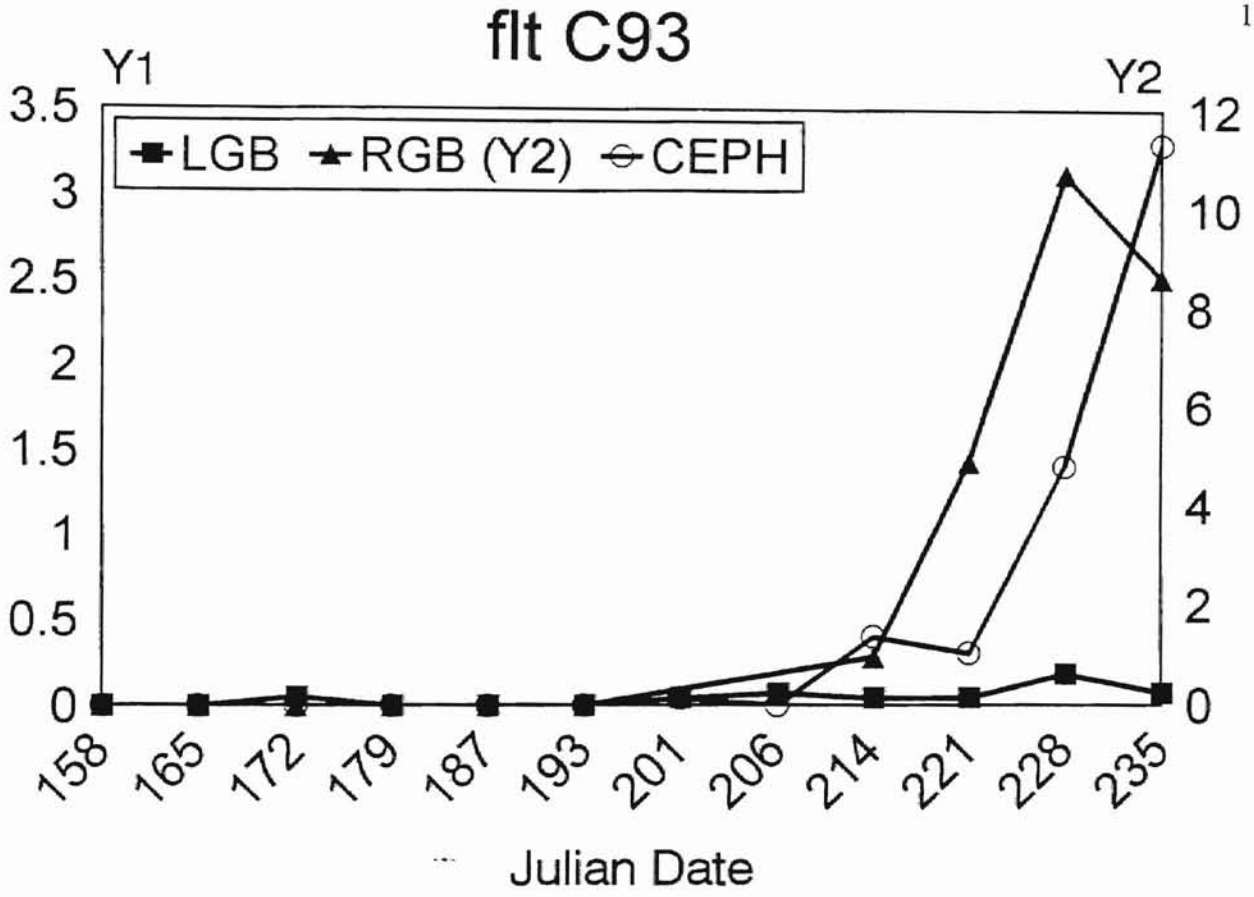

flt K94
Avg. No. Insects
LGB
RGB
CEPH
1.4
1.2
1
0.8
0.6
0.4
0.2
0
137
144
151
158
165
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 4. Average number of adult insects captured in flight traps at Crescent in 1993-1994

Key: A) Average number of adult insects captured in flight traps from June 7 to August 23 at Crescent in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps from May 17 to August 16 at Crescent in 1994; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


flt C93
Y1
Y2
LGB
RGB (Y2)
CEPH
3.5
3
2.5
2
1.5
1
0.5
0
12
10
8
6
4
2
0
158
165
172
179
187
193
201
206
214
221
228
235
Julian Date

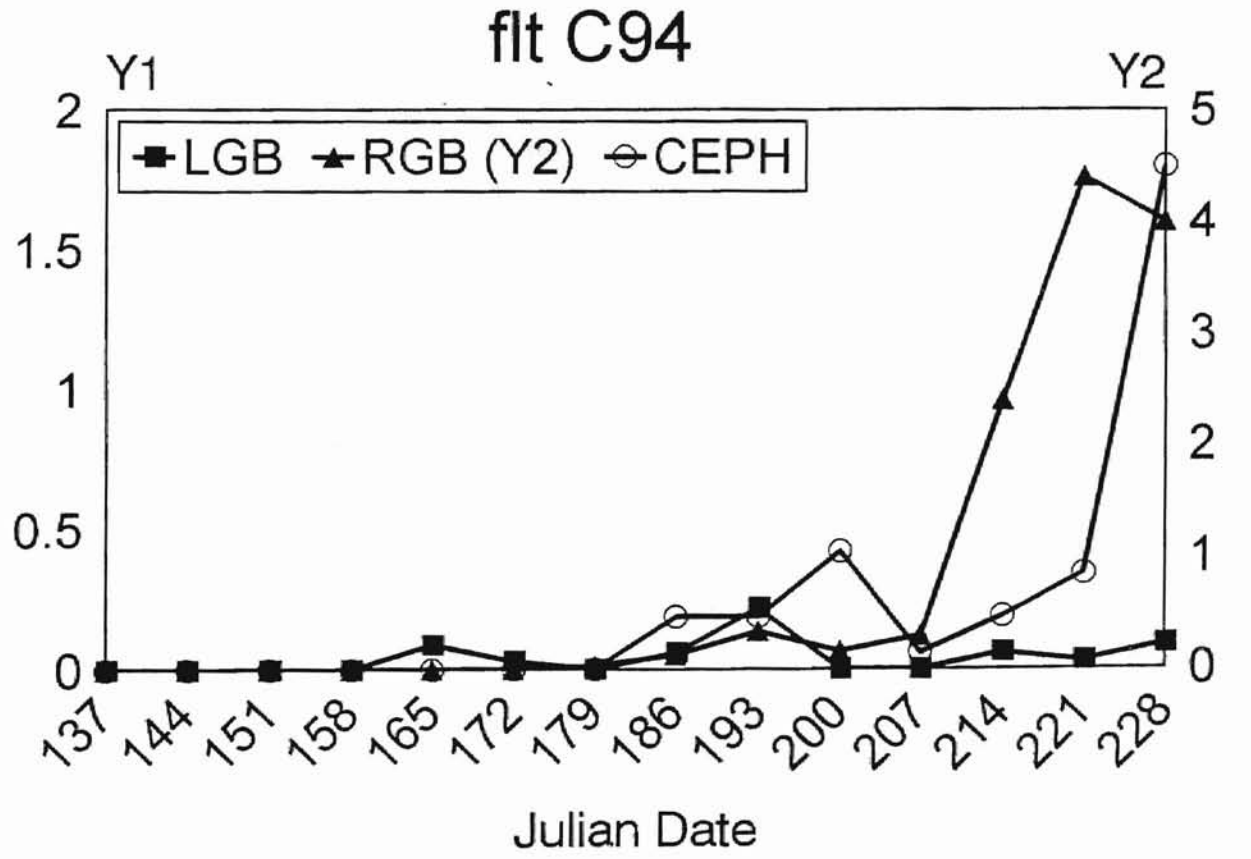
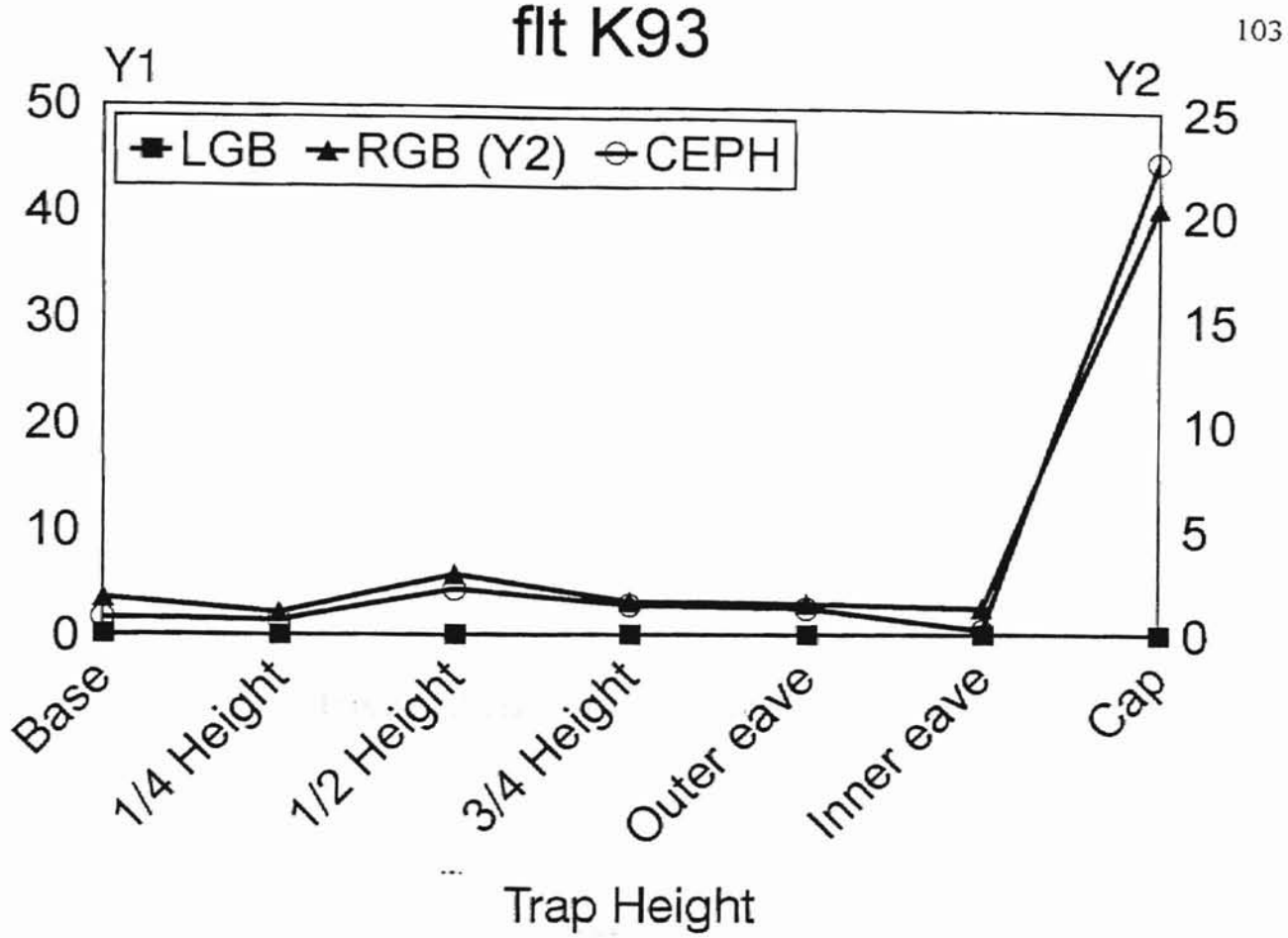

flt C94
Y1
Y2
LGB
RGB (Y2)
CEPH
2
1.5
1
0.5
0
5
4
3
2
1
0
137
144
151
158
165
172
179
186
193
200
207
214
221
228
Julian Date

Fig. 5. Average number of adult insects captured in flight traps by trap height at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in flight traps by trap height at Kingfisher in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps by trap height at Kingfisher in 1994; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


flt K93
Y1
Y2
50
40
30
20
10
0
25
20
15
10
5
0
LGB
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Cap
Trap Height

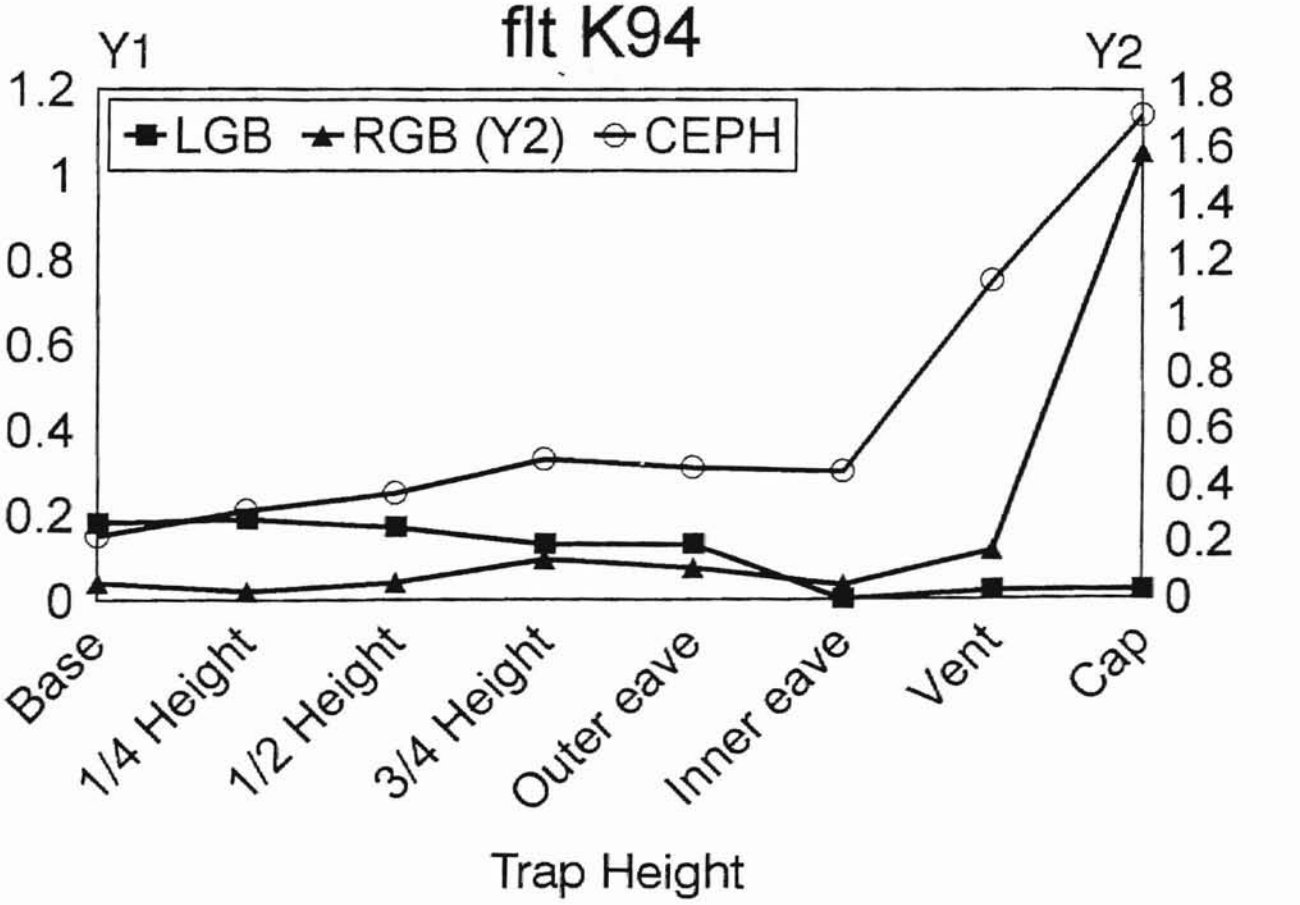
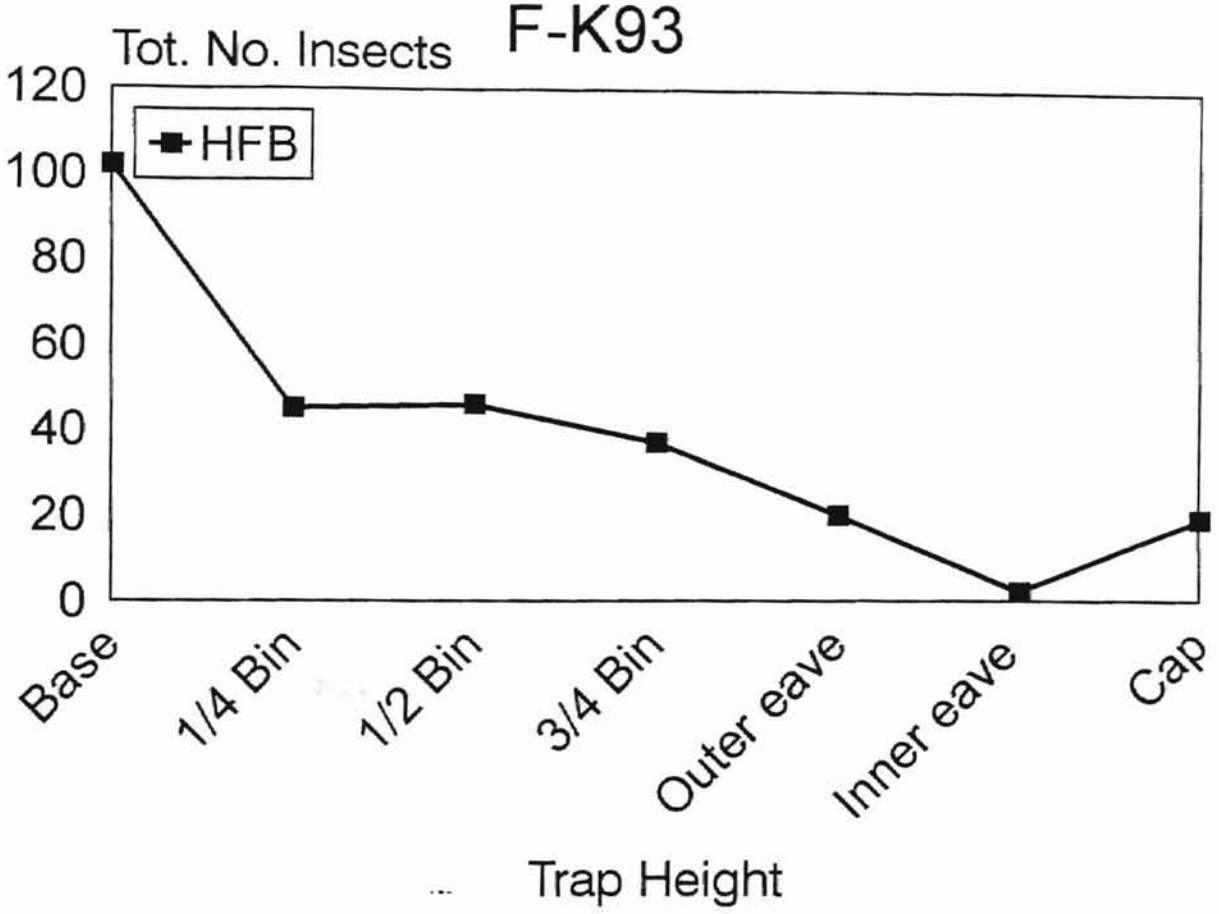

flt K94
Y1
Y2
1.2
1
0.8
0.6
0.4
0.2
0
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
LGB
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 6. Total number of adult insects captured in flight traps by trap height at Kingfisher in 1993-1994

Key: A) Total number of adult insects captured in flight traps by trap height at Kingfisher in 1993; HFB, hairy fungus beetle, *T. stercorea* (Y1); B) Total number of adult insects captured in flight traps by trap height at Kingfisher in 1994; HFB, hairy fungus beetle, *T. stercorea* (Y1);


F-K93
Tot. No. Insects
120
100
80
60
40
20
0
HFB
Base
1/4 Bin
1/2 Bin
3/4 Bin
Outer eave
Inner eave
Cap
Trap Height

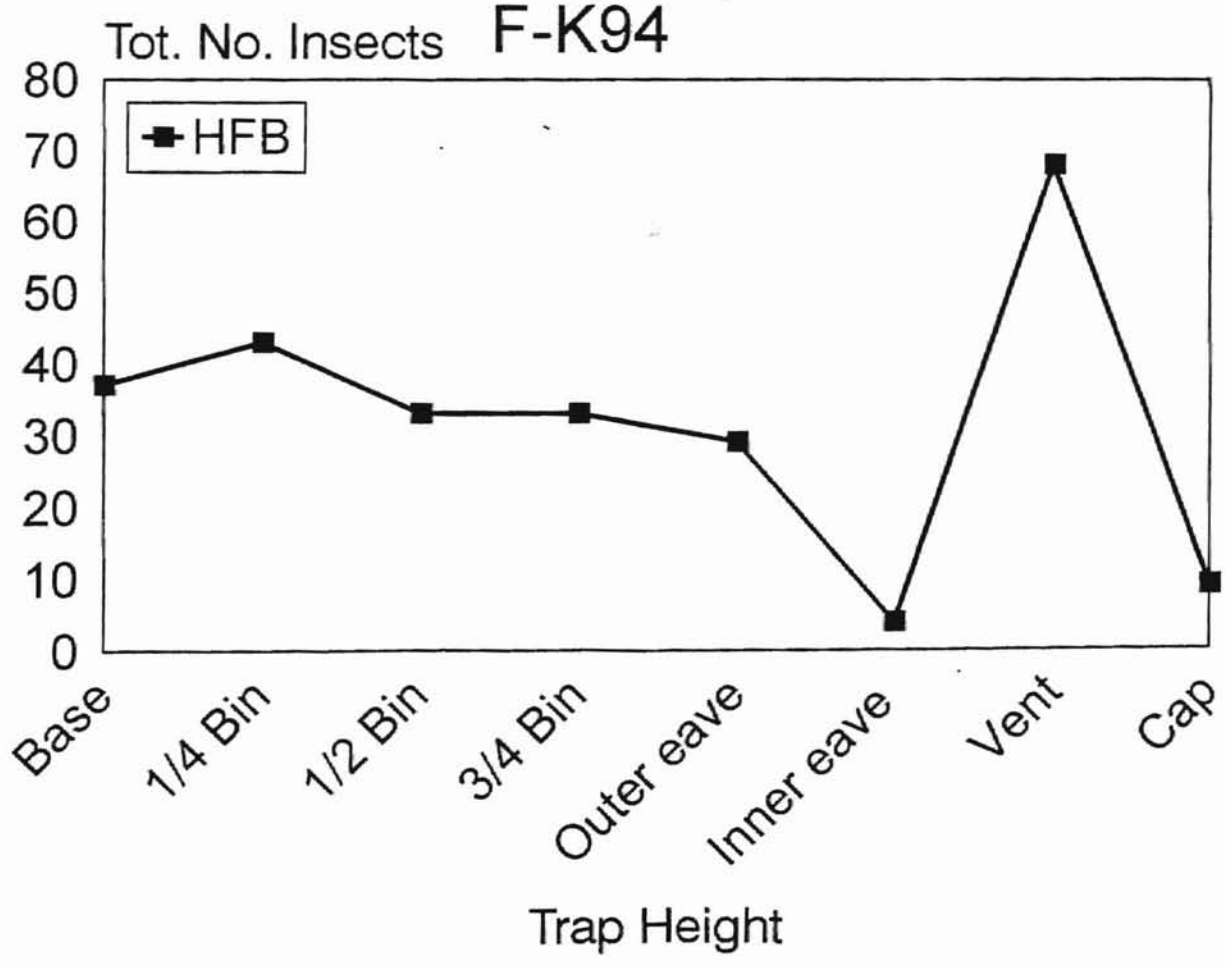
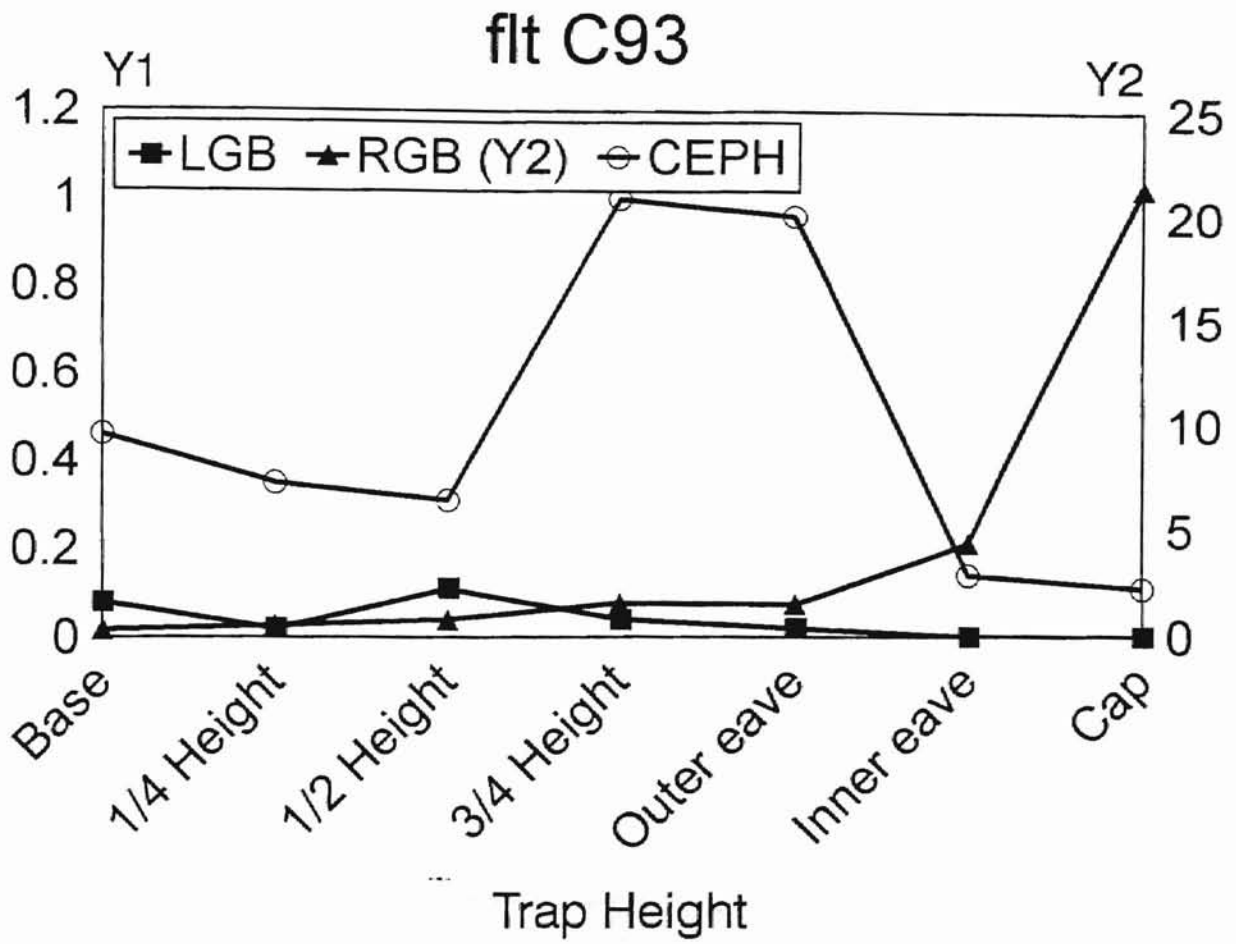

F-K94
Tot. No. Insects
80
70
60
50
40
30
20
10
0
HFB
Base
1/4 Bin
1/2 Bin
3/4 Bin
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 7. Average number of adult insects captured in flight traps by trap height at Crescent in 1993-1994

Key: A) Average number of adult insects captured in flight traps by trap height at Crescent in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps by trap height at Crescent in 1994; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


flt C93
Y1
Y2
LGB
RGB (Y2)
CEPH
1.2
1
0.8
0.6
0.4
0.2
0
25
20
15
10
5
0
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Cap
Trap Height

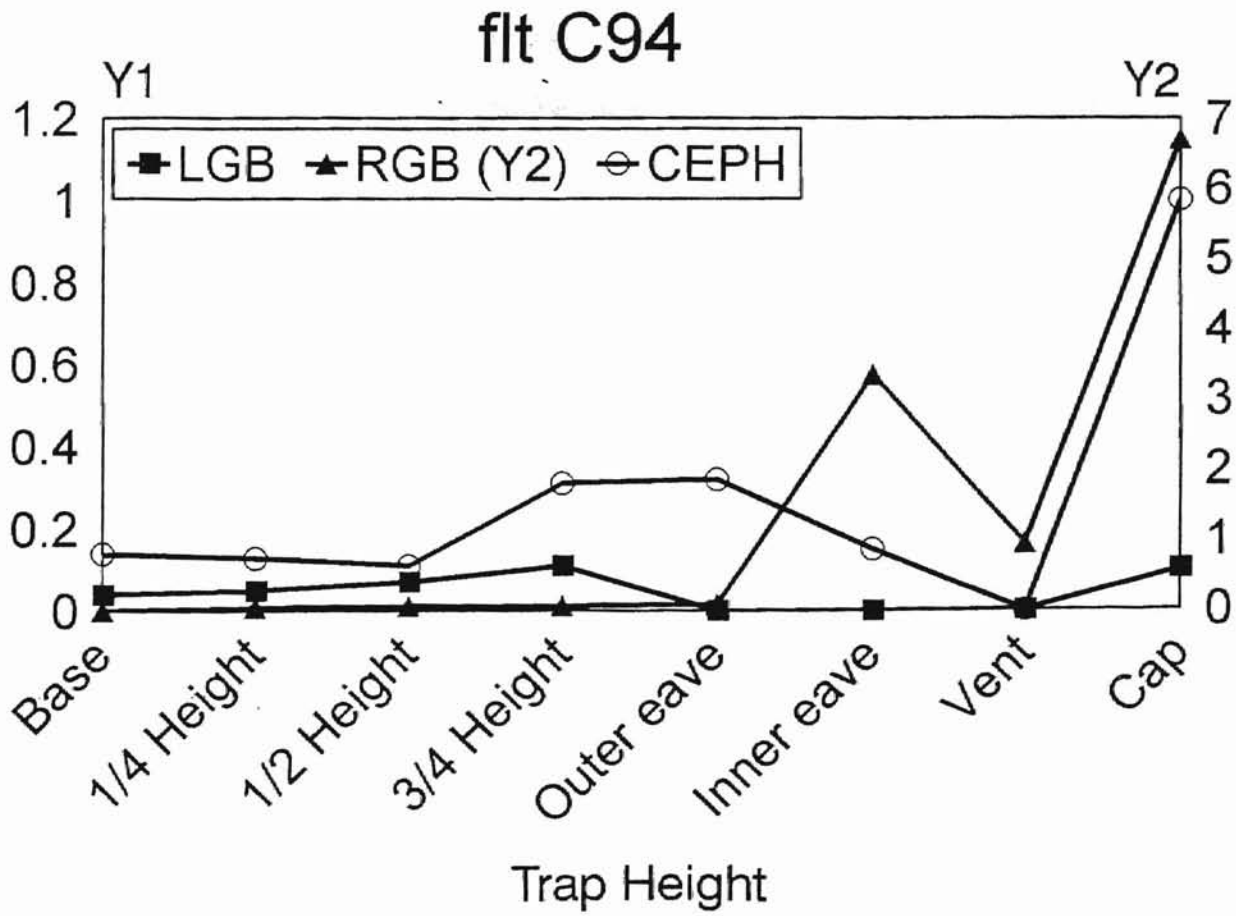
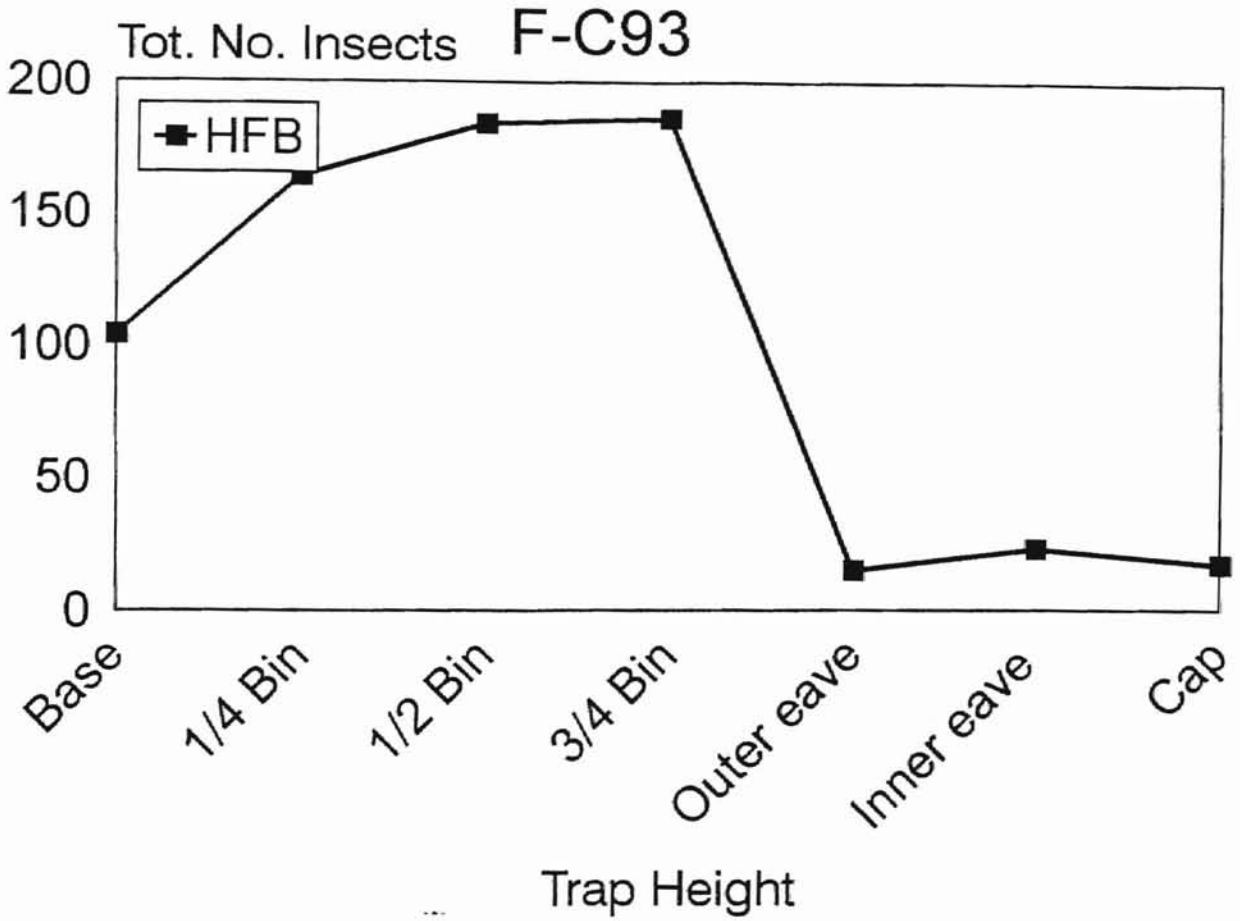

flt C94
Y1
Y2
LGB
RGB (Y2)
CEPH
1.2
1
0.8
0.6
0.4
0.2
0
7
6
5
4
3
2
1
0
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 8. Total number of adult insects captured in flight traps by trap height at Crescent in 1993-1994

Key: A) Total number of adult insects captured in flight traps by trap height at Crescent in 1993; HFB, hairy fungus beetle, *T. stercorea* (Y1); B) Total number of adult insects captured in flight traps by trap height at Crescent in 1994; HFB, hairy fungus beetle, *T. stercorea* (Y1);


F-C93
Tot. No. Insects
200
150
100
50
0
HFB
Base
1/4 Bin
1/2 Bin
3/4 Bin
Outer eave
Inner eave
Cap
Trap Height

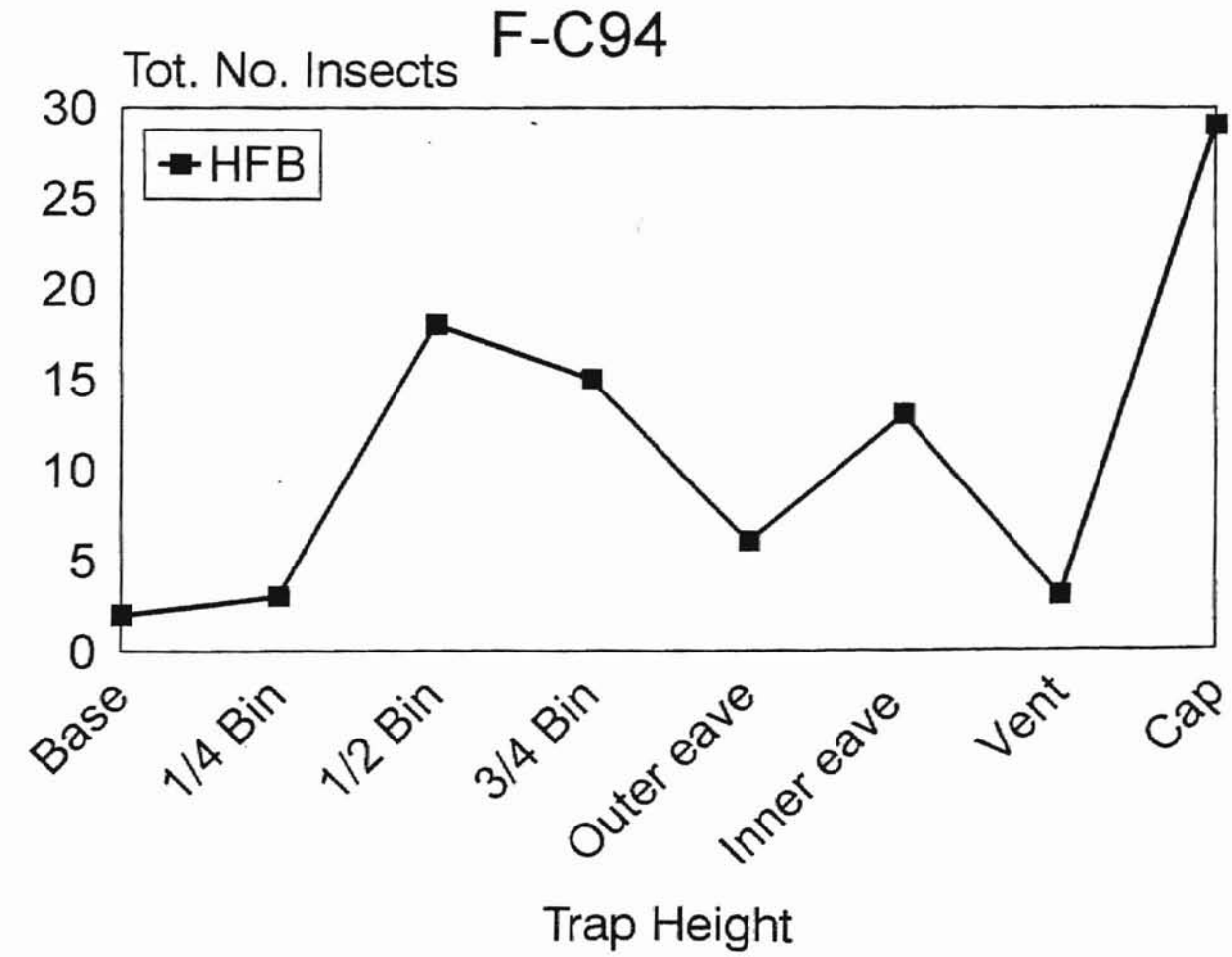
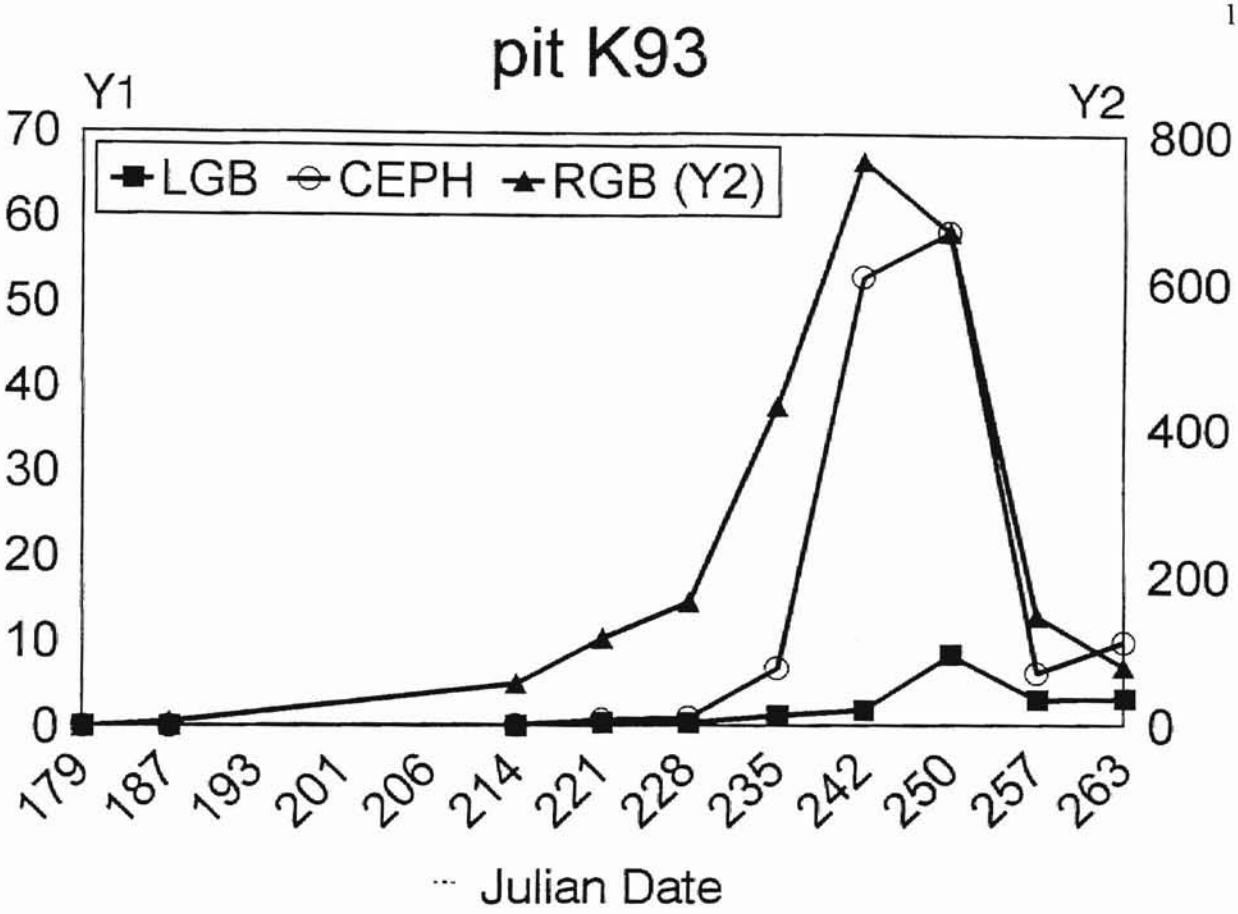

F-C94
Tot. No. Insects
30
25
20
15
10
5
0
HFB
Base
1/4 Bin
1/2 Bin
3/4 Bin
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 9. Average number of adult insects captured in pitfall probe traps at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in pitfall probe traps from June 28 to September 20 at Kingfisher in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in pitfall probe traps from June 21 to September 13 at Kingfisher in 1994; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


pit K93
Y1
Y2
LGB
CEPH
RGB (Y2)
70
60
50
40
30
20
10
0
800
600
400
200
0
179
187
193
201
206
214
221
228
235
242
250
257
263
Julian Date

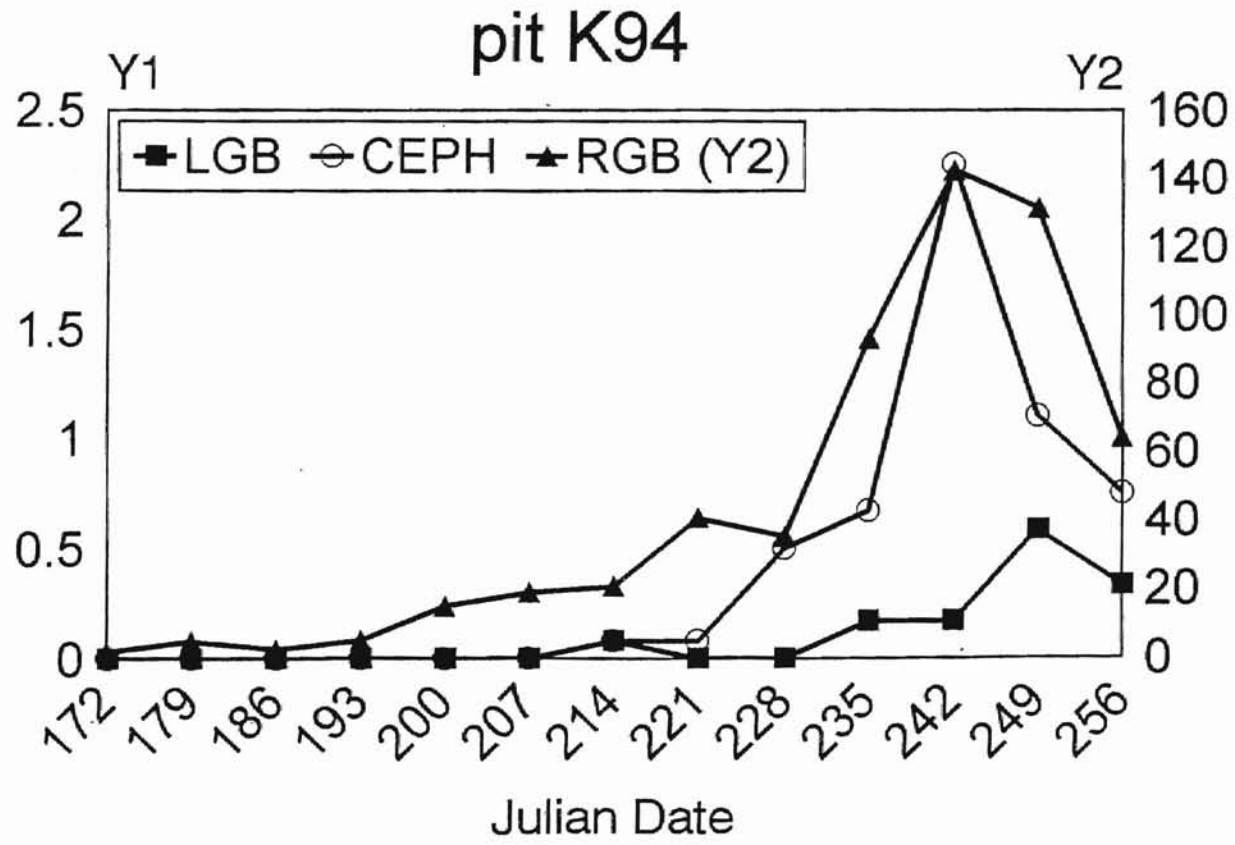
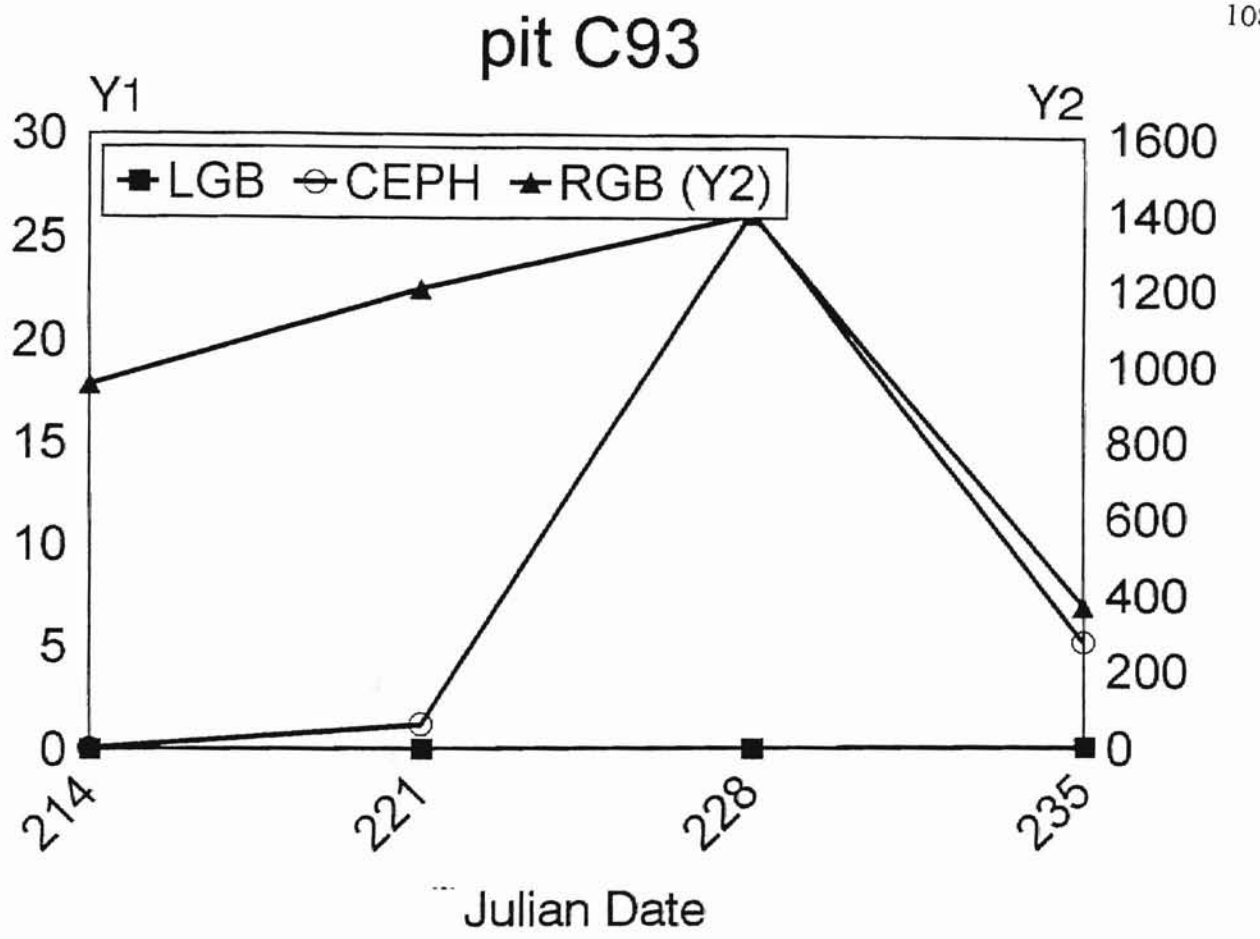

pit K94
Y1
Y2
LGB
CEPH
RGB (Y2)
2.5
2
1.5
1
0.5
0
160
140
120
100
80
60
40
20
0
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 10. Average number of adult insects captured in pitfall probe traps at Crescent in 1993-1994

Key: A) Average number of adult insects captured in pitfall probe traps from August 2 to August 23 at Crescent in 1993; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in pitfall probe traps from June 28 to August 23 at Crescent in 1994; LGB, lesser grain borer, *R. dominica* (Y1); RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


pit C93
Y1
Y2
LGB
CEPH
RGB (Y2)
30
25
20
15
10
5
0
1600
1400
1200
1000
800
600
400
200
0
214
221
228
235
Julian Date

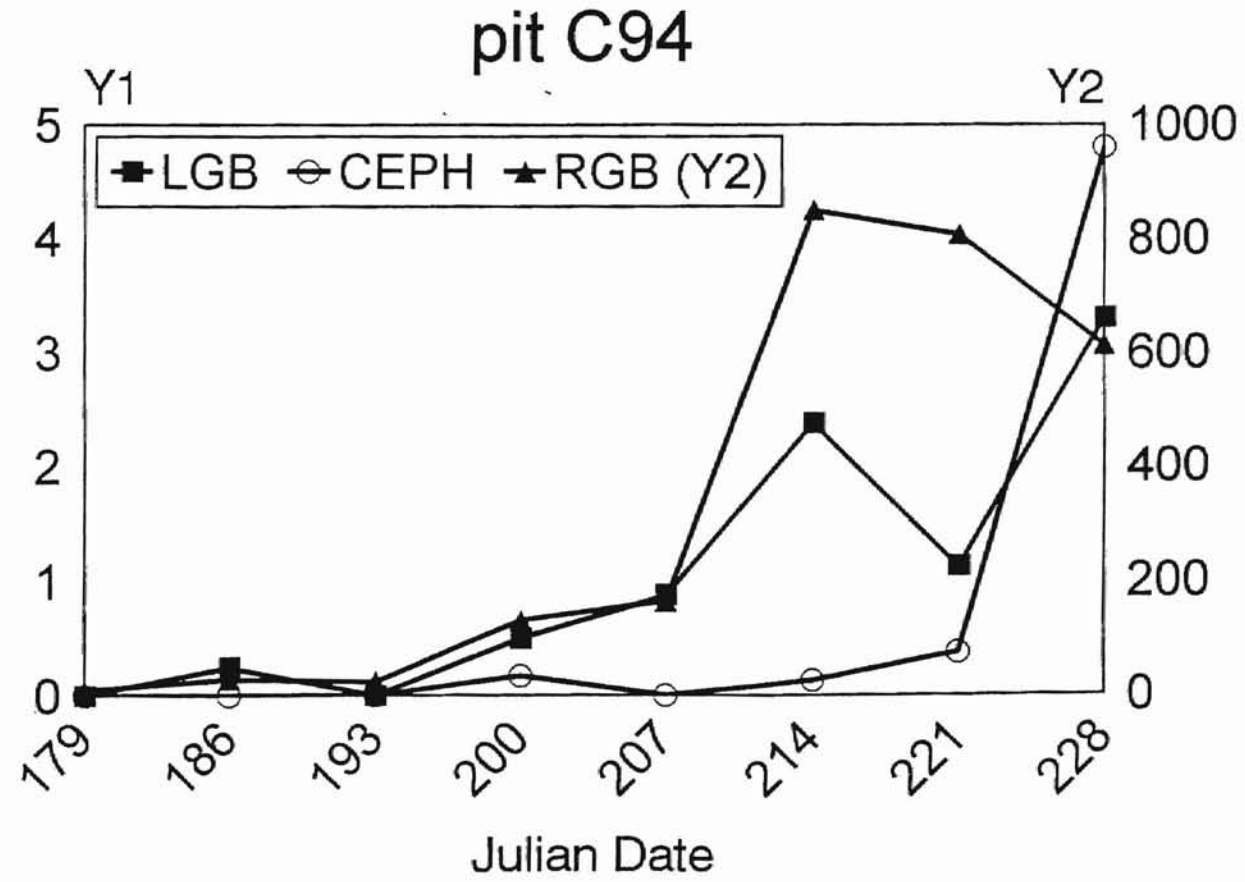
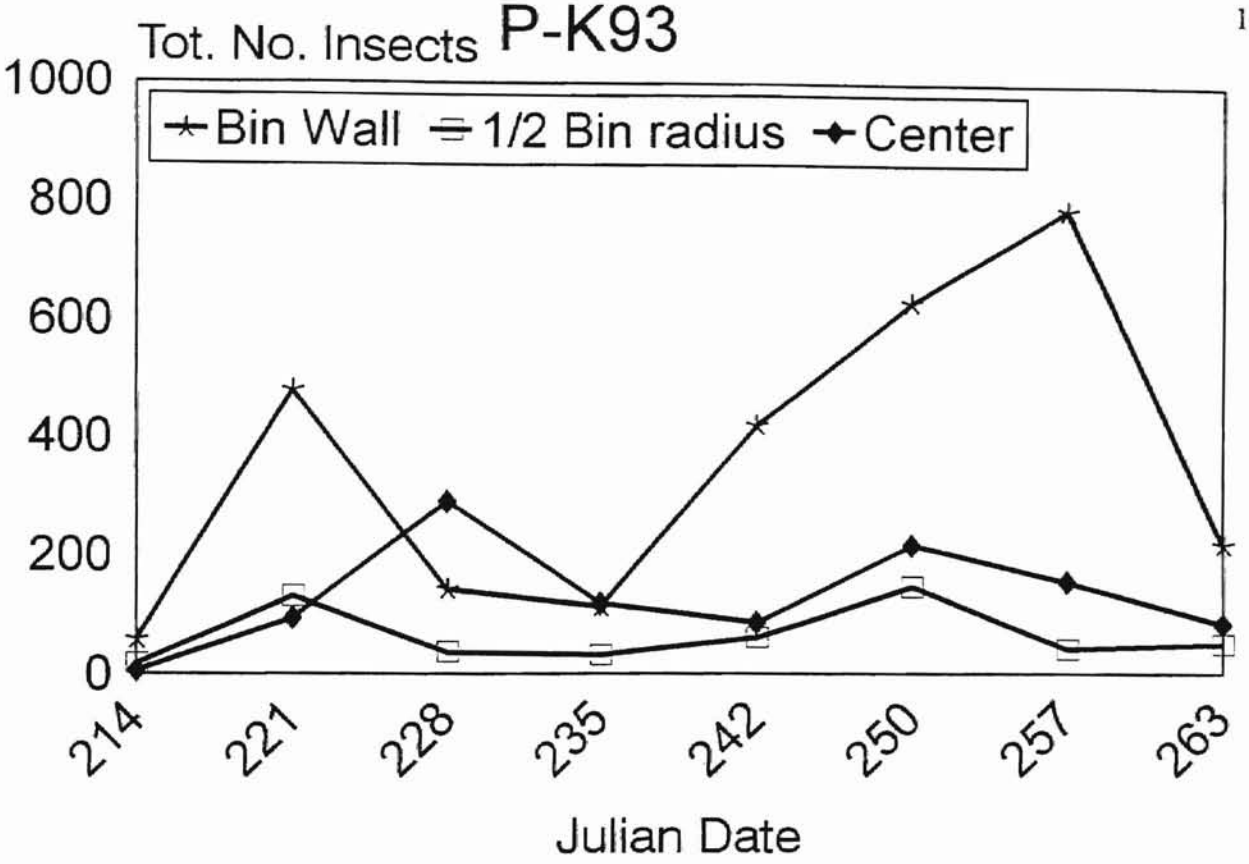

pit C94
Y1
Y2
LGB
CEPH
RGB (Y2)
5
4
3
2
1
0
1000
800
600
400
200
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 11. Total number of adult insects captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Total number of adult insects captured in pitfall probe traps by trap distance from bin wall from June 28 to September 20 at Kingfisher in 1993; HFB, hairy fungus beetle, *T. stercorea* (Y1); B) Total number of adult insects captured in pitfall probe traps by trap distance from bin wall from June 21 to September 13 at Kingfisher in 1994; HFB, hairy fungus beetle, *T. stercorea* (Y1);


Tot. No. Insects P-K93
Bin Wall
1/2 Bin radius
Center
1000
800
600
400
200
0
214
221
228
235
242
250
257
263
Julian Date

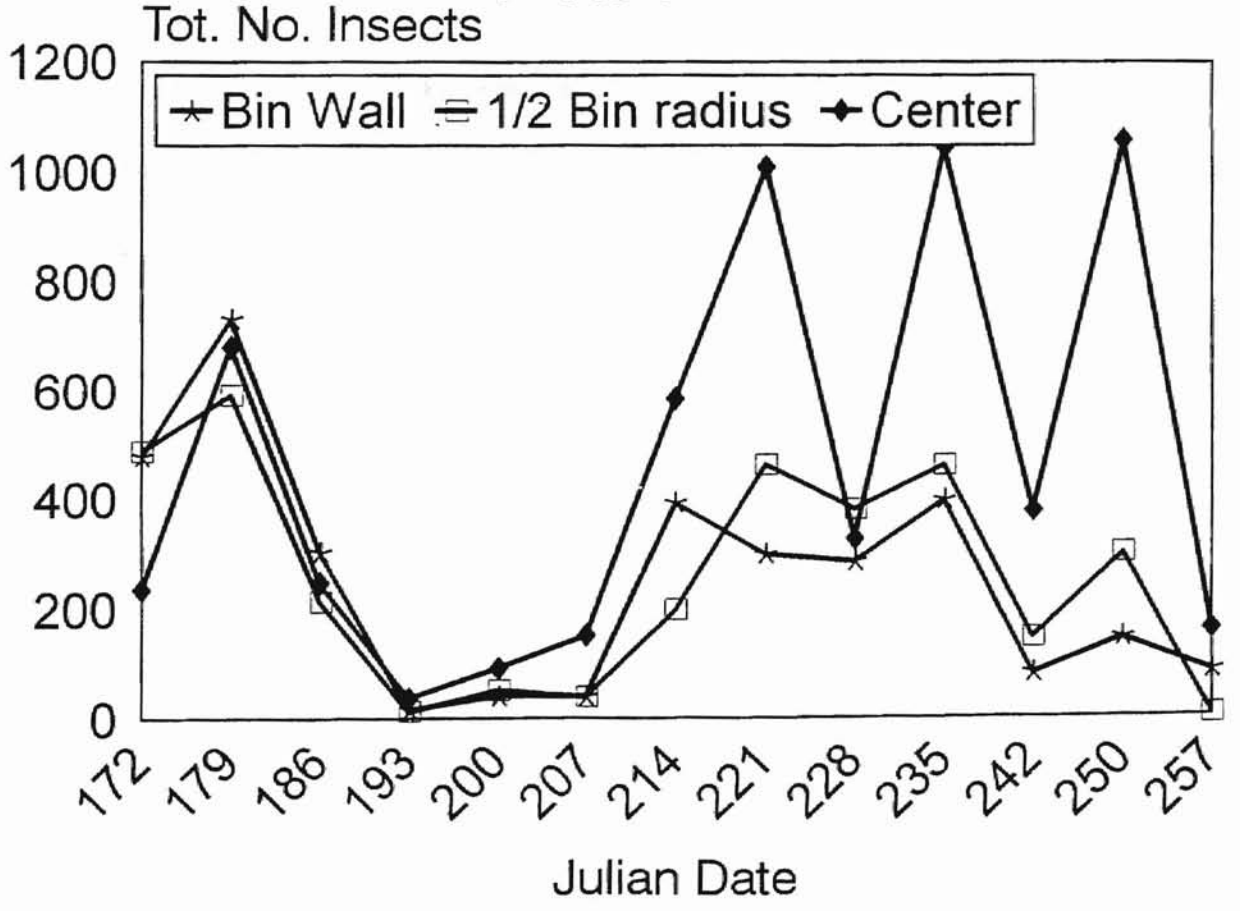
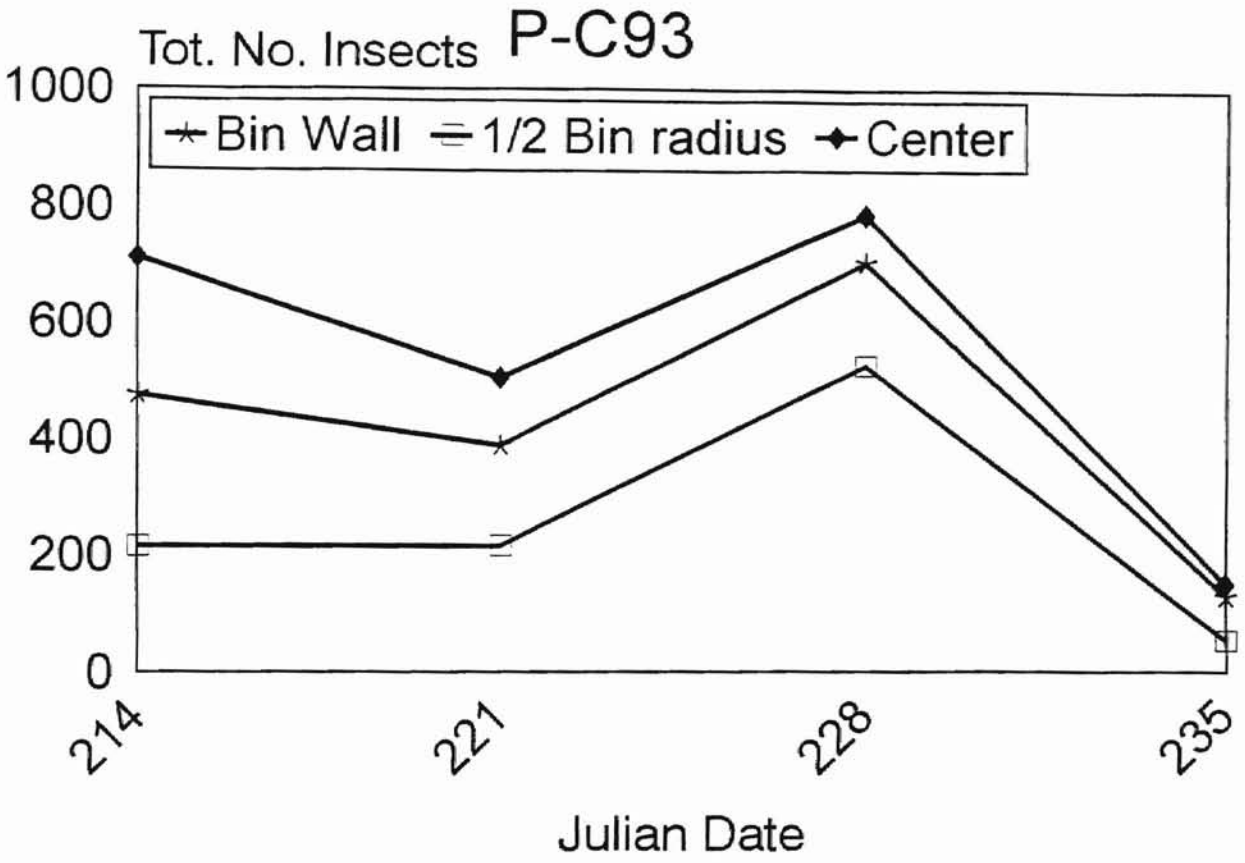

P-K94
Tot. No. Insects
Bin Wall
1/2 Bin radius
Center
1200
1000
800
600
400
200
0
172
179
186
193
200
207
214
221
228
235
242
250
257
Julian Date

Fig. 12. Total number of adult insects captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Total number of adult insects captured in pitfall probe traps by trap distance from bin wall from August 2 to August 23 at Crescent in 1993; HFB, hairy fungus beetle, *T. stercorea* (Y1); B) Total number of adult insects captured in pitfall probe traps by trap distance from bin wall from June 28 to August 23 at Crescent in 1994; HFB, hairy fungus beetle, *T. stercorea* (Y1);


Tot. No. Insects P-C93
Bin Wall
1/2 Bin radius
Center
1000
800
600
400
200
0
214
221
228
235
Julian Date

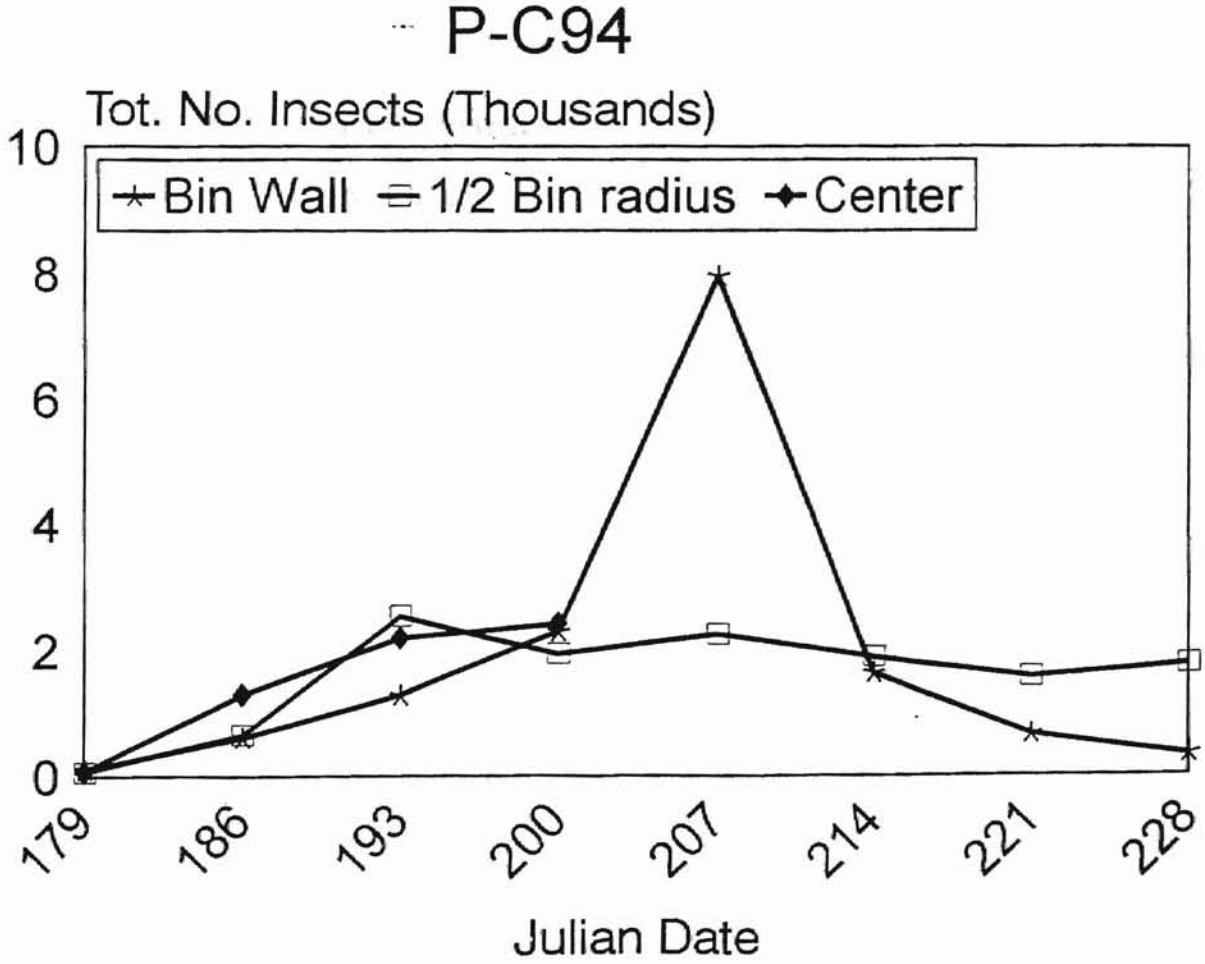
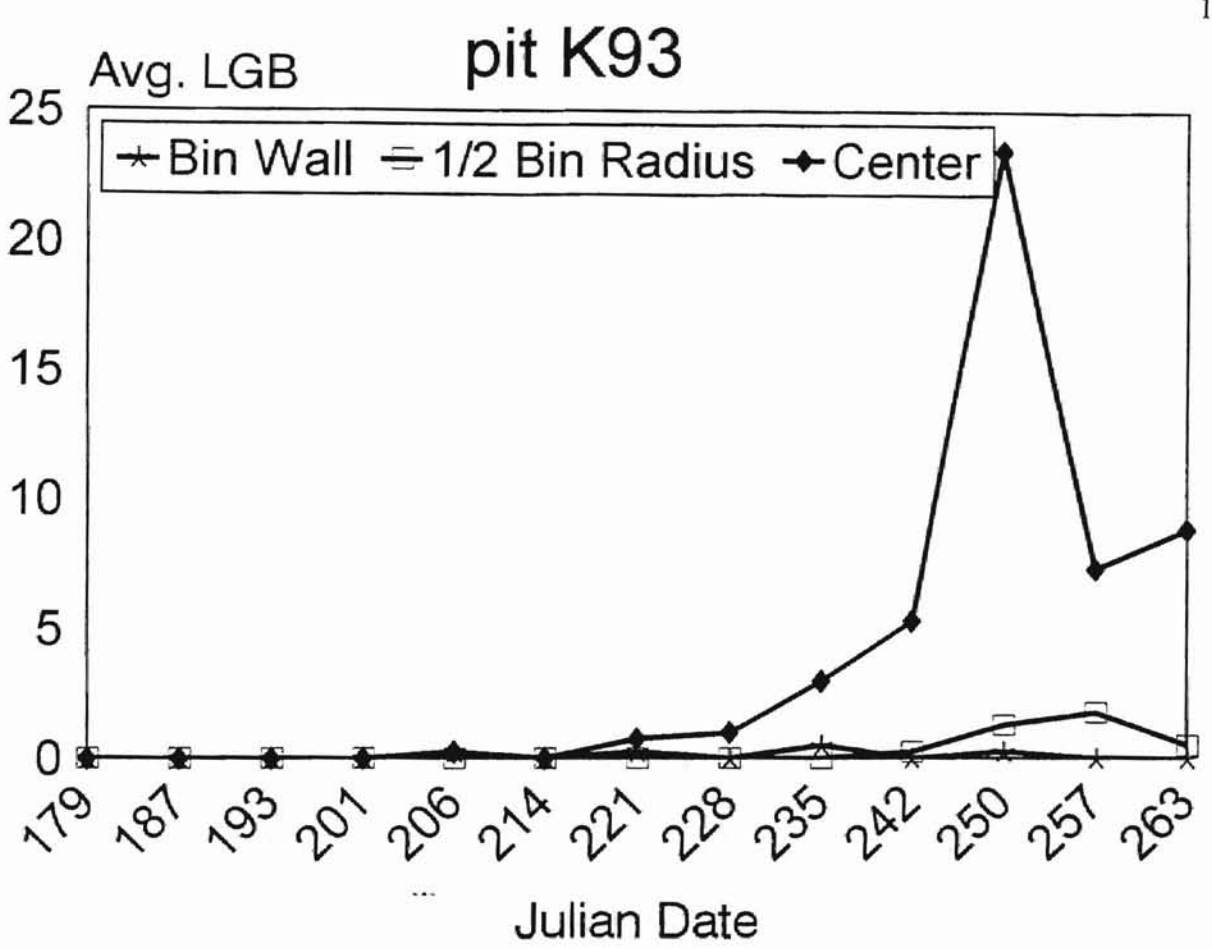

P-C94
Tot. No. Insects (Thousands)
Bin Wall
1/2 Bin radius
Center
10
8
6
4
2
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 13. Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall from June 28 to September 20 at Kingfisher in 1993; B) Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 13 at Kingfisher in 1994


pit K93
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
25
20
15
10
5
0
179
187
193
201
206
214
221
228
235
242
250
257
263
Julian Date

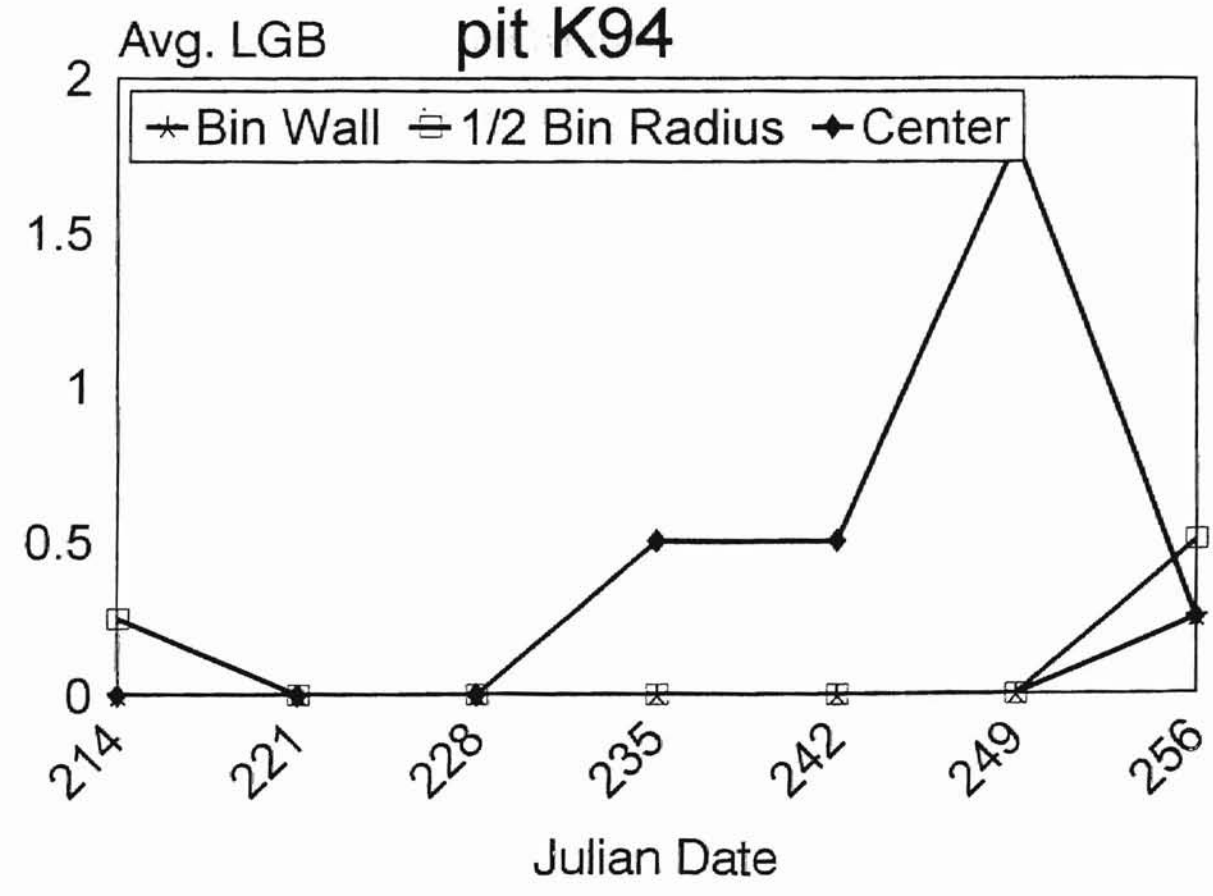
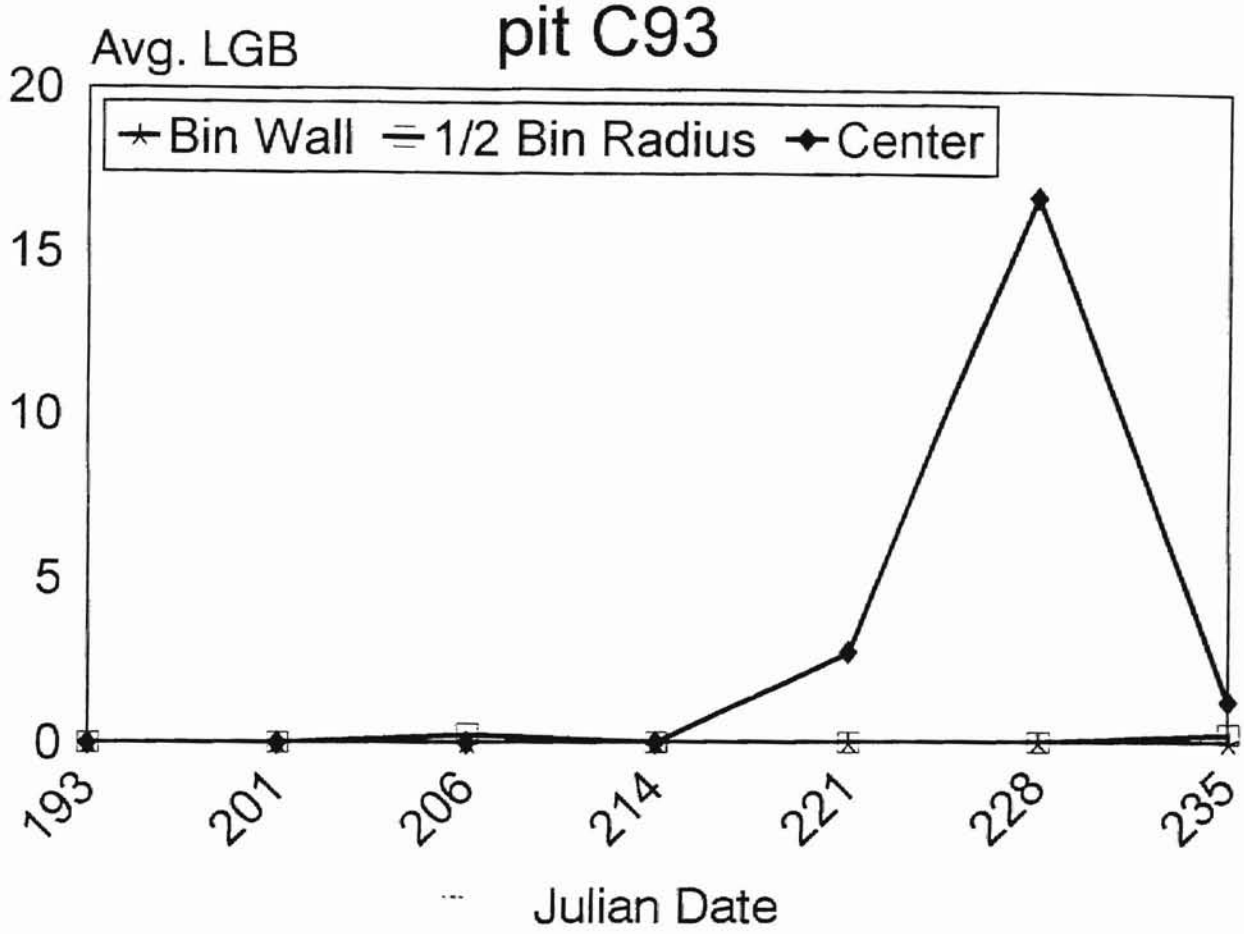

pit K94
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
2
1.5
1
0.5
0
214
221
228
235
242
249
256
Julian Date

Fig. 14. Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall from July 12 to August 23 at Crescent in 1993; B) Average number of adult *R. dominica* captured in pitfall probe traps by trap distance from bin wall from June 28 to August 16 at Crescent in 1994


pit C93
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
20
15
10
5
0
193
201
206
214
221
228
235
Julian Date

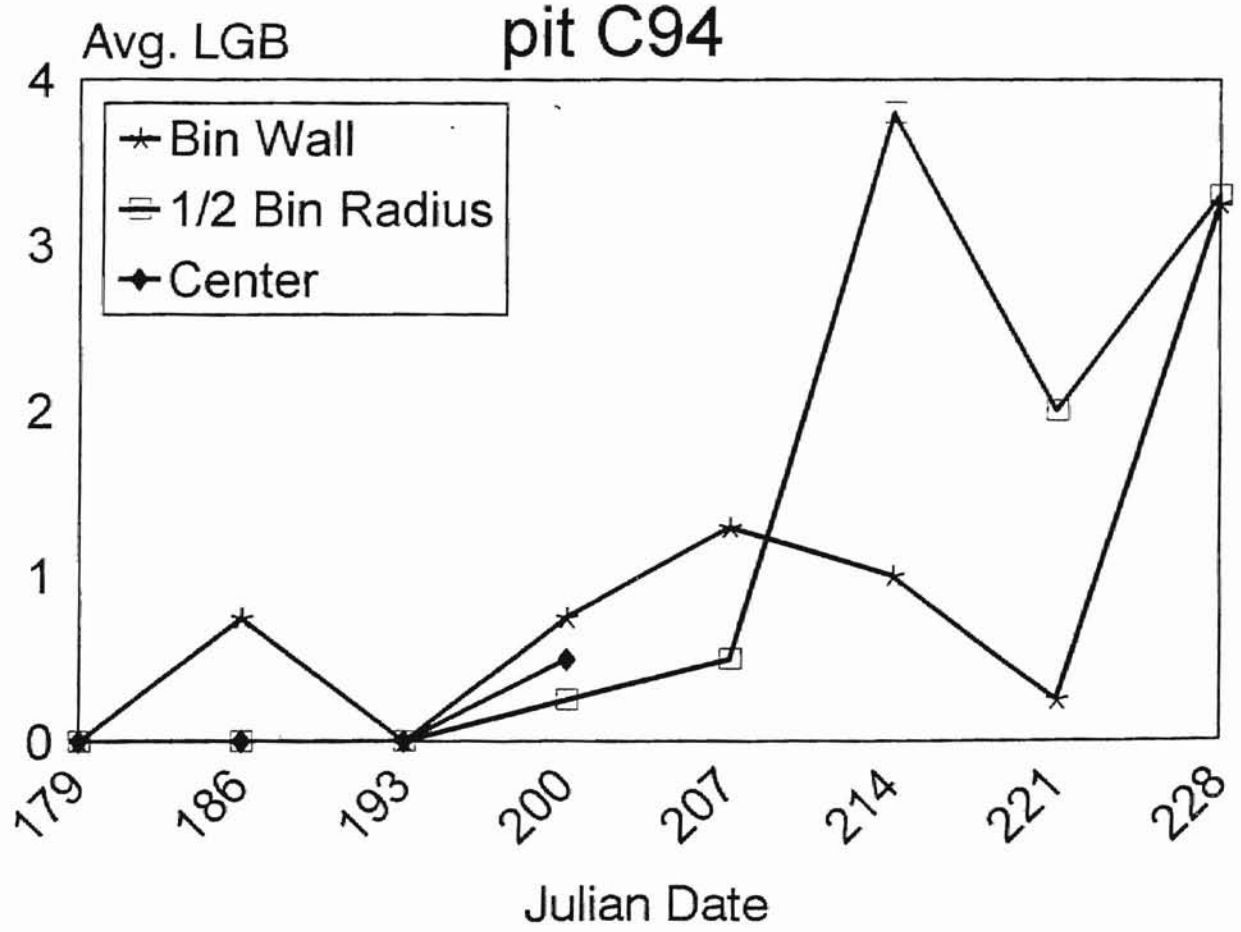
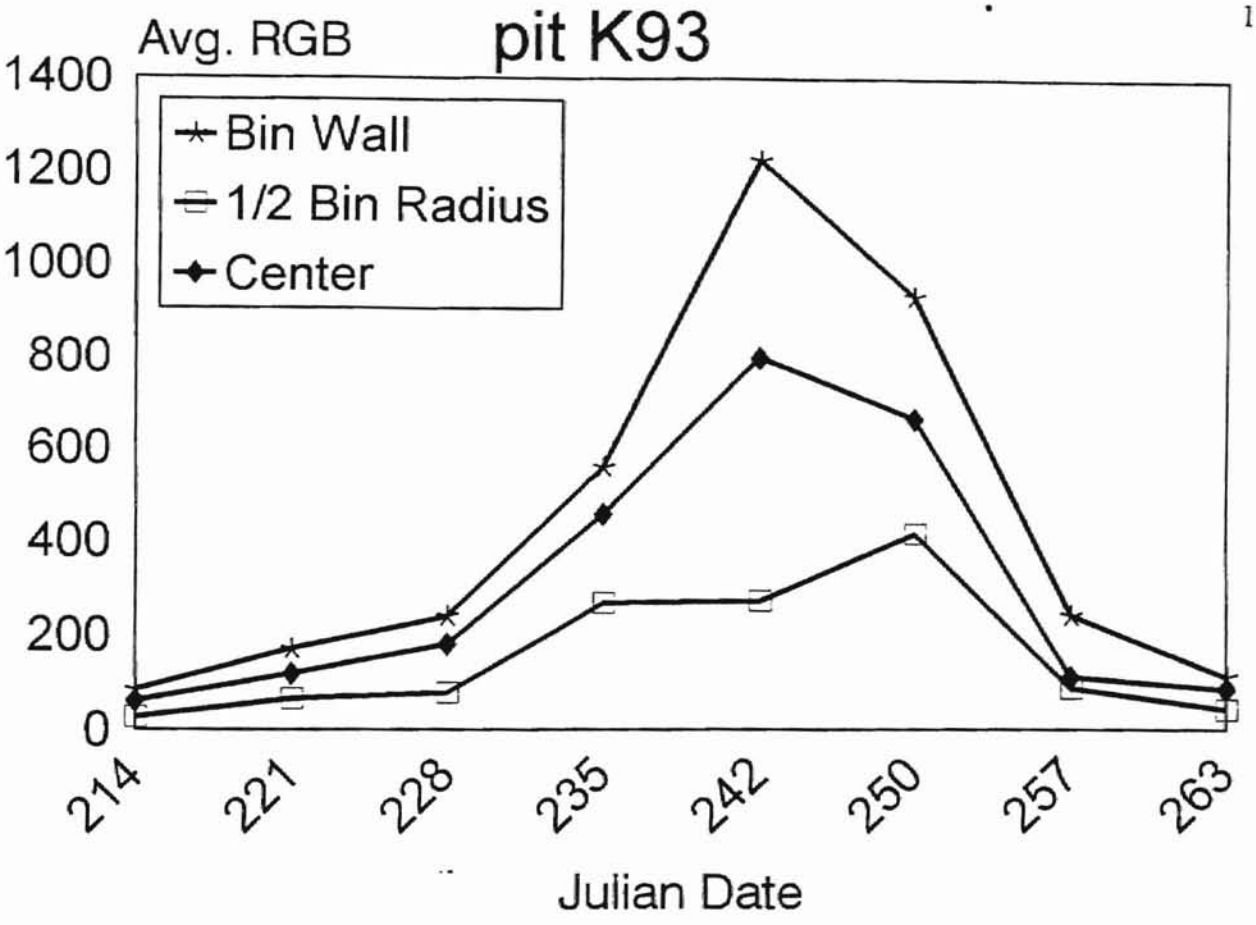

pit C94
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
4
3
2
1
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 15. Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 20 at Kingfisher in 1993; B) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from June 21 to September 13 at Kingfisher in 1994


Avg. RGB
pit K93
Bin Wall
1/2 Bin Radius
Center
1400
1200
1000
800
600
400
200
0
214
221
228
235
242
250
257
263
Julian Date

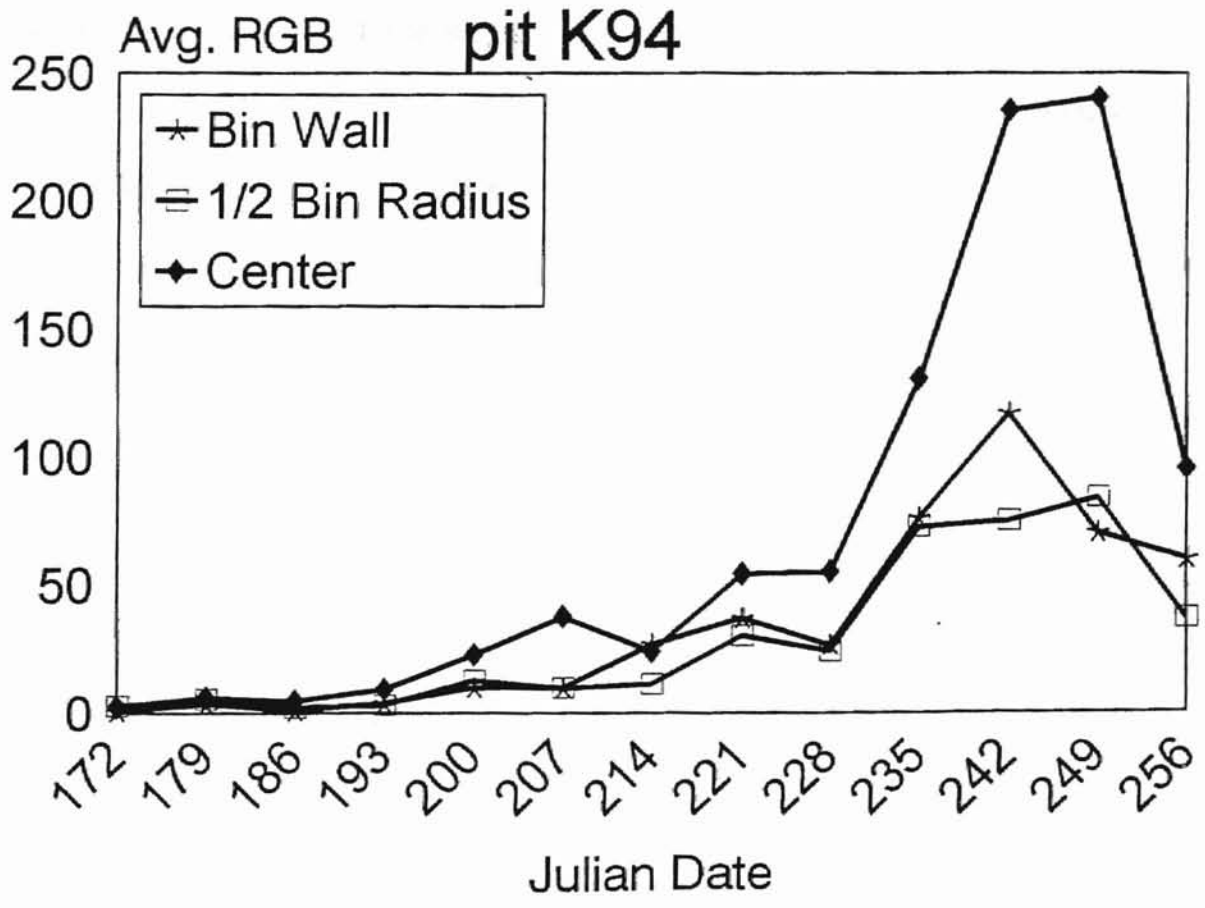
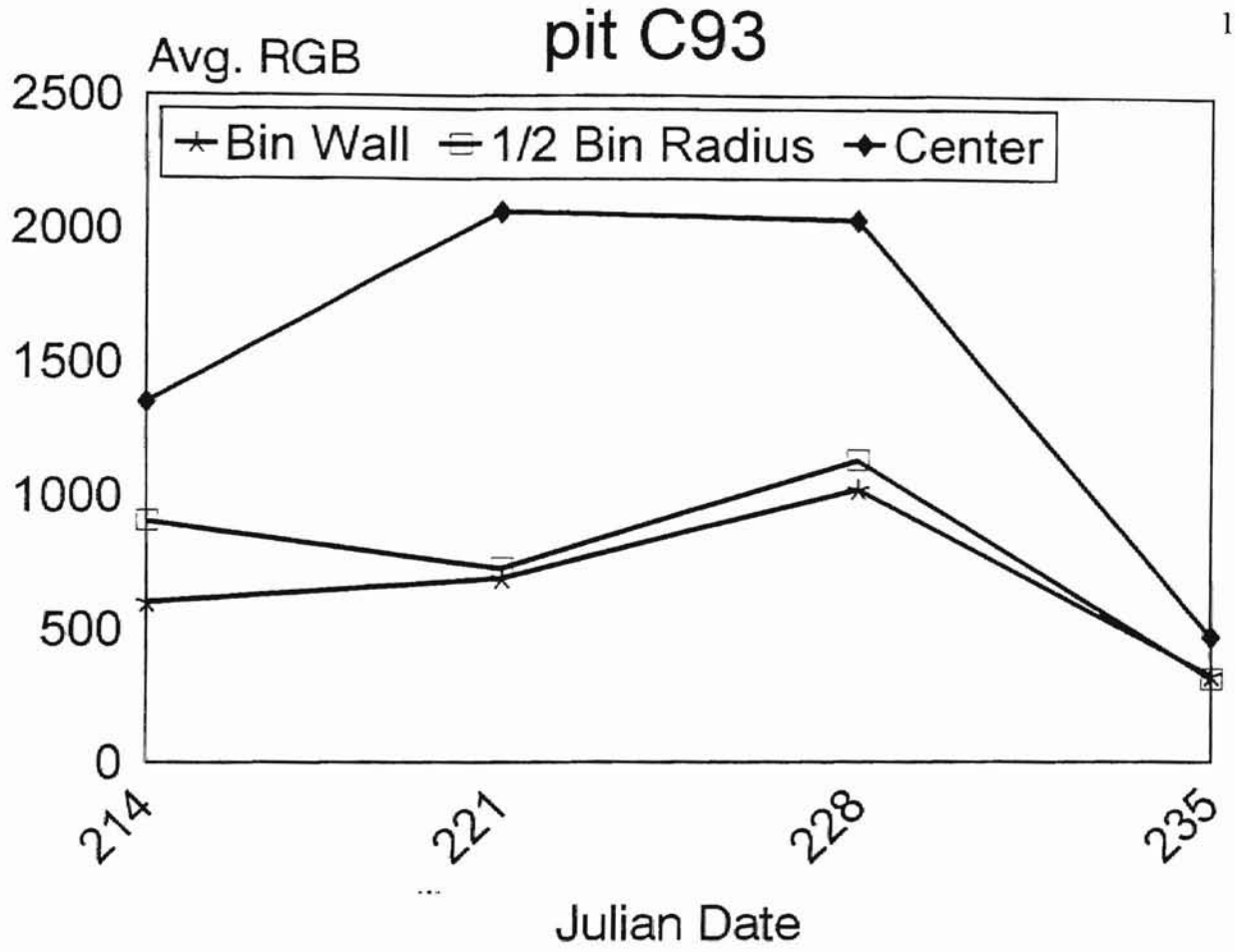

Avg. RGB
pit K94
Bin Wall
1/2 Bin Radius
Center
250
200
150
100
50
0
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 16. Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from June 28 to August 16 at Crescent in 1994


pit C93
Avg. RGB
2500
2000
1500
1000
500
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
Julian Date

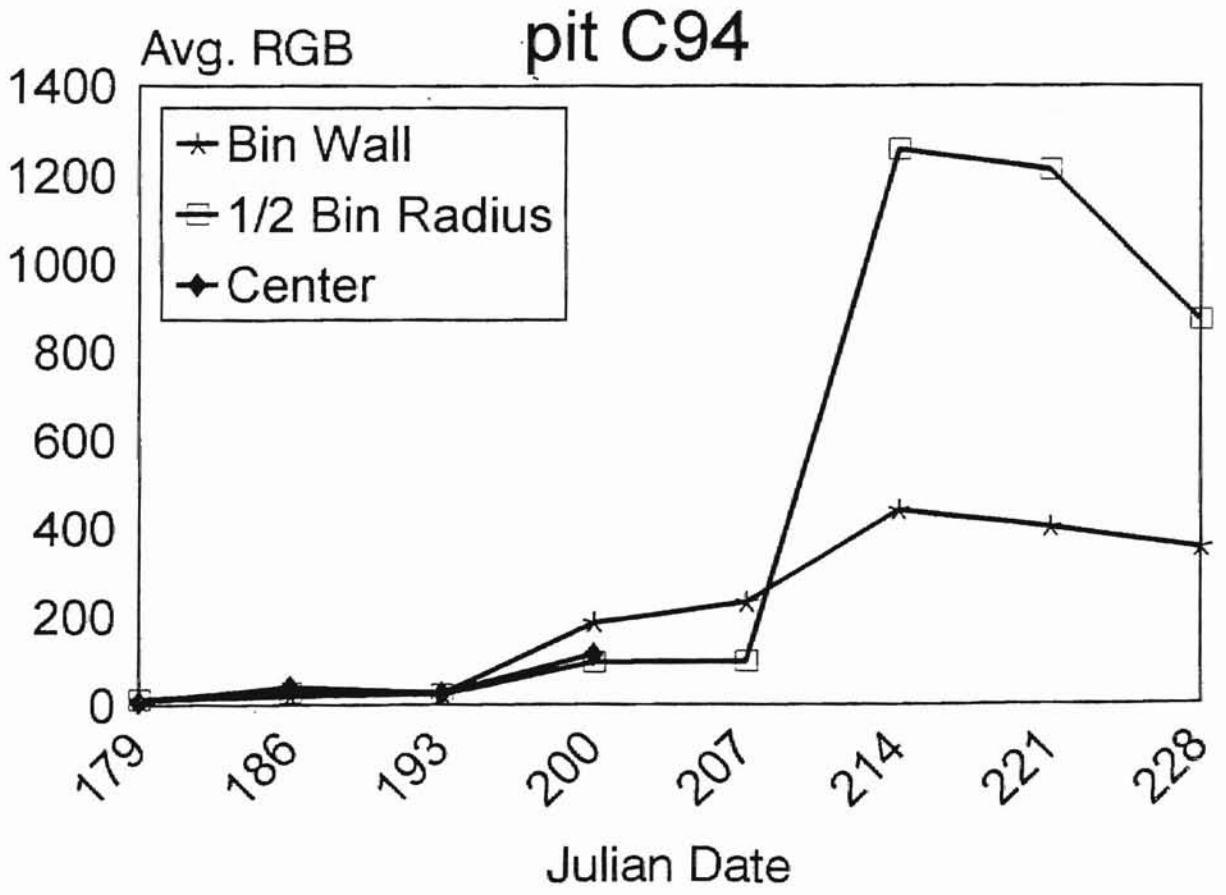
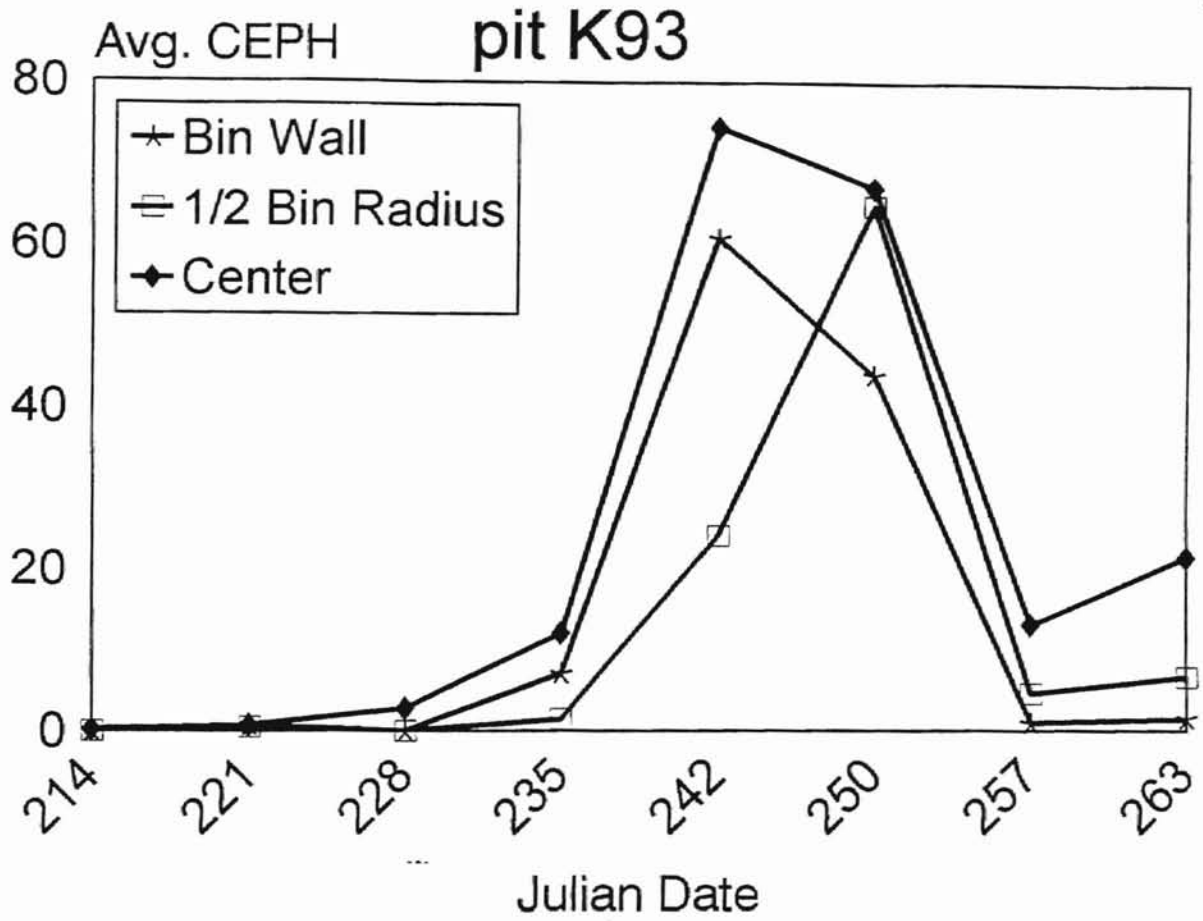

pit C94
Avg. RGB
1400
1200
1000
800
600
400
200
0
Bin Wall
1/2 Bin Radius
Center
179
186
193
200
207
214
221
228
Julian Date

Fig. 17. Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 20 at Kingfisher in 1993; B) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 13 at Kingfisher in 1994


Avg. CEPH
pit K93
80
60
40
20
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
242
250
257
263
Julian Date

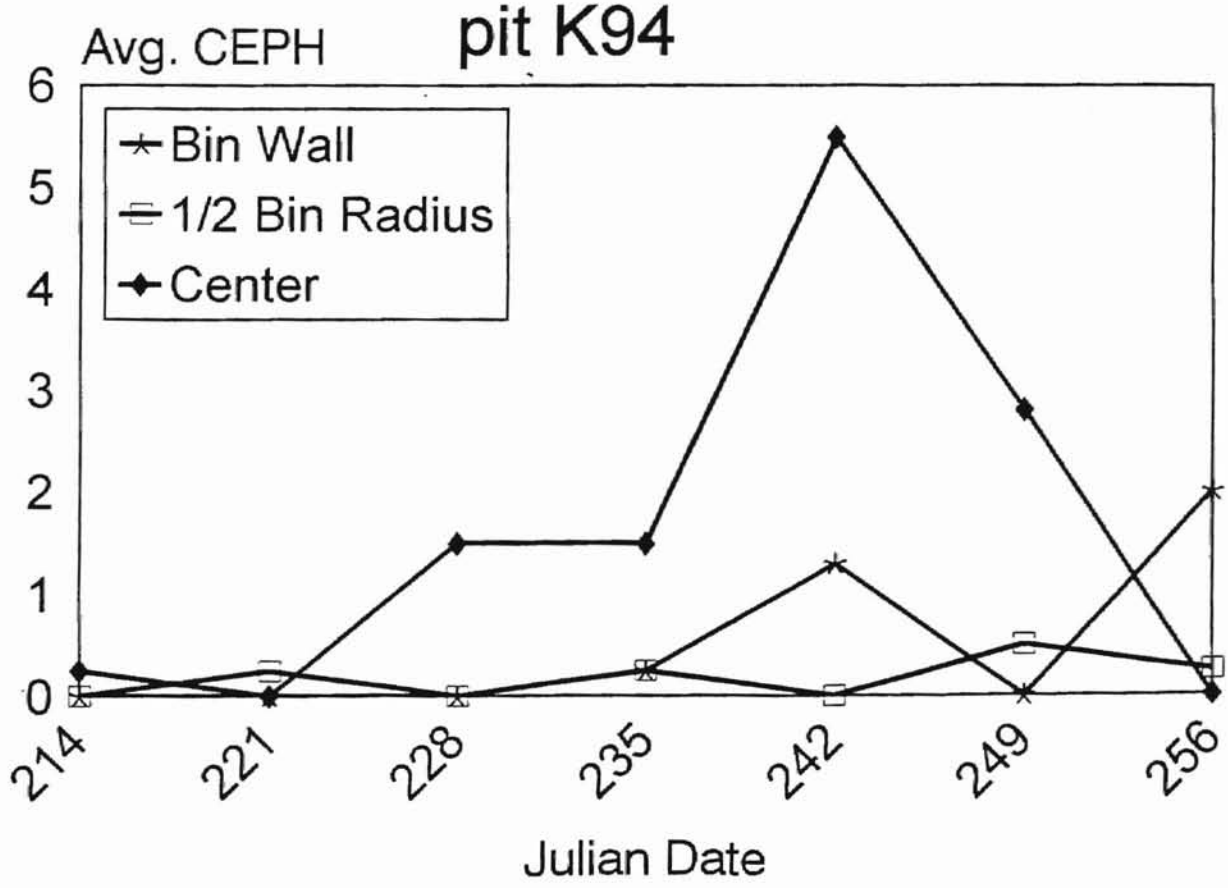
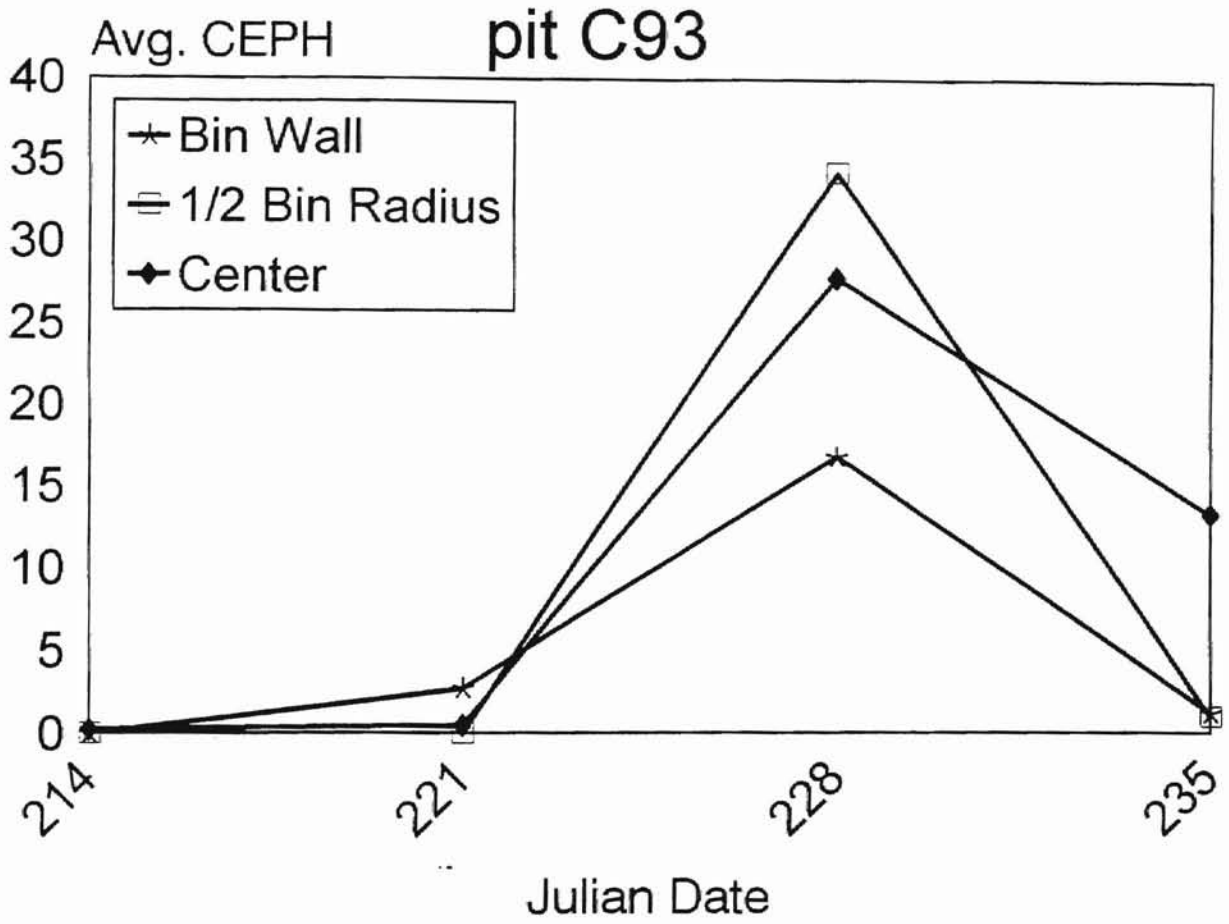

Avg. CEPH
pit K94
6
5
4
3
2
1
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
242
249
256
Julian Date

Fig. 18. Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from June 28 to August 16 at Crescent in 1994


Avg. CEPH
pit C93
Bin Wall
1/2 Bin Radius
Center
40
35
30
25
20
15
10
5
0
214
221
228
235
Julian Date

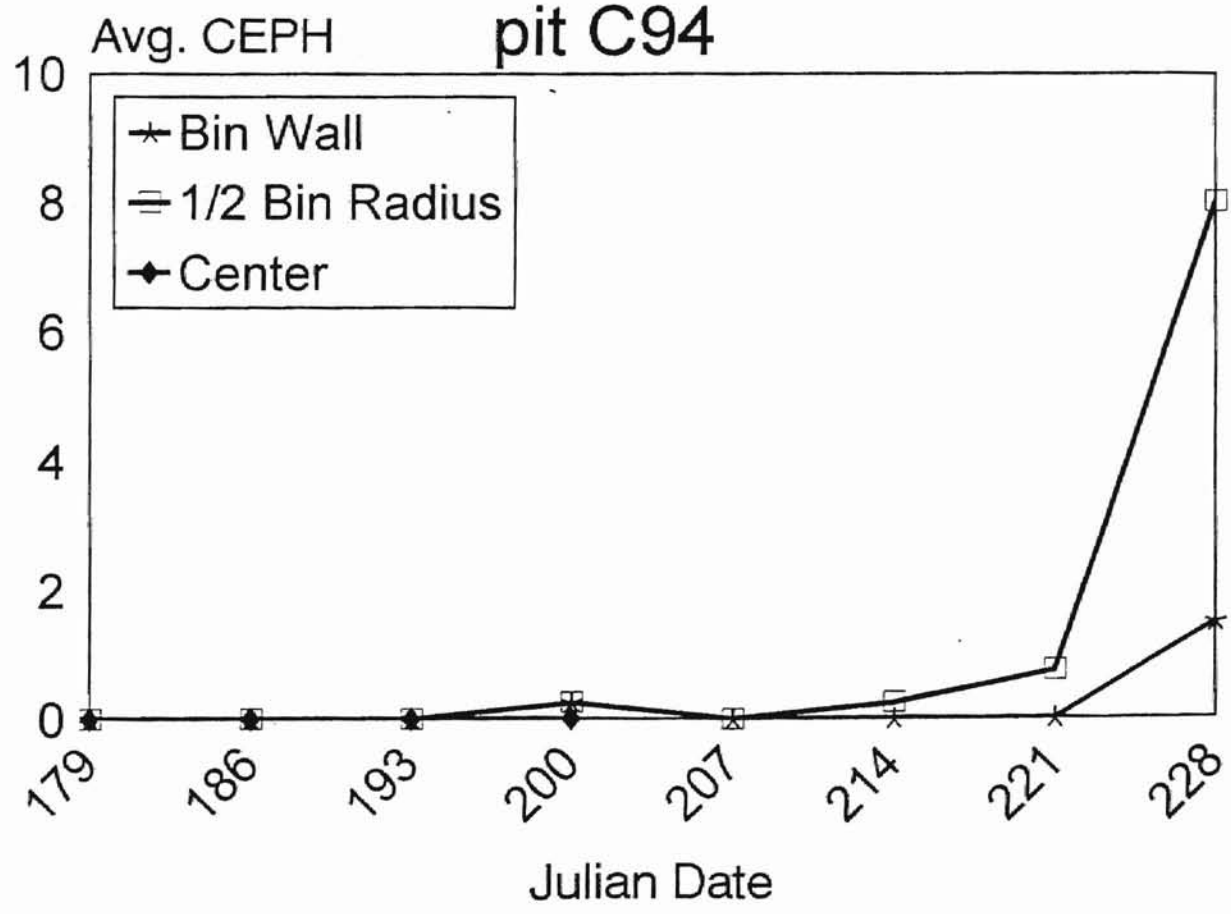
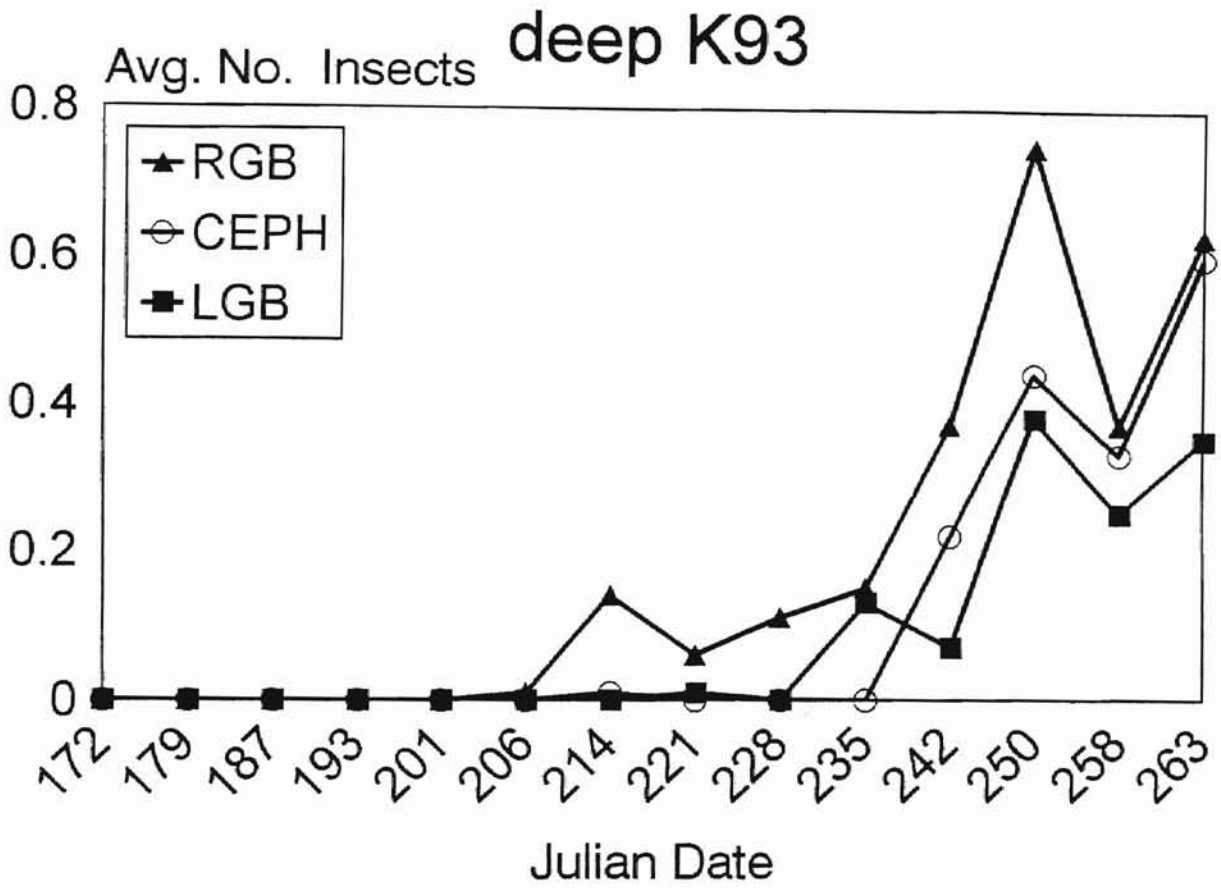

Avg. CEPH
pit C94
Bin Wall
1/2 Bin Radius
Center
10
8
6
4
2
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 19. Average number of adult insects captured in deep cup probe samples at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in deep cup probe samples from June 21 to September 20 at Kingfisher in 1993; LGB, lesser grain borer, *R. dominica*; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni* ; B) Average number of adult insects captured in deep cup probe samples from June 21 to September 20 at Kingfisher in 1994; LGB, lesser grain borer, *R. dominica*; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni*


deep K93
Avg. No. Insects
0.8
0.6
0.4
0.2
0
RGB
CEPH
LGB
172
179
187
193
201
206
214
221
228
235
242
250
258
263
Julian Date

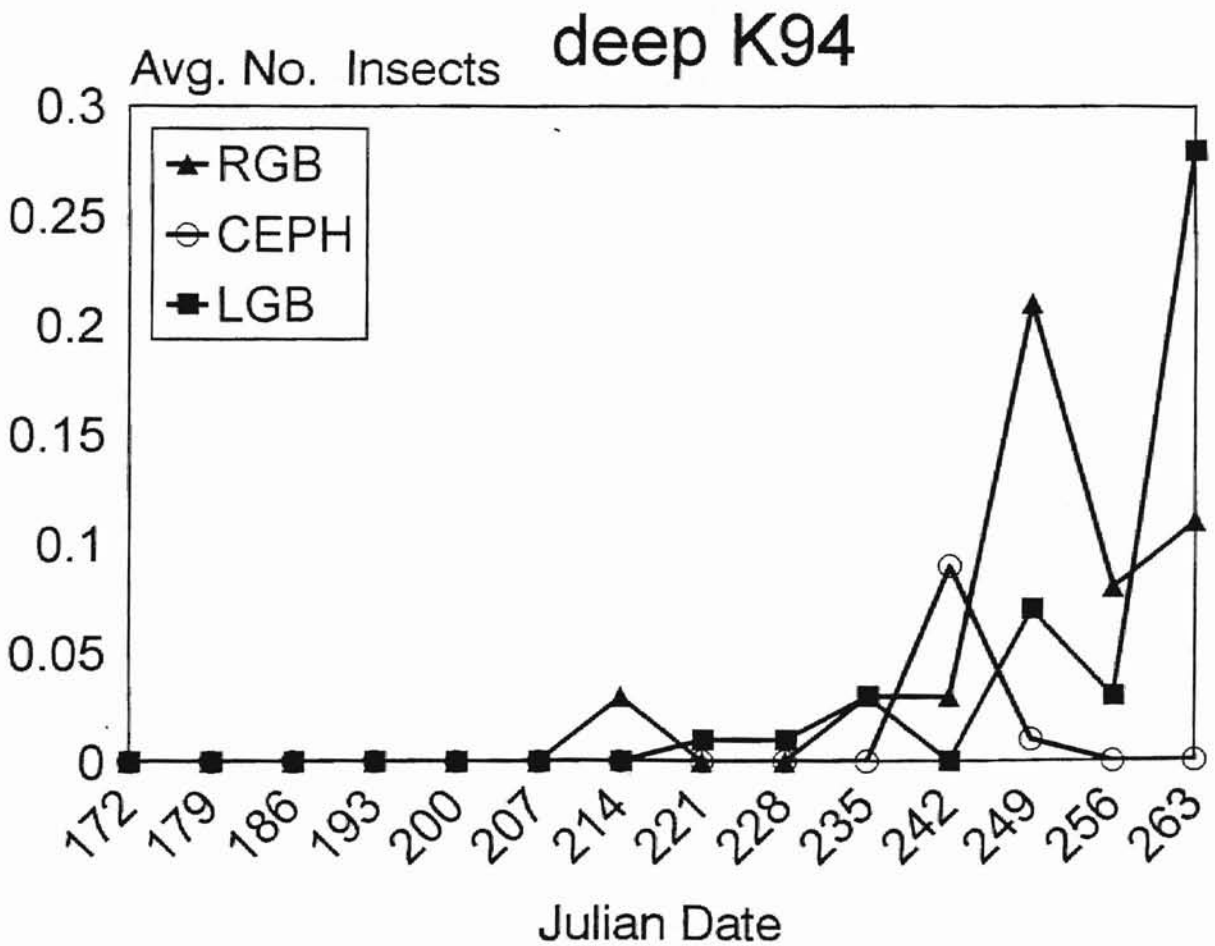
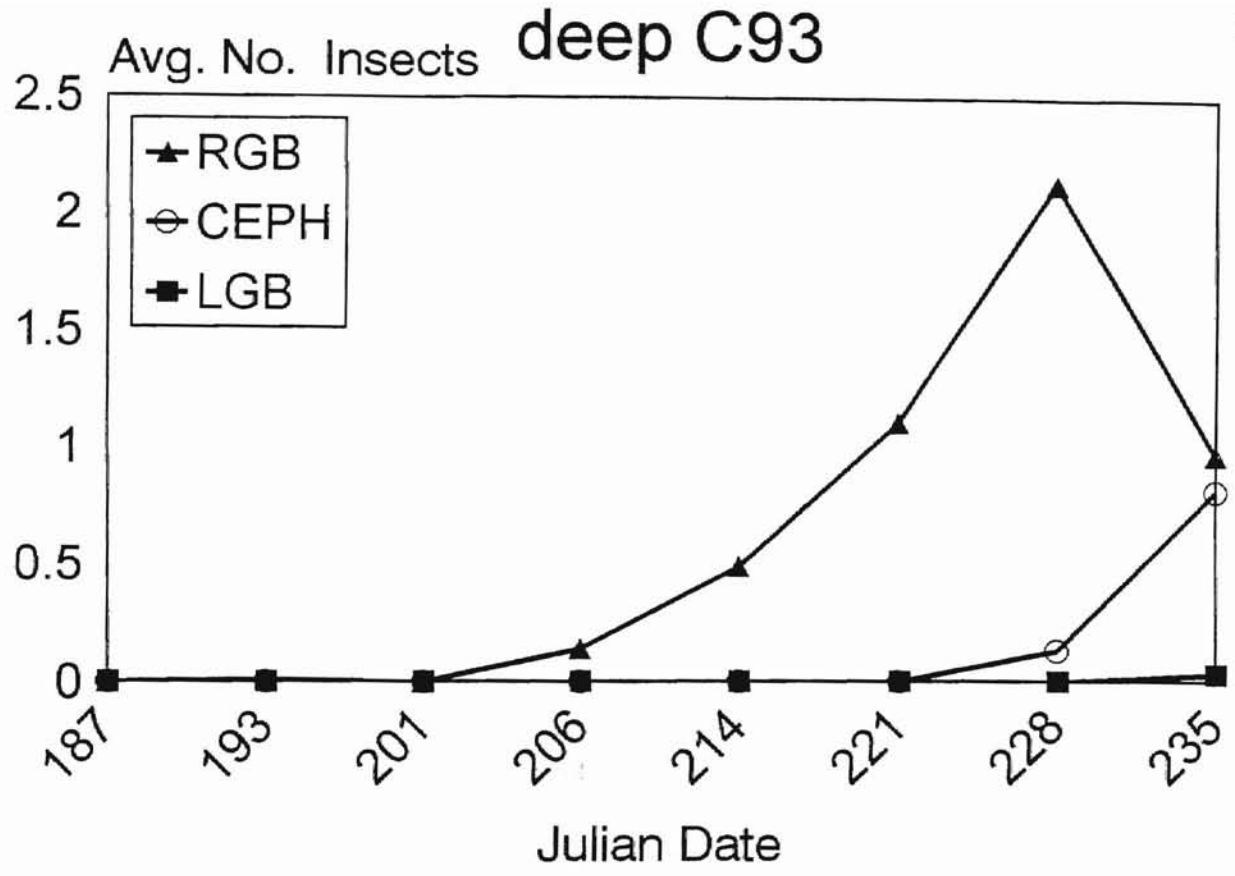

deep K94
Avg. No. Insects
0.3
0.25
0.2
0.15
0.1
0.05
0
RGB
CEPH
LGB
172
179
186
193
200
207
214
221
228
235
242
249
256
263
Julian Date

Fig. 20. Average number of adult insects captured in deep cup probe samples at Crescent in 1993-1994

Key: A) Average number of adult insects captured in deep cup probe samples from July 6 to August 23 at Crescent in 1993; LGB, lesser grain borer, *R. dominica*; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni* ; B) Average number of adult insects captured in deep cup probe samples from July 5 to August 23 at Crescent in 1994; LGB, lesser grain borer, *R. dominica*; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni*


deep C93
Avg. No. Insects
2.5
2
1.5
1
0.5
0
RGB
CEPH
LGB
187
193
201
206
214
221
228
235
Julian Date

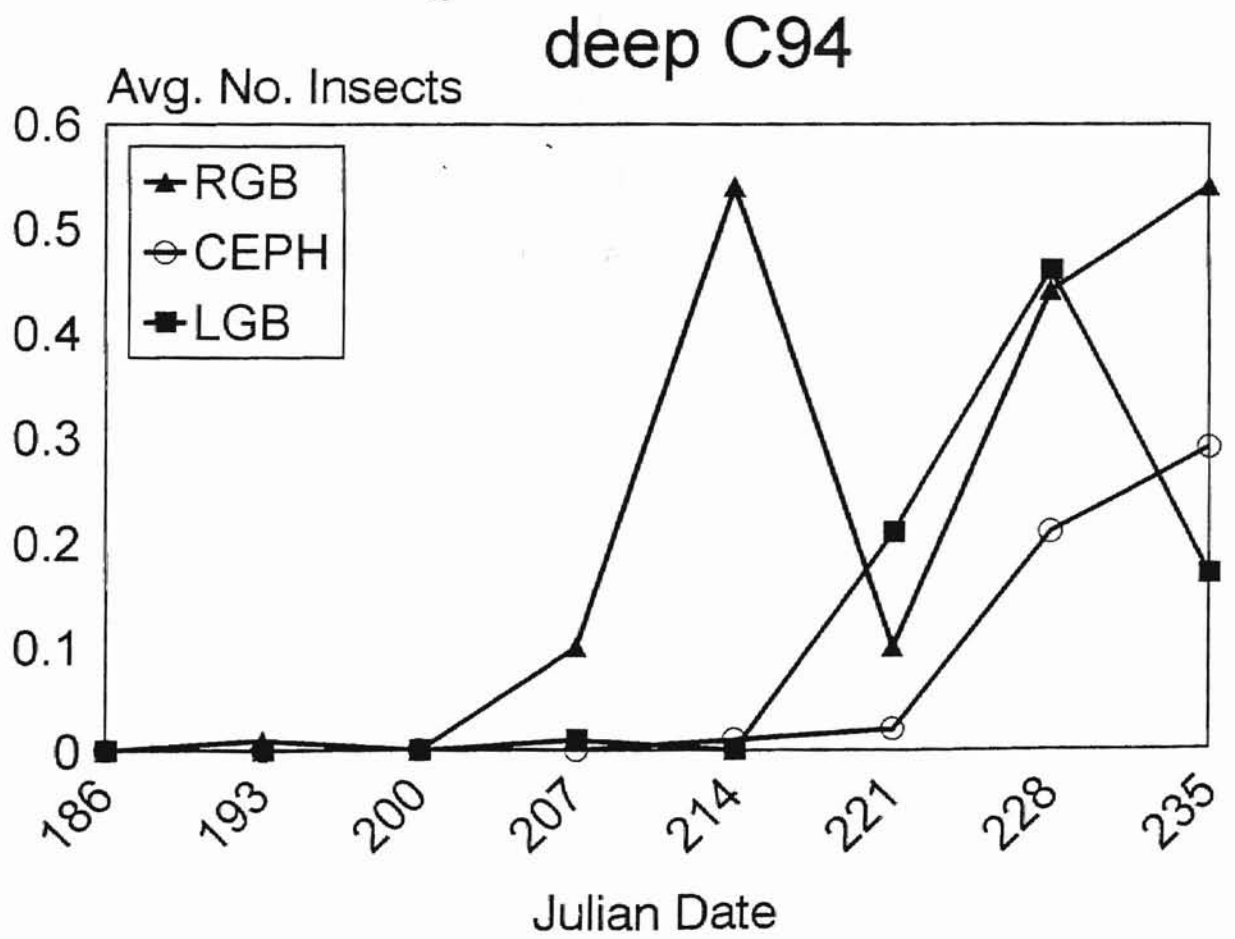
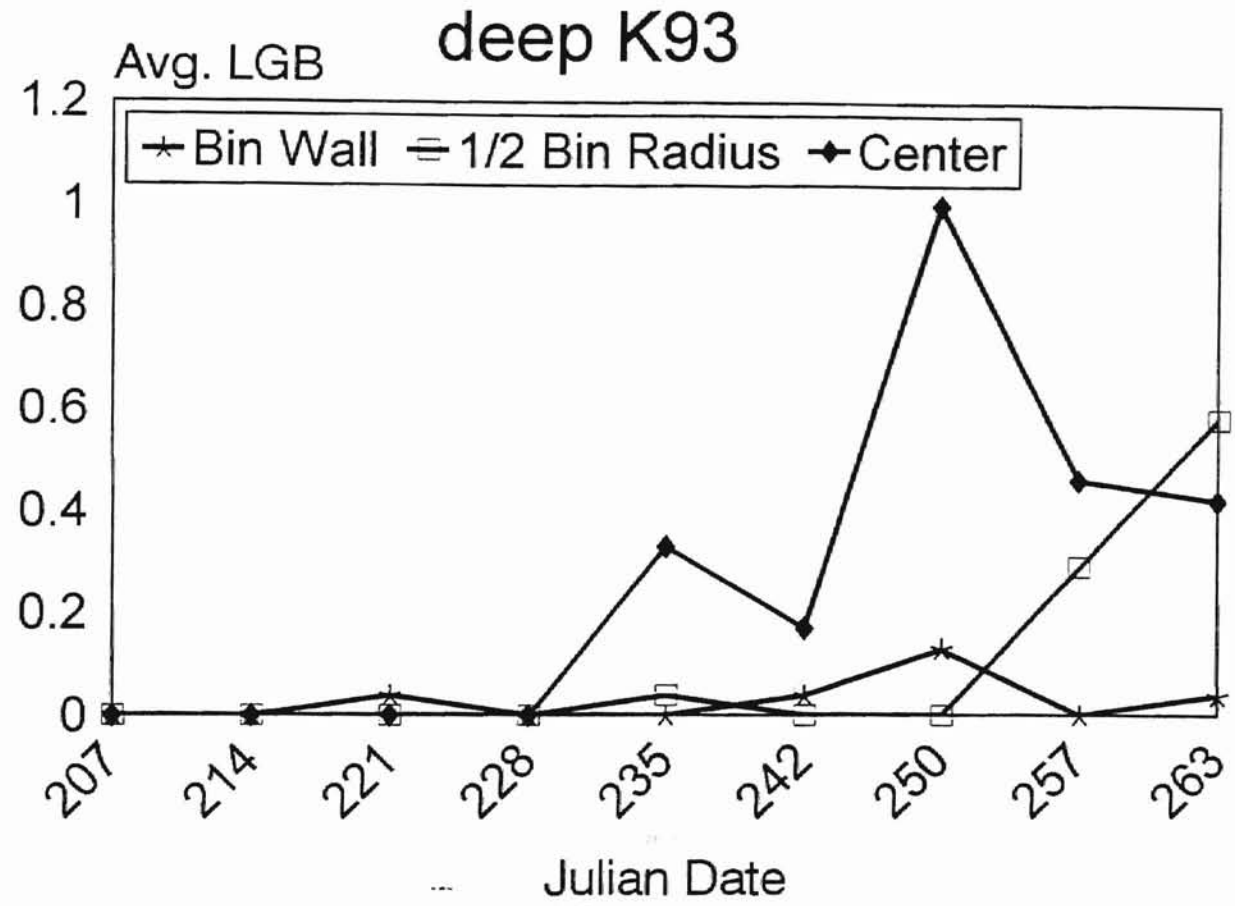

deep C94
Avg. No. Insects
0.6
0.5
0.4
0.3
0.2
0.1
0
RGB
CEPH
LGB
186
193
200
207
214
221
228
235
Julian Date

Fig. 21. Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1993; B) Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1994


deep K93
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
1.2
1
0.8
0.6
0.4
0.2
0
207
214
221
228
235
242
250
257
263
Julian Date

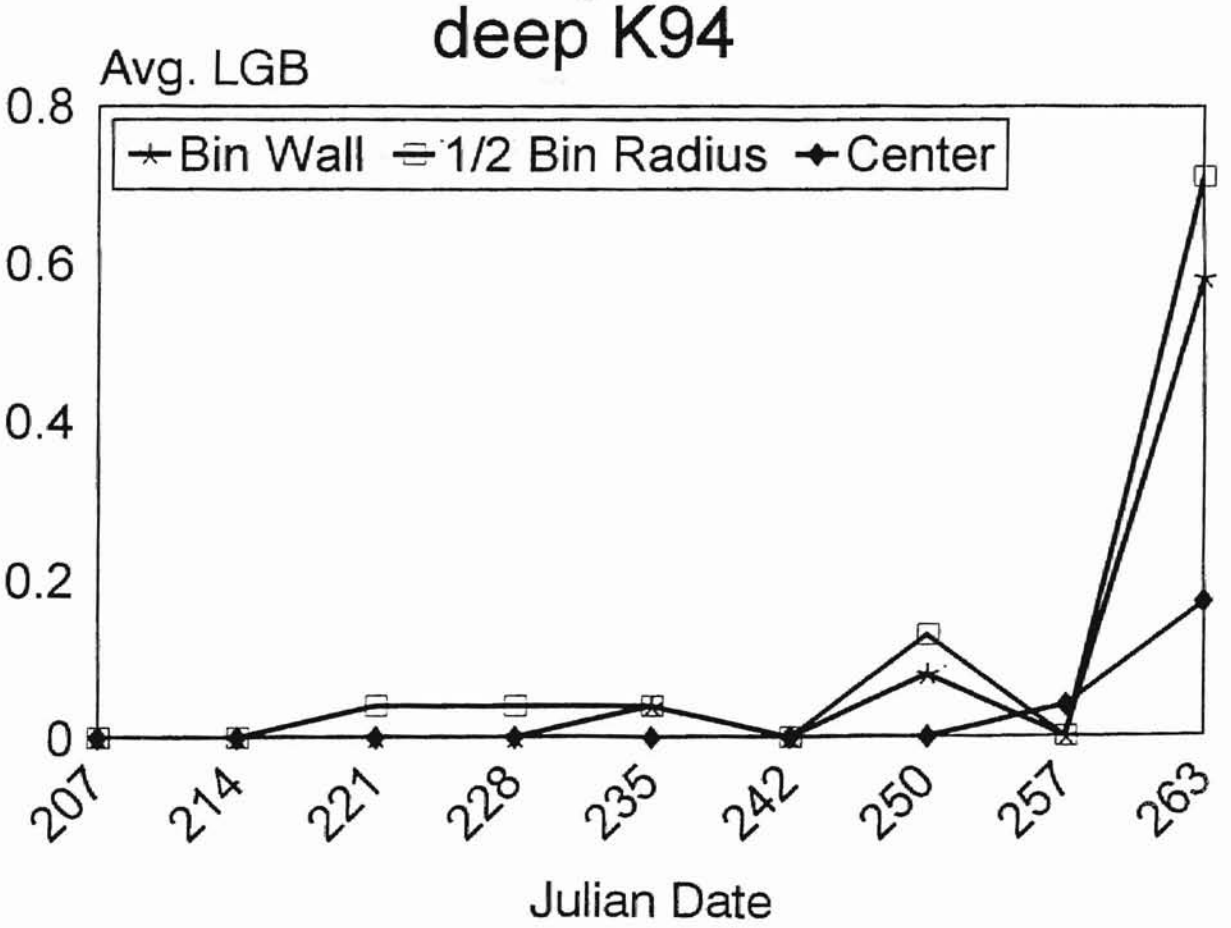
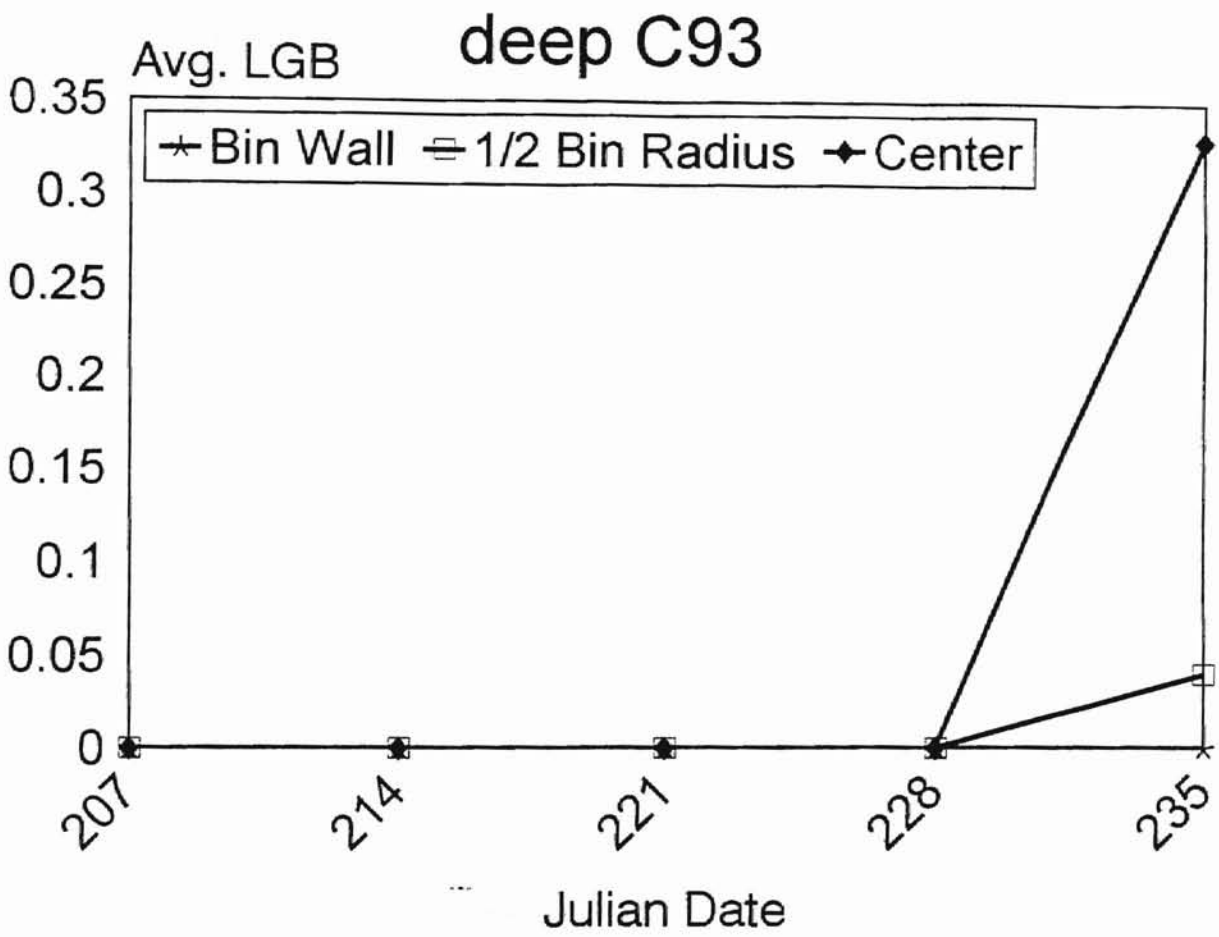

deep K94
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
0.8
0.6
0.4
0.2
0
207
214
221
228
235
242
250
257
263
Julian Date

Fig. 22. Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *R. dominica* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1994


deep C93
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
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0.3
0.25
0.2
0.15
0.1
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0
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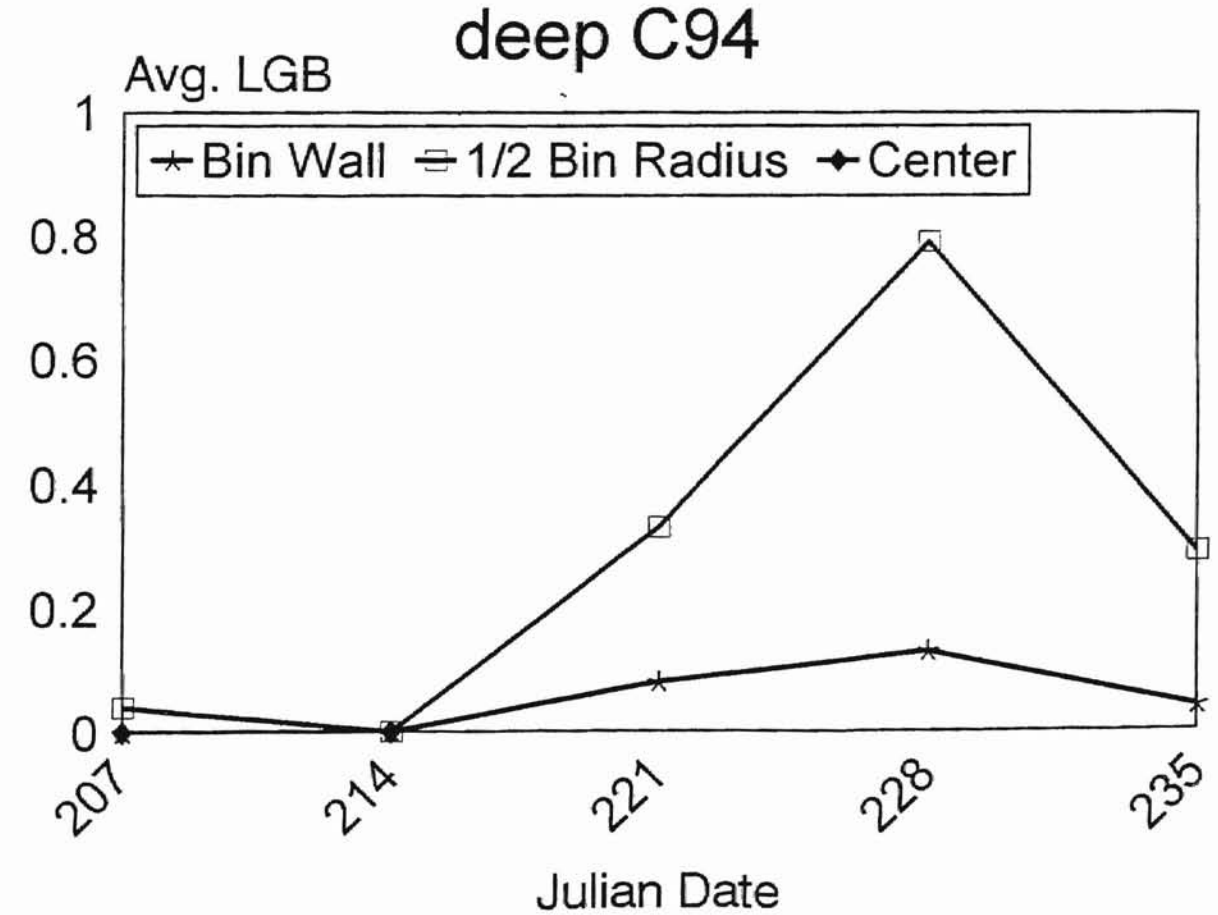
221
228
235
Julian Date


deep C94
Avg. LGB
Bin Wall
1/2 Bin Radius
Center
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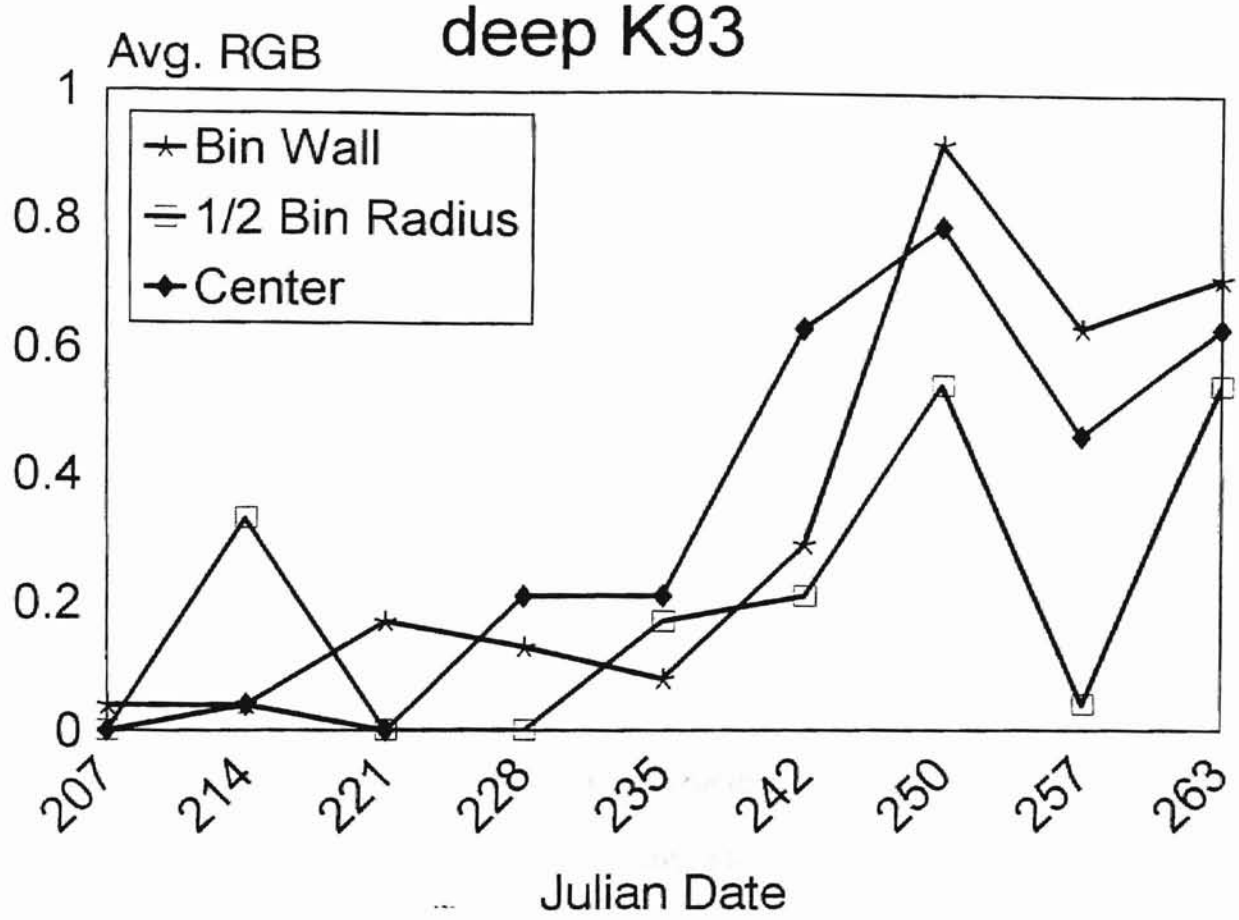
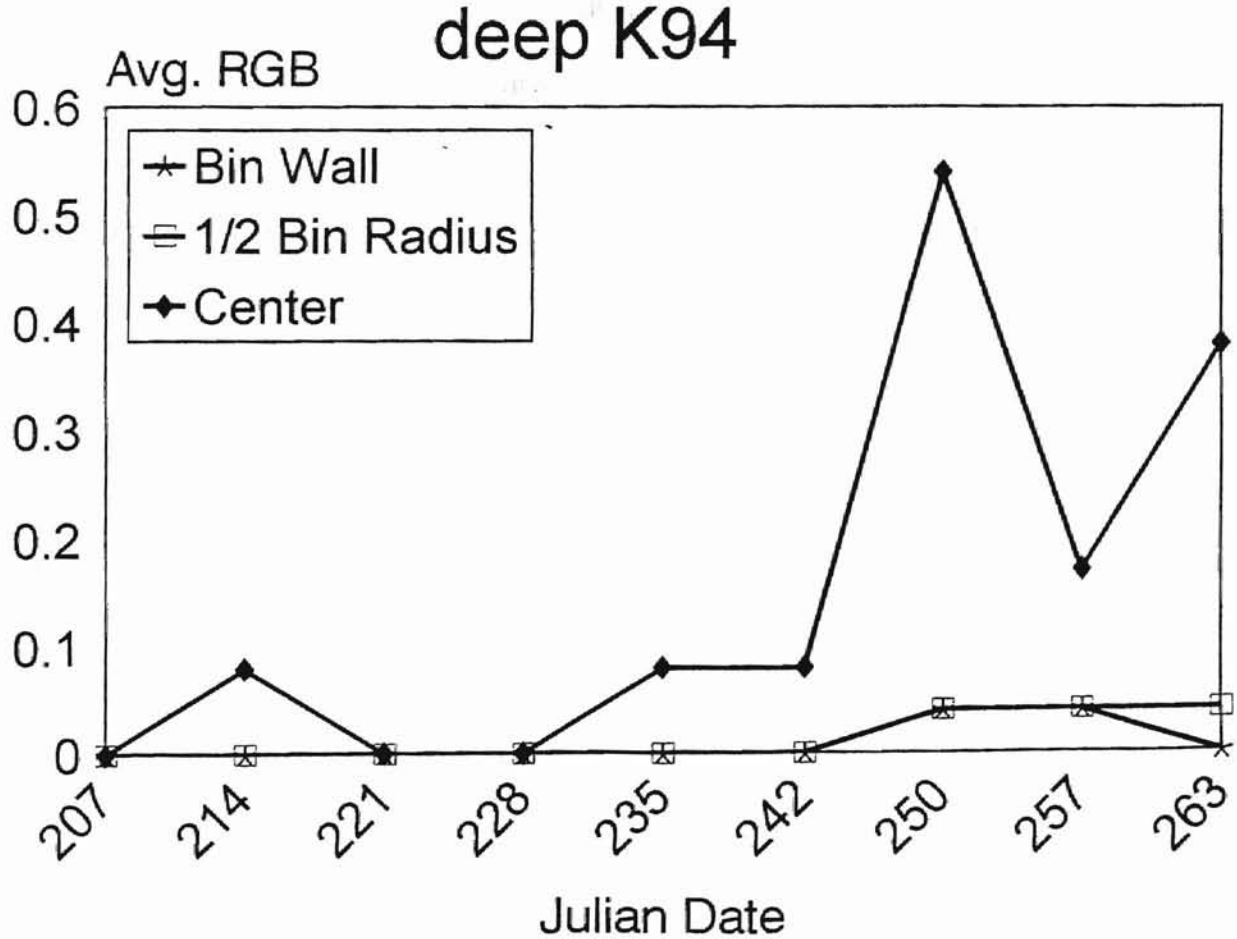
0.8
0.6
0.4
0.2
0
207
214
221
228
235
Julian Date

Fig. 23. Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1993; B) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1994


deep K93
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
1
0.8
0.6
0.4
0.2
0
207
214
221
228
235
242
250
257
263
Julian Date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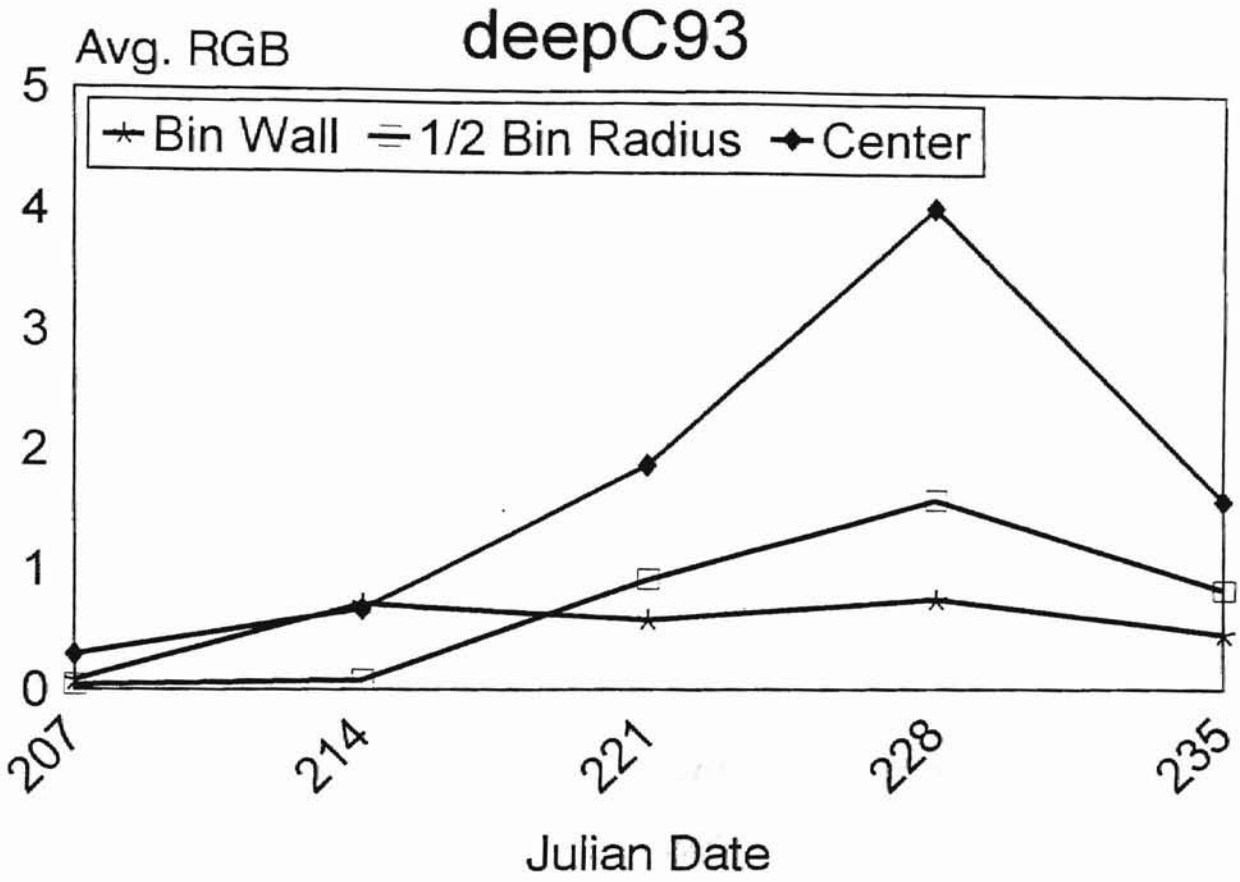
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
0.6
0.5
0.4
0.3
0.2
0.1
0
207
214
221
228
235
242
250
257
263
Julian Date

Fig. 24. Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1994


deepC93
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
5
4
3
2
1
0
207
214
221
228
235
Julian Date

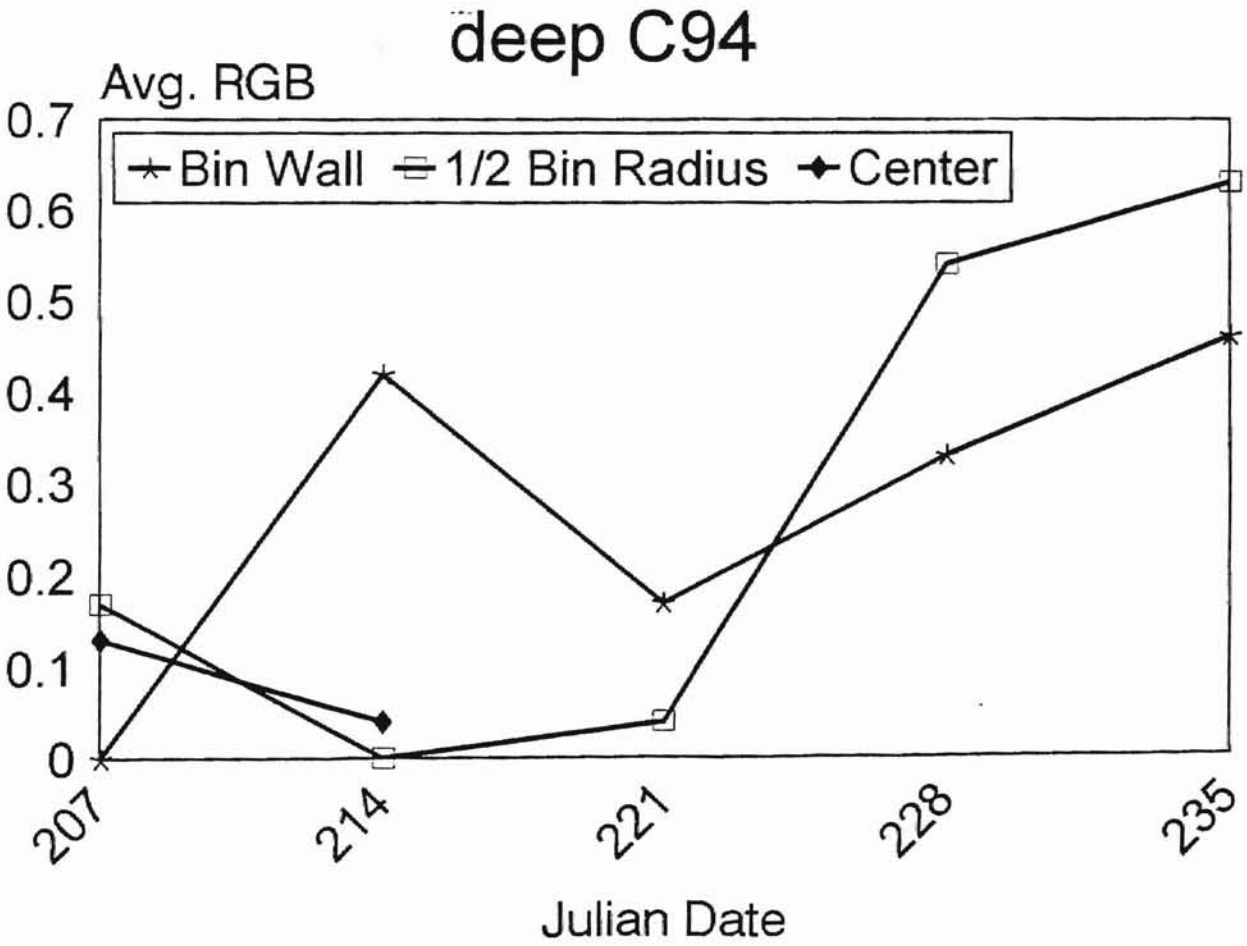
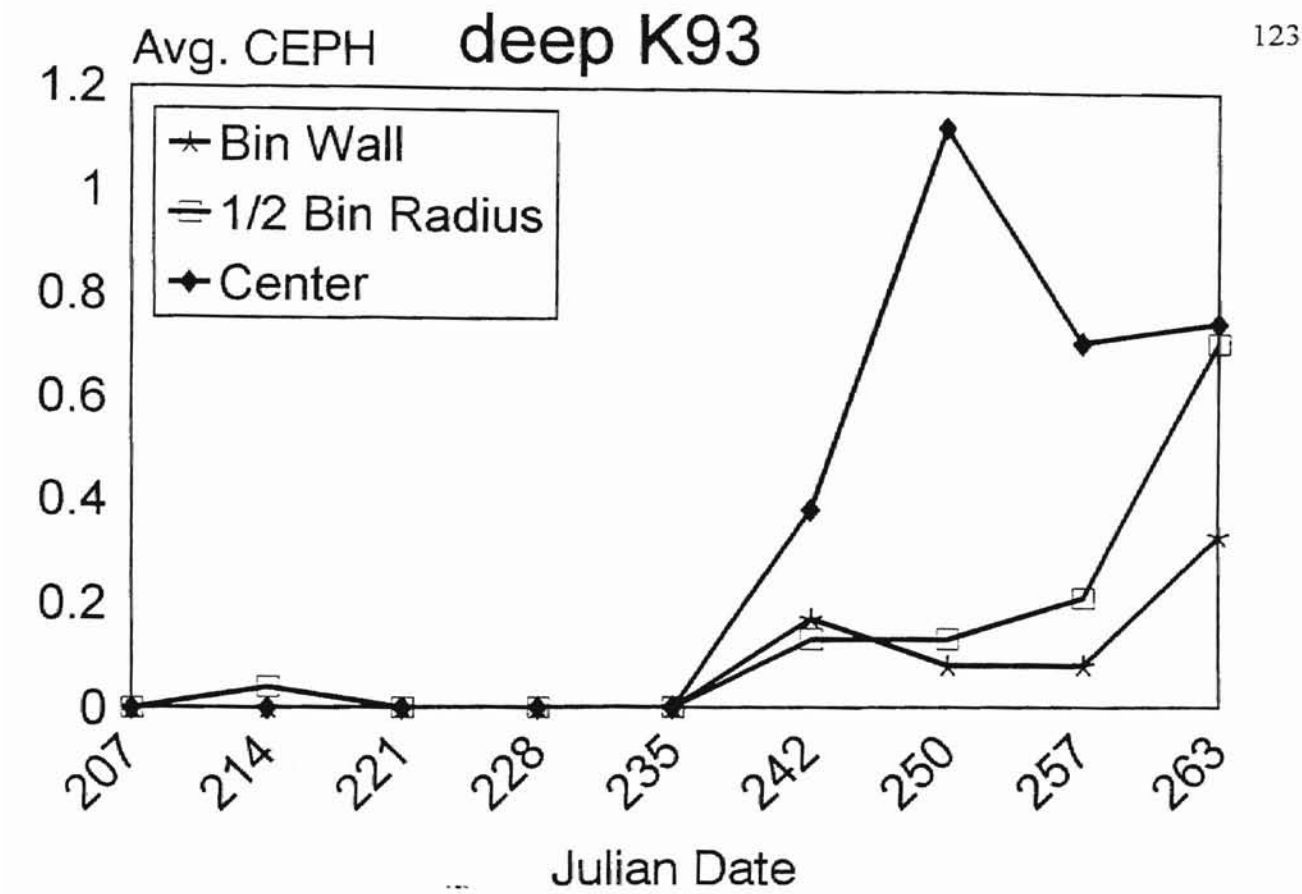

deep C94
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
207
214
221
228
235
Julian Date

Fig. 25. Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1993; B) Average number of *adult . waterstoni* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1994


deep K93
Avg. CEPH
1.2
1
0.8
0.6
0.4
0.2
0
Bin Wall
1/2 Bin Radius
Center
207
214
221
228
235
242
250
257
263
Julian Date

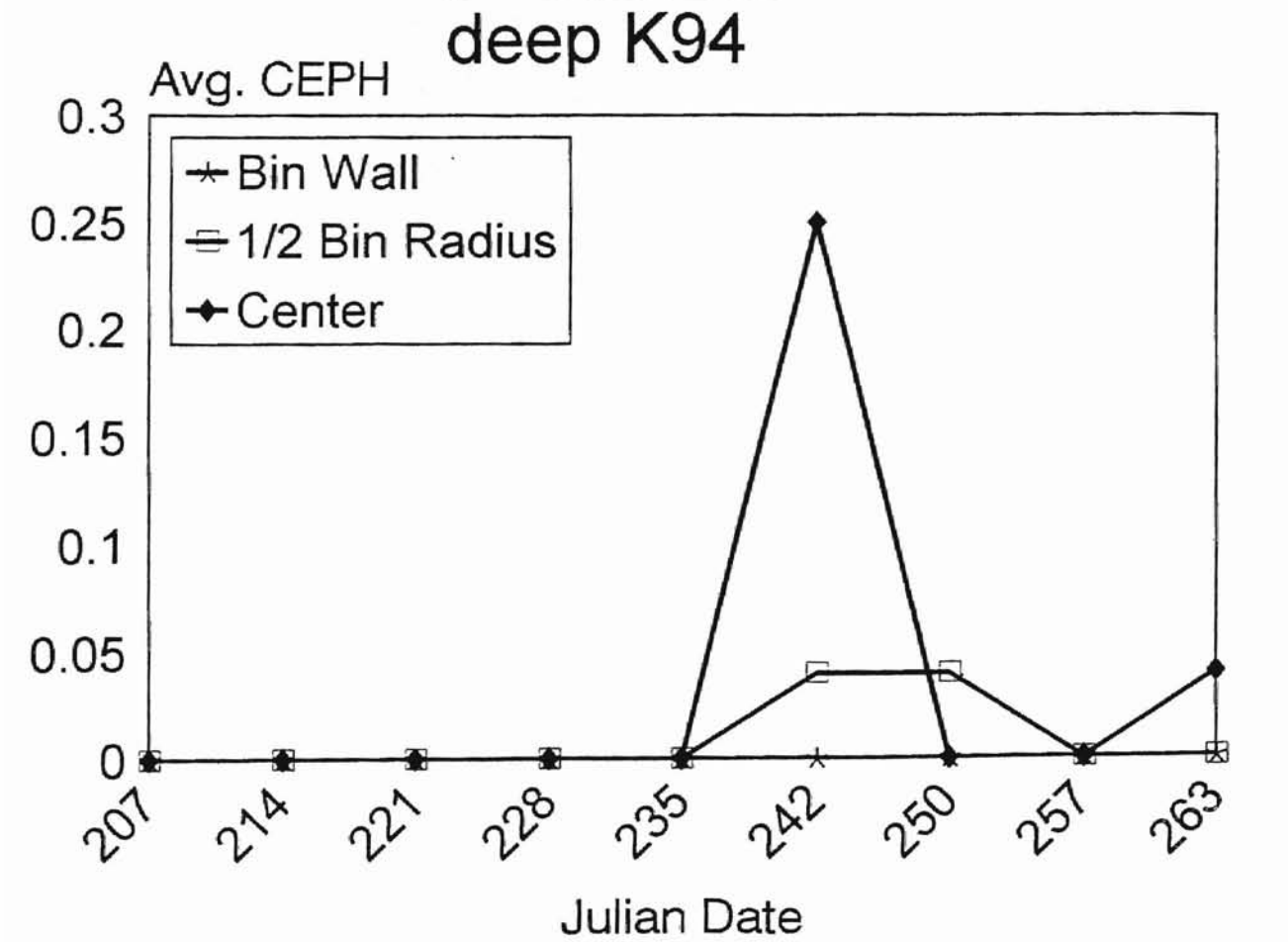
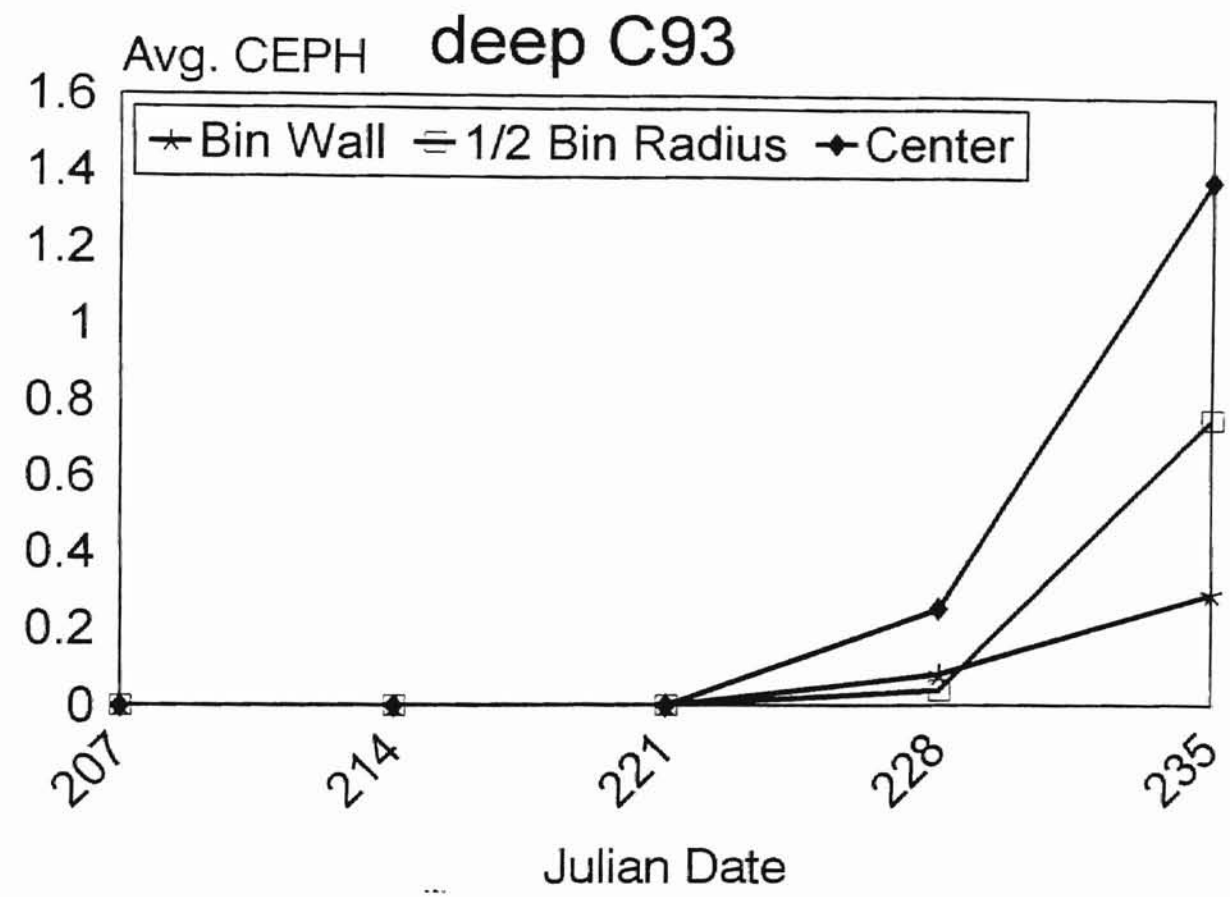

deep K94
Avg. CEPH
0.3
0.25
0.2
0.15
0.1
0.05
0
Bin Wall
1/2 Bin Radius
Center
207
214
221
228
235
242
250
257
263
Julian Date

Fig. 26. Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1994


deep C93
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
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1.4
1.2
1
0.8
0.6
0.4
0.2
0
207
214
221
228
235
Julian Date

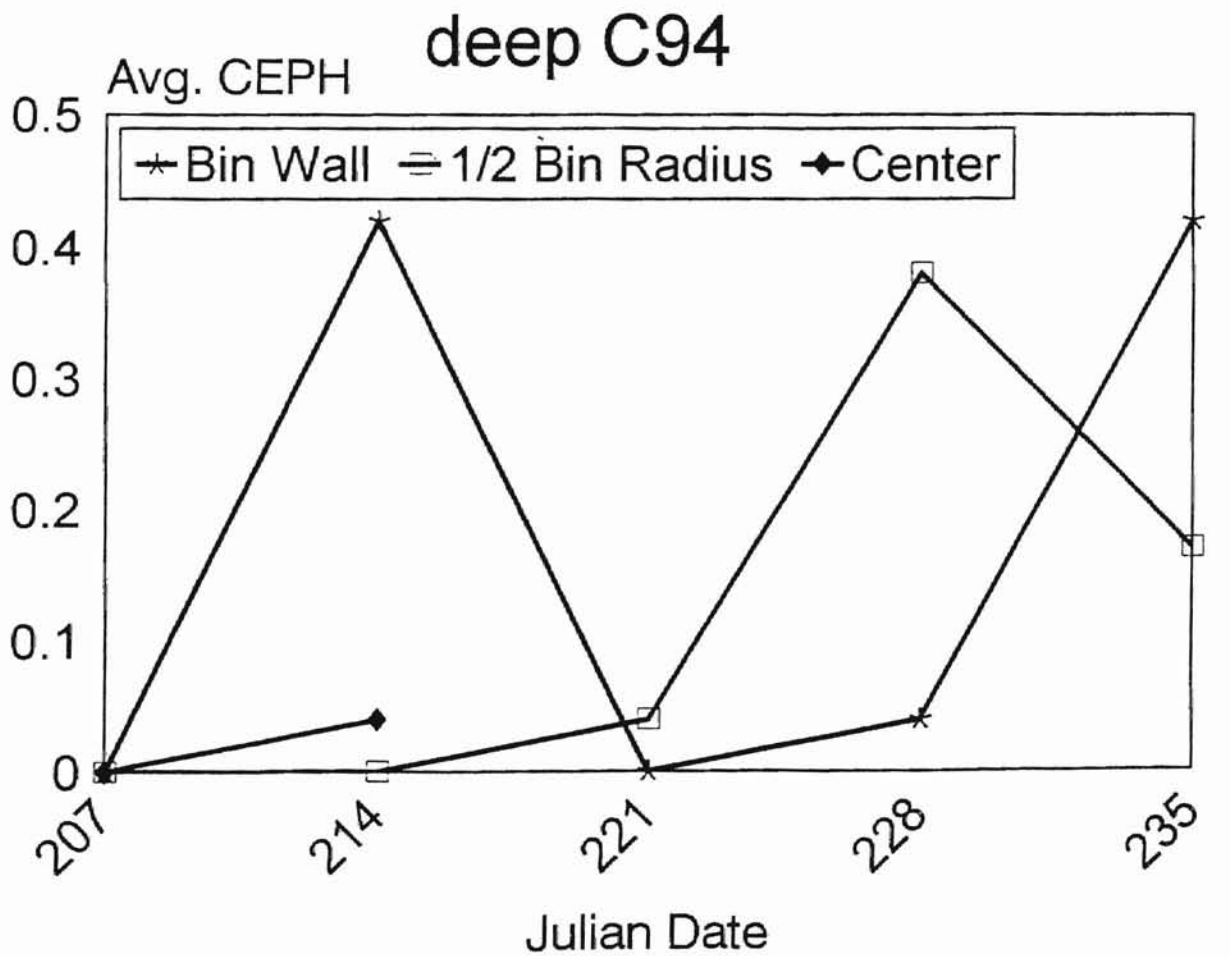
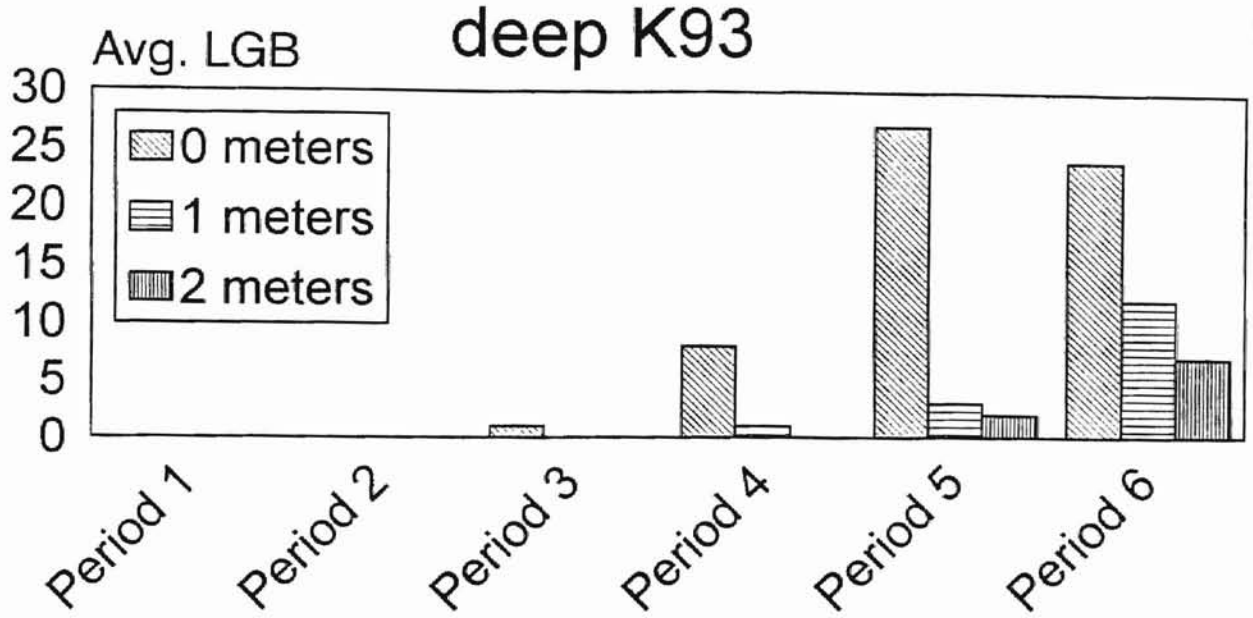
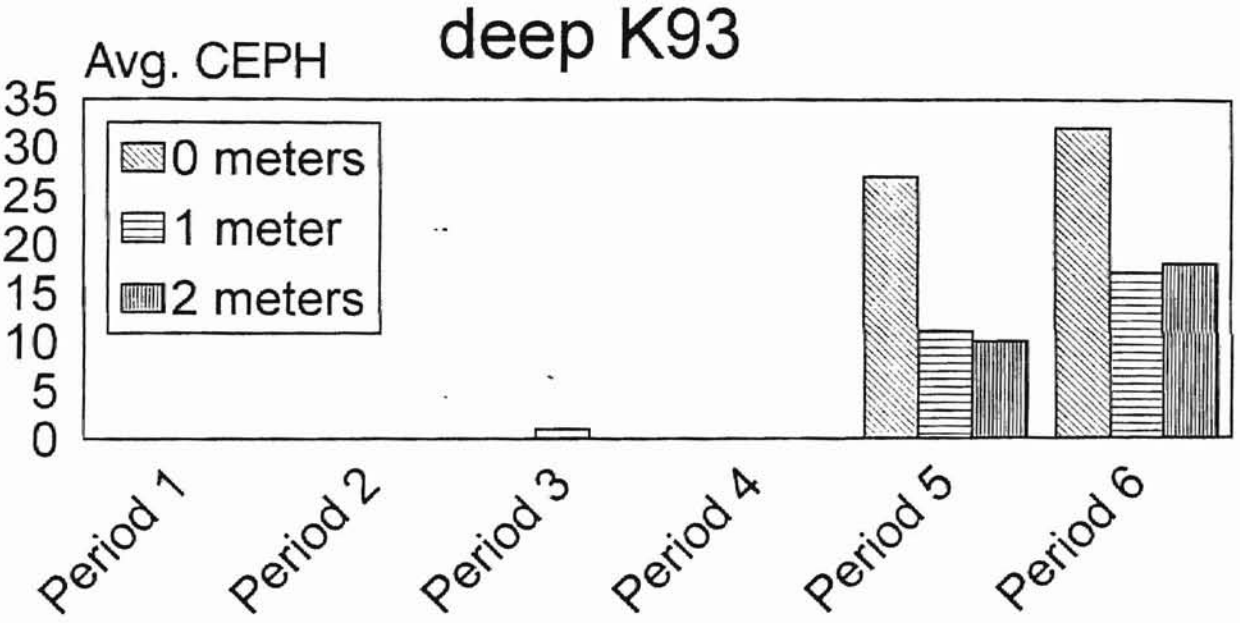

deep C94
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
0.5
0.4
0.3
0.2
0.1
0
207
214
221
228
235
Julian Date

Fig. 27. Average number of adult insects captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993

Key: A) Average number of adult *R. dominica* captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993; B) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993; C) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993; Period 1, July 5 & 12; Period 2, July 19 & 26; Period 3, August 2 & 9; Period 4, August 16 & 23; Period 5, August 30 and September 7; Period 6, September 14 & 20


deep K93
Avg. LGB
30
25
20
15
10
5
0
0 meters
1 meters
2 meters
Period 1
Period 2
Period 3
Period 4
Period 5
Period 6


deep K93
Avg. CEPH
35
30
25
20
15
10
5
0
0 meters
1 meter
2 meters
Period 1
Period 2
Period 3
Period 4
Period 5
Period 6

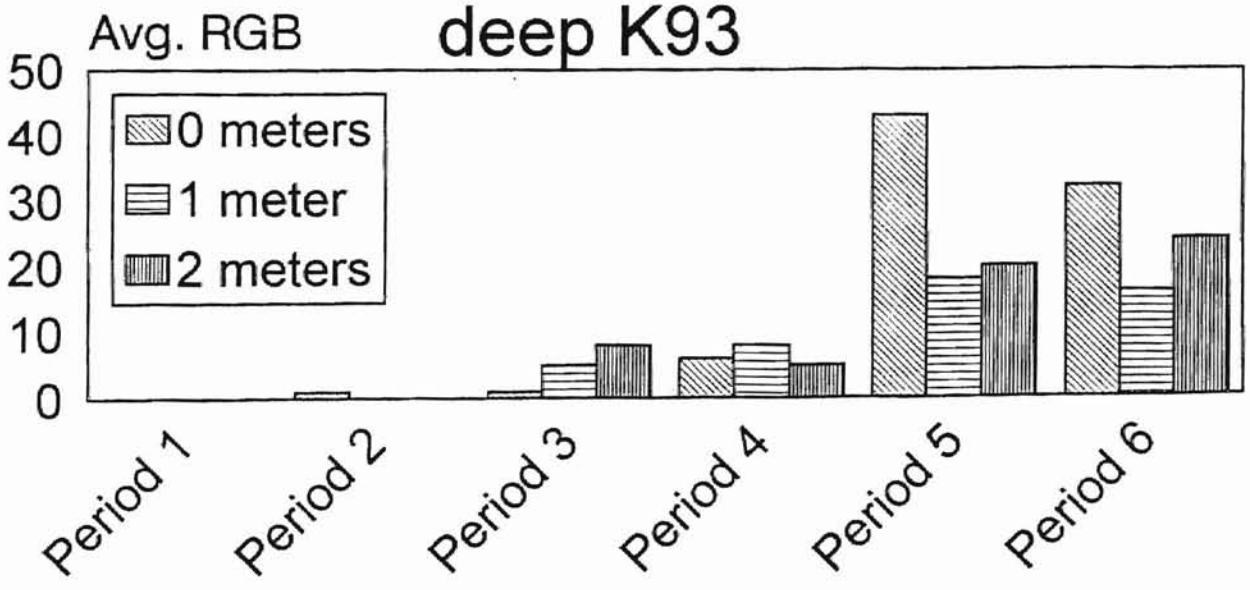
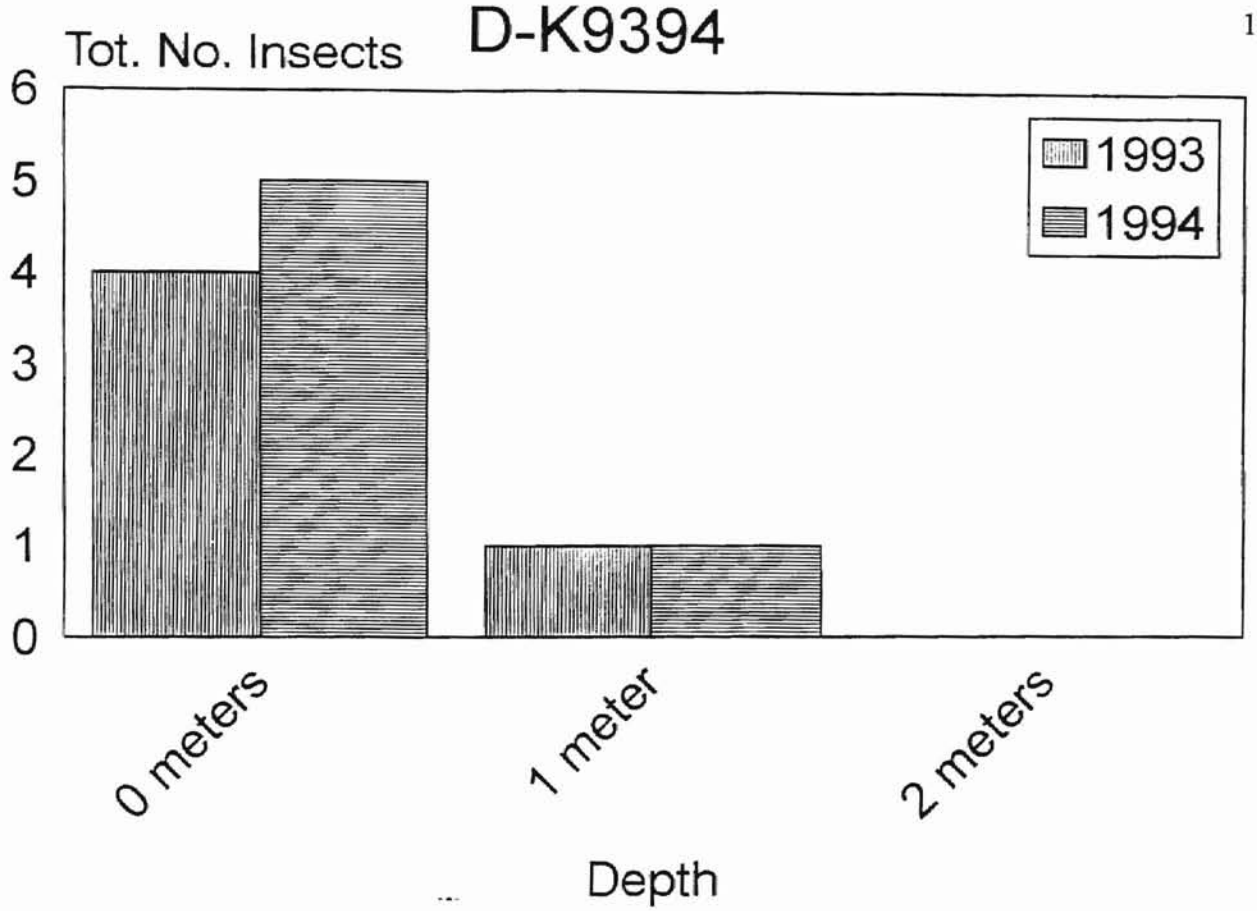
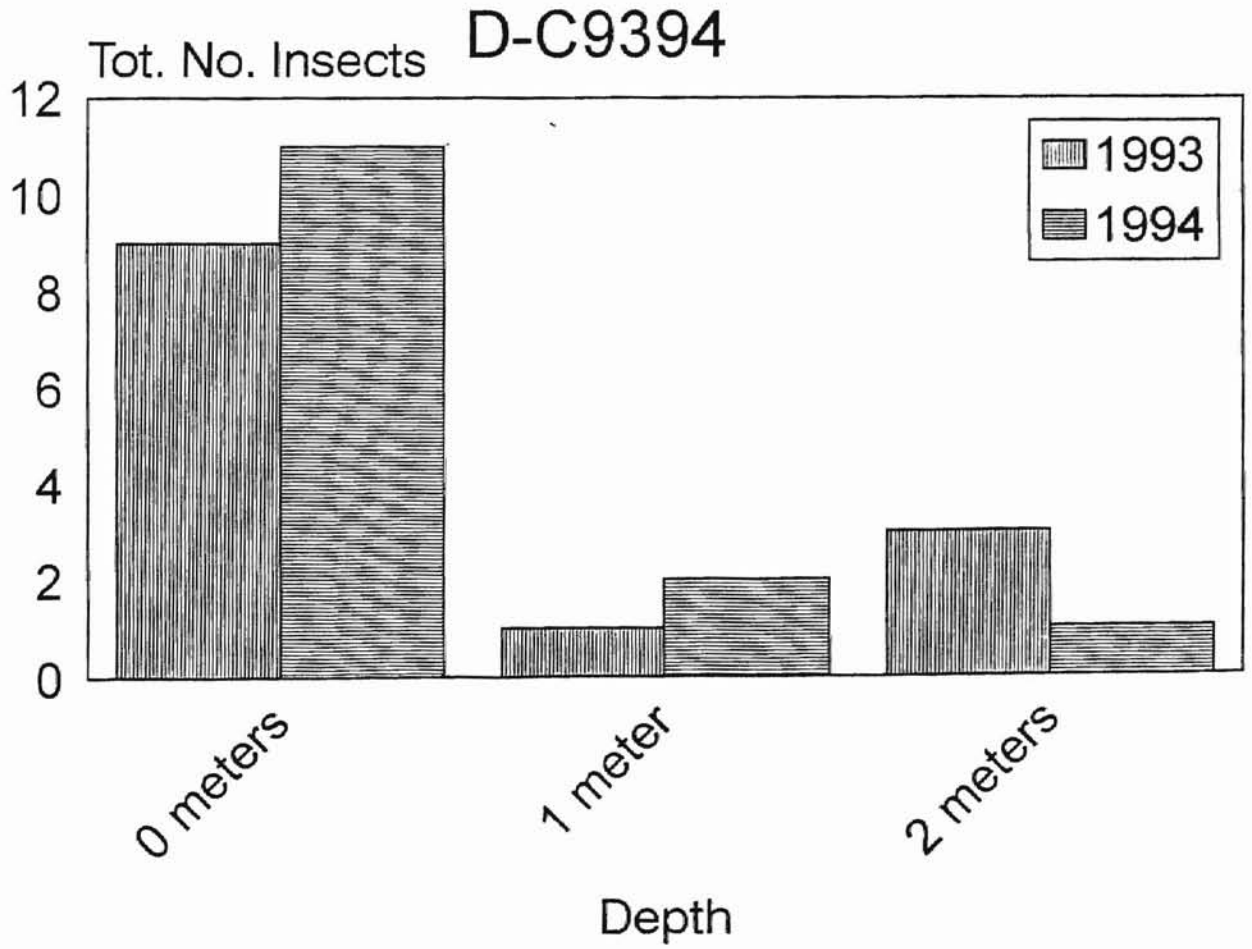

deep K93
Avg. RGB
50
40
30
20
10
0
0 meters
1 meter
2 meters
Period 1
Period 2
Period 3
Period 4
Period 5
Period 6

Fig. 28. Total number of adult *T. stercorea* captured in deep cup samples by sample depth at Kingfisher and Crescent in 1993-1994


D-K9394
Tot. No. Insects
6
5
4
3
2
1
0
1993
1994
0 meters
1 meter
2 meters
Depth


D-C9394
Tot. No. Insects
12
10
8
6
4
2
0
1993
1994
0 meters
1 meter
2 meters
Depth

CHAPTER III

PARASITOID/HOST INTERACTIONS

Abstract

The focus of this study is determining the types and abundance of parasitoids and predators of stored grain insects found in commercial wheat storages in Oklahoma and to elucidate information about the interactions of these insects with their host/prey species. We initially hoped to detect *Choetospila elegans* Westwood, a hymenopterous parasitoid of the destructive pest *Rhyzopertha dominica* (F.). We found essentially none of these parasitoids present, instead, we discovered large populations of *Cephalonomia waterstoni* (Gahan), a parasite of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens). We examined the relationship between *C. ferrugineus* and *Cephalonomia waterstoni* in two commercial wheat storage facilities in 1993-94 in North Central Oklahoma. These insects were trapped by unbaited flight traps, pitfall probe traps, and deep cup probe samples. Flight traps placed interiorly near the cap and exteriorly at the eave caught more insects than traps placed in the vents, inner eaves, or along the bin wall exteriorly. Within the grain mass, these insects were generally captured most often at the center of the bin near the grain surface. There were differences in average temperatures with respect to distance from bin wall and depth in the grain mass. Moistures also varied extremely with grain depth and distance from the bin wall. The significant recovery of *Cephalonomia waterstoni* correlated positively with *C. ferrugineus* populations. We observed this parasitoid to have a beneficial effect in reducing *C. ferrugineus* populations.

Introduction

Traditional methods of controlling insect pests in stored grain involve protectants and fumigants. Reliance on pesticides is favored for a variety of reasons: low cost, ease of application, difficulty of monitoring large bulks, risk reduction, and the susceptibility of the commodity early in storage (Arthur 1994). Protectants, such as malathion, provide inexpensive, residual protection as the grain is binned or as a top dressing. Fumigants like the widely-used phosphine reduce existing insect populations to near zero and have no residual activity.

However, recent trends toward an integrated pest management (IPM) approach in stored grain pest management has resulted from several factors. The increasing numbers of control failures due to insect resistance caused by the constant use or misuse of many pesticides coupled with insect exposure to sublethal doses (Arthur 1994, Collins 1994). Regulatory requirements of the EPA have caused cancellations of pesticides as well as decreased the ability of a registrant to recover developmental costs.

The development of insecticide resistance is not a recent occurrence. Many pesticides used against stored-product insects have lost or are losing their effectiveness. These insects acquire pesticide resistance from the selection pressure of high chemical application rates, number of applications, and high dosages. Multiple generations per year allow the most tolerant insects to survive to rapidly pass their resistance genes on to subsequent generations, resulting in increased control failure rates in grain storages. However, control failures, particularly with fumigants, may be partially caused by

inadequate sealing of the structure prior to treatment. Zettler et al. (1989) concluded that control failures of the common fumigant phosphine resulted from inefficient fumigation practices rather than resistance itself. Many elevator managers may overcompensate for the inability to seal a structure by overdosing (Zettler & Cuperus 1990). This practice may also contribute to insect resistance by exposing the insects to sublethal doses.

Insect resistance to the protectant malathion is widely documented (Haliscak & Beeman 1983, Herron 1990, Zettler & Cuperus 1990, Arthur & Zettler 1991). Newer, related protectants like chlorpyrifos-methyl and pirimphos-methyl are also showing early stage insect resistance (Beeman & Wright 1990, Arthur 1992). Resistance to phosphine has been detected in six stored grain insects, including *R. dominica* (Zettler et al. 1989, Herron 1990). In the United States, phosphine resistance is not yet widespread and resistance levels are low, however, it is only a matter of time until phosphine loses its effectiveness. Zettler & Cuperus (1990) screened 8 and 21 strains of *Tribolium castaneum* (Herbst) and *R. dominica* respectively collected from 61 storages in western Oklahoma. They found that one *T. castaneum* and 8 of 12 *R. dominica* strains were resistant to phosphine, with some having survival frequencies as high as 92% to discriminating doses. In addition to insect resistance, protectants in the organophosphate family tend to degrade upon exposure to high commodity temperature and moisture (Watters 1959, Strong & Subr 1960, Quinlan et al. 1979, Arthur et al. 1992, Collins 1994). In high-risk storage areas like Oklahoma, these conditions limit the effectiveness of these compounds particularly when coupled with the extended storage period before winter temperatures (Cuperus et al. 1986, Epperly et al. 1987).

Increasingly stringent EPA requirements for chemical controls is limiting the type and number of pesticides available on the market mainly because developers cannot recoup costs if elevator managers are not purchasing a costlier, compliant product. Furthermore, many once widely used pesticides have or will be removed for sale. Methyl bromide, a common fumigant, will be phased out by the year 2001. Malathion will not be re-registered as a grain protectant in the US in its liquid formula (Arthur 1994) and it is possible that phosphine may ultimately be removed. The removal of phosphine from the market would have far-reaching effects. Elevator managers surveyed in 1992 by Kenkel et al. (1993) stated that there were no alternatives to phosphine. Modified atmospheres might be the next best "fumigation style" alternative. This technique utilizes gases such as carbon dioxide or nitrogen to kill insects. However, facility modifications needed in order to use this method are costly, which may prohibit smaller operations from using it. Managers would be more likely to use empty bin treatments, protectants, and temperature control to reduce insect populations. They could increase sampling at time of receipt or substantially discount infested grain. Increased use of aeration would help control insect problems, but again, installing an aeration system in facilities that do not have them is costly. A viable, non-toxic alternative to pesticides is biological control in the context of a well-balanced IPM program.

Many scientists are advocating multi-faceted IPM programs that emphasize alternative controls and reduced pesticide inputs. Sanitation, grain cleaning, aeration, monitoring, and biological control are all components of a complete IPM program. One aspect of this research is the determination of natural parasitoid populations and its

relationship with its host.

Biological control involves the use of natural enemies, parasitoids or predators, to reduce an insect infestation to tolerable levels. The insect orders Hymenoptera, Coleoptera, and Hemiptera contain species which possess potential and actual abilities to decrease pest insect populations.

Biological control in the stored-product ecosystem is advantageous because no dangerous residues are left on the product. They are harmless to humans and require no special knowledge or certification to apply. Additionally, they have great reproductive potential and may provide continued control with later generations (Brower et al. 1991).

Parasitic biocontrol agents usually have high host-specificities and might be ineffective if many pest species are present. Coupling a host-specific parasitoid with a polyphagous predator, or with other parasitoids having different host specificities can enhance pest suppression (Press et al. 1982, Brower & Press 1990, Brower et al. 1991). Biocontrol agents are slow-acting and do not provide the rapid, dramatic reductions in pest populations like pesticides. Frequent, massive releases of biocontrol agents may be required for effective control and can be expensive. However, as more commercial suppliers of biocontrol agents perfect mass-rearing techniques, prices are likely to decrease (Brower et al. 1991, Parker & Nilakhe 1990).

The FDA still has contamination of the product by parasitoid and predator insect parts labeled as "filth", which may impede their use in manufactured food products at milling plants, etc. Although bulk-stored products can be cleaned to eradicate this contamination prior to any consequent processing (Brower et al. 1991).

Many species of beneficials naturally colonize grain storages, yet, they seldom occur in numbers sufficient for effective control of a pest (Nilakhe & Parker 1990). Augmentation of naturally-occurring beneficial populations with lab-reared insects provides an increased probability of success partly due to the enclosed nature of the storage structure containing the beneficials.

Predators are effective in controlling various stored grain pests in laboratory and commercial experiments. They are limited in comparison to parasitoids because they are general feeders and attack a wide range of insects. A study by Press et al. (1982) compared the suppression abilities of two parasitoids and a predator. Wasps achieved 97% and 92.2% control while the predator had significantly less control at 78.3%. Although combined use of both has been successful (Keever et al. 1986), they can also be antagonistic as the predator may consume the parasitoid eggs (Parajulee & Philips 1994) as well as cannibalizing their own nymphs (Arbogast 1979). The relatively larger size of predators may limit their degree of penetration within the product. Press et al. (1978) found that *Xylocoris flavipes* (Reuter) did not penetrate into finely cracked material or dust. Pest insects occurring deeper in a compacted grain mass or in an area high in fines may be safe from predator attack.

Parasitoids are usually very host-specific and can forage deep within a grain mass. Most parasitoids in the order Hymenoptera are very small (1-2mm). Their host specificity is typically a narrow range within a certain genus or species. Most parasitoids attack the egg or larval stage in a one-to-one relationship. Parasitized pests ultimately die without damaging the commodity or the amount of damage is reduced considerably.

Two classifications of parasitoids exist: endoparasitoids and ectoparasitoids. This is based on where their eggs are deposited on the host. Endoparasitoids oviposit internally on a host, while ectoparasitoids affix their eggs externally. Parasitization occurs once an egg is laid on or in the host's egg or larva. Parasitoid larvae emerge and consume a portion of the host until their development is complete. The host does not develop and therefore does not damage the grain or reproduce.

Parasitoids alone have shown tremendous potential in studies on both the commercial and laboratory level. Brower (1988) released 3,000 *Trichogramma pretiosum* Riley weekly for 14 weeks into metal storages containing 200 kg of peanuts naturally infested with *P. interpunctella*. An average of 92.8 *P. interpunctella* per kg were found in the control bin while only 39.6 per kg remained in the bin treated with the parasitoid. Synergistic effects by using two species of parasitoid were achieved when introduced together to control *P. interpunctella* than each alone (Brower & Press 1990). Flinn et al. (1994) effectively suppressed *R. dominica* in wheat with *Choetospila elegans* Westwood. After 198 d of storage, wheat in the control and treated bins averaged 2.06 and 0.05 *R. dominica* per kg.

The objectives of this study were to determine what types of beneficials occurred in commercially stored wheat and their relative abundance. The traps and samples detected large populations of *C. ferrugineus* and its parasitoid, *C. waterstoni*, and examined the interactions of both species in the stored grain environment.

C. ferrugineus is a cosmopolitan pest of stored grain throughout the United States. Its potential for damaging grain is great in Oklahoma due to the high ambient

temperatures, high relative humidities, early harvest dates, and longer storage times before the onset of cooler temperatures. In Oklahoma, this genus is ranked second in destructiveness (Cuperus et al. 1990). The necessity for effective control of this insect is obvious, and as increasing numbers of traditional chemical controls are removed from the market, the demand for alternative suppressants escalates.

C. ferrugineus is a secondary pest of stored wheat that is usually found feeding under bark in nature (Linsley 1944). This cosmopolitan pest feeds in both the larval and adult stages. It consumes both the germ and endosperm (Rilett 1949a) of broken or cracked kernels, but cannot damage whole, sound grain. This beetle can also survive well on molds, dust, and fines (Rilett 1949a, Loschiavo & Sinha 1966, Dolinski & Loschiavo 1973). Molds, in particular, reduce mortality and developmental time of *C. ferrugineus* (Rilett 1949a). Fungi growing on kernels may provide nutritional supplements as well as exposing germ and endosperm for feeding (Rilett 1949a, Dolinski & Loschiavo 1973).

Female *C. ferrugineus* deposit eggs in small cracks and crevices in the wheat kernels, or intergranular spaces by means of an extensible ovipositor (Rilett 1949b). One mated female lays an average of 2.54 eggs per day and the eggs hatch in 3-4 days. The larvae emerge and begin to search for food. The first through third instars feed internally on broken or damaged kernels, while the fourth is quite mobile as it searches for a pupation site (Rilett 1949a, Smith 1972). *C. ferrugineus* adults also have high locomotory abilities (Watters 1969).

Adults mate 1-2 days after emergence and oviposition ensues soon after. The adults eat broken kernels and dust but occasionally return to larval burrows to consume

previously exposed endosperm and germ (Rilett 1949a). The optimum conditions for development of *C. ferrugineus,* as well as most other stored grain insects, are 25-33°C (Fields 1992) and ≥75% RH. However, *C. ferrugineus* displays decreased developmental time and mortality with increased temperature and moisture (within the optimal range) (Rilett 1949b).

C. ferrugineus is a consistent inhabitant of commercially stored grain in Oklahoma (Cuperus et al. 1990). A parasitoid of *C. ferrugineus*, *Cephalonomia waterstoni*, a bethylid wasp, is also present in wheat storages in Kansas, Australia, and Oklahoma (Schwitzgebel & Walkden 1944, Sinclair 1982, Hagstrum 1987, Vela de Garza 1993). These populations are usually insufficient to provide effective control of *C. ferrugineus* and must be augmented with lab-reared wasps.

Cephalonomia waterstoni is a parasitoid whose host specificity is larval *C. ferrugineus*. It typically parasitizes fourth instars because they are actively searching for a pupation site within the grain mass (Rilett 1949a, Smith 1972) while first through third instars feed inside the kernel, thus protected from attack. This small (1-2mm) hymenopteran is effective at penetrating the grain mass in search of its prey by following host kairomonal trails (Howard & Flinn 1990). Once a suitable host is found, the parasitoid grasps it with its mandibles and stings it into submission (Rilett 1949b, Finlayson 1950). Paralyzed, the larva is removed to a secluded oviposition site. Most commonly, one or two eggs, rarely up to four, are laid externally on the host's venter between or behind the metathoracic legs (Rilett 1949b, Finlayson 1950). At 90°F and 75% RH, a female wasp lays 1-3 eggs per day. The eggs hatch in 30 hrs. and the larvae

reach full size in 23 hrs. at this temperature. Newly emerged *C. waterstoni* larvae remain affixed to the host and consume haemolymph after piercing the host's cuticle. One *C. ferrugineus* larva provides enough nourishment for the complete development of two wasp larvae.

Cephalonomia waterstoni provided 73% control, depending on the time of release, in a modeling study conducted by Flinn & Hagstrum (1994). However, no experiments have examined this insect's occurrence and efficacy in commercial storages.

The objectives of this study are threefold: 1) to characterize the abundance of beneficial insects in commercial facilities, 2) to determine the time and location of insect immigration into commercial grain storages, and 3) to characterize the parasitoid/host population dynamics of these insects within the storage facilities. Understanding these insects' biologies and population dynamics in commercial facilities provides a foundation from which to perform further experimentation. Knowledge of the manner in which these stored grain insects immigrate into and interact within commercial storages can provide a basis for implementing an effective, IPM-based management program.

Materials and Methods

Two commercial, steel bins located in Crescent and Kingfisher, Oklahoma, with capacities of ≈ 4,500 and 6,000 metric tons (total height of ≈ 18.4m and ≈ 21.5m), respectively, and filled with hard red winter wheat *Triticum aestivum* (L.) were used for this study. The bins were sampled during the storage years of 1993 and 1994. Before grain binning (Crescent: July 6, 1993 and June 28, 1994; Kingfisher: June 21, 1993-94), the bins were swept clean and the empty bins were fumigated with chloropicrin at

recommended rates. During the 1993 storage year, the Crescent facility was only half-full. At Crescent in 1994, the unforeseen removal of six truckloads of grain at the end of July resulted in an inverted cone rather than a peaked grain mass in our study bin. All of the center traps and thermocouples were irretrievably pulled into the grain mass, effectively disrupting established insect populations in this region. We were forced to discontinue our sampling/trapping in the center for the remainder of the 1994 season.

Before the start of wheat harvest (June 9, 1993 and June 10, 1994), 20 unbaited flight traps (Phercon II; Trécé Inc., Salinas, CA) were attached to ropes exteriorly on the bins in the cardinal directions. Each rope held five traps at the following heights: ground level, one-quarter bin height, one-half bin height, three-quarters bin height and outside eaves. The ropes ran through pulleys bolted through the roof eaves for efficient trap replacement. After wheat binning (June 21 1993, June 21 1994), additional traps were placed inside the bins. In 1993, four traps per height, positioned in the cardinal directions, were placed both in the inner eaves and cap. In 1994, four traps per height were placed at the following heights: inner eave, vents at one-half bin radius, and in the cap. Traps were affixed to the inner eave and vent flight traps with magnetic clips. Cap traps were positioned beneath the center of the bin roof with a ≈ 6.0m length of 5cm diameter PVC pipe. The lower ≈ 3.0m of this pipe was inserted into the peak of the grain mass, while the upper end held a 1.2m square PVC pipe "X" (one trap placed distally on each "arm" of this "X").

Twelve plastic pitfall traps (Storgard WB II Probe traps; Trécé Inc., Salinas, CA) were placed in each bin after grain binning (July 6, June 21, 1993; June 28, 21, 1994).

Three traps were placed in each cardinal direction at ≈1.5m from the bin wall, one-half bin radius and in the center of the bin. The four center traps formed the corners of a 1.5m x 1.5m square.

Removal of grain samples required the use of a 2.0m deep cup probe with a brass cup (250 g capacity; Seedburo Equipment Co., Chicago, IL) at the 12 trap locations. Samples were removed from each trap location at three depths: 0, 1, 2 meters from the surface. Two samples (≈500 g each), taken at each depth at each sampling site, resulted in 72 samples per bin.

Vacuum probe samples occurred monthly (June 21, July 26, and September 13 (Kingfisher 1993); June 21, August 9, and September 2 (Kingfisher 1994); July 6 and August 9 (Crescent 1993); June 28, July 26, and August 16 (Crescent 1994)) each year at five locations in each bin: one in each cardinal direction (one-half bin radius) and one in the center. We removed two samples of ≈ 1-2 kg each at 3.0, 6.0 and 9.0m below the grain surface at each sampling site in the grain mass, for a total of 30 samples per bin for each sampling date.

Sampling and collection of trap catch was completed weekly. Flight traps, deep cup probe samples, and pitfall trap catches were placed in labeled plastic bags and taken to the laboratory for processing. All insects caught in flight and pitfall traps were identified and counted in the laboratory. Deep cup and vacuum probe samples were processed over a modified incline sieve (White 1983) three times per sample to remove the insects from the grain. Insects were then identified and counted. All of the 1993 samples were weighed and moisture contents determined using an electronic balance (Ohaus Lume-O-

Gram balance; Ohaus scale corp., Florham Park, NJ) and an hygrometer (Agromatic WK II; ASIDIC Ltd., Clear Lake, IA). All of the 1994 samples were weighed with an electronic balance (Fisher Scientific XD-8KD; Denver Instruments, Inc.; Denver, CO) and reweighed after baking for 24 hrs at 105°C in an oven (Fisher Isotemp® Oven, Model 438F; Fisher Scientific; Indiana, PA) to determine moisture content.

The Crescent facility was fumigated (≈ August 25, 1993 and ≈ August 30, 1994) due to high insect populations. However, the Kingfisher facility was sampled until September of both years.

Twelve thermocouples, placed in the grain at the beginning of each sampling year and left for the duration of the sampling period, were used to record grain temperature at the time of sample collection. Temperatures were taken at the four cardinal directions and depths corresponding to the deep cup probe samples.

Insects captured in each of the trapping/sampling devices were analyzed using SAS Categorical Modeling (CATMOD) (SAS Institute, 1988) which employed a log-linear model to determine the causes of insect catch variation and to partition it into various sources. The SAS General Linear Models (GLM) (SAS Institute, 1988) was used to determine the sources of variation of the temperature and moistures readings taken throughout the grain mass.

Pearson product-moment correlations were calculated using the SAS correlation procedure (CORR) (SAS Institute, 1988) to determine the relationship between the number of insects captured and temperature and moisture content.

Results

Temperature and Moisture Content: The temperatures measured in 1993 were analyzed with the PROC GLM procedure (SAS Institute, 1988) . The average temperature at Kingfisher was 29.01 ± 7.59 °C and at Crescent 33.60 ± 6.24 °C (Fig. 1). Due to the large amount of variation in the temperature readings, the data were analyzed by location and julian date in order to obtain a model that fit well and to partition some of the variability caused by location and julian date in the original model. Generally, the main sources of variation in temperature were distance from wall and depth, indicating that temperatures are different at each level of each factor. The temperature data from 1994 were analyzed similarly. The average temperature at Kingfisher was 27.58 ± 4.75 °C and 19.18 ± 11.39 °C at Crescent (Fig. 2). Trends similar to the 1993 temperatures were evident with distance from wall and depth significant contributors to temperature variation. The trends with respect to sources of temperature variation were consistent for both years.

The grain moisture data taken in 1993 were analyzed with the PROC GLM procedure (SAS Institute, 1988). The mean moisture content from deep cup probe samples in 1993 was 11.36 ± 1.24% at Kingfisher and 12.97 ± 1.19% at Crescent. Due to the large amount of variation in the moisture readings, the data were analyzed by location and julian date in order to obtain a model that fit well and to partition some of the variability caused by location and julian date in the original model. Moisture variations originated from many sources over the course of the sampling period. No single main effect or interaction stands out consistently during the storage period, although most of

the main effects and interactions responsible for moisture variation were significant. The mean moisture content from deep cup probe samples in 1994 was 8.78 ± 3.02% at Kingfisher and 10.02 ± 2.65% at Crescent. Like 1993, no single main effect or interaction is prominent during the storage period.

We used several trapping and sampling techniques in order to obtain our information on insect populations. The unbaited, sticky flight traps provided an early indication of which insects occurred in the vicinity of the storages prior to grain binning as well as immigration into the facility after harvest. The pitfall probe traps detected insect populations in the grain mass early in the storage season because of their sensitivity to low population levels. The deep cup probes provided an instantaneous measure of insect density in the grain, but did not detect insects until population levels rose. The vacuum samples that we removed enabled us to determine if insects entered the structure from the bottom plus the depth and extent of insect penetration into the grain mass.

Flight Traps: Flight traps provided the earliest indication of insect populations well before grain binning for both storage years and locations. During bin filling (began ≈ June 9, 1993 and June 10, 1994), the overall flight trap catch increased, particularly in the outer eave traps and those located interiorly near the cap. During both storage years, insects caught in flight traps was greatest in the cap (Figs. 3, 4). *C. ferrugineus* was captured in the highest numbers at each location for both years with the exception of Kingfisher in 1993 where *C. waterstoni* was most prevalent.

C. ferrugineus was initially detected on July 12, 1993 and June 14, 1994 at Kingfisher and June 21, 1993 and June 28, 1994 at Crescent. *C. waterstoni*, detected on

July 12, 1993 and June 5, 1994 at Kingfisher and July 19, 1993 and July 5, 1994 at Crescent was generally caught after the first detection of its host, *C. ferrugineus* (Figs. 5, 6). Both *C. ferrugineus* and *C. waterstoni* numbers caught increased for both locations into mid to late August and decreased thereafter. However, *C. waterstoni* populations continued to increase for one week after the initial decline of *C. ferrugineus* trap catch (Figs. 5, 6).

For both years and sampling locations, trap height had a highly significant effect with respect to trap catch. Trap height had a significant effect for both *C. waterstoni* (df=6, χ^2=25.09, p=0.0003) (Table 2) and *C. ferrugineus* in 1993 (Table 3), and for both in 1994 (df=7, χ^2=111.76, p=0.0000) (Table 4), (df=7, χ^2=367.88, p=0.0000) (Tables 5), respectively. This is probably the result of the random flight vectors of the insects toward the grain mass as well as fluctuations in trap catch based on wind speed and direction. More of these insects were captured inside (highest trap heights) because they are highly mobile and usually fly within the bin after immigrating.

Pitfall Traps: Pitfall traps did not detect any insects during the first week of trapping in 1993 at Kingfisher (June 21) or Crescent (July 6). However, traps detected *C. ferrugineus* at both locations during the first week of sampling in 1994: Kingfisher (June 21), Crescent (June 28) (Figs.7, 8).

C. ferrugineus and *C. waterstoni* were found in pitfall traps from August 2-16, 1993 at Crescent and increased steadily. On August 23 (the last sampling date), trap catch dropped sharply (Fig. 8), possibly due in part to decreasing grain temperatures after August 2. At Kingfisher in 1993, both insect species' trap counts increased from August 2

through September 7, at which point the trap counts decreased until the final sampling date on September 20 (Fig. 7). At Crescent in 1994, *C. ferrugineus* trap catch rose steadily from June 28 to peak on August 2 and gradually declined thereafter until August 16 (last sampling date) (Fig. 8). The Crescent *C. waterstoni* counts in 1994 were sporadic throughout the season until peaking sharply on August 16 (Fig. 8). At Kingfisher, both *C. ferrugineus* and *C. waterstoni* trap counts escalated until cresting on August 30 (Fig. 7). *C. waterstoni* closely paralleled *C. ferrugineus* populations, usually peaking near or shortly after *C. ferrugineus*.

For the pitfall counts of *C. ferrugineus* and *C. waterstoni* in 1993, the data was analyzed by location and distance from wall in order to attempt to separate the variation. There was a highly significant directional effect on trap catch at every level of location and trap distance from the wall (Tables 6, 7). Figures 9-12 display the trap captures by trap distance from the bin wall. It is evident that these insects closely relate to one another and prefer locations at or near the center of the grain mass.

The data for *C. waterstoni* from 1994 a strong locational effect (df=1, χ^2= 6.72, p=0.0096) (Table 8) and this strong effect may be partially responsible for the significant location by direction and location by distance from wall interactive effects on trap catch. These parasitoids cluster near the center of the bin where the majority of the *C. ferrugineus* populations occur.

The pitfall counts of *C. ferrugineus* in 1994, were analyzed by location and distance from wall in order to attempt to elucidate causes of variation. There was a highly significant directional effect on trap catch at every level of location and trap

distance from the wall (Table 9). The counts were quite different between each level of distance from wall at each location. The insects preferred the center of the bin at Kingfisher (Fig. 9).

Deep Cup Probes: The deep cup probe samples detected insects much later than did the pitfall probe traps. We usually captured *C. ferrugineus* first because it reached higher population densities faster than did *C. waterstoni* though both have significant locomotory abilities (Figs. 13, 14). Approximately 1-4 weeks later we began capturing *C. waterstoni* in appreciable numbers.

C. waterstoni captured in deep cup probes in 1993 showed significant ($p<0.05$) depth and temperature effects on insect populations as well as a location by direction interactive effect, probably due mainly to the differences between the locations rather than direction alone (Table 10). The strong temperature effect is probably due to sampling in the early morning when the majority of the actual temperature readings were <75°F rather than a preference for that temperature range.

Because of the differences seen in the *C. ferrugineus* populations between sampling locations, the data for Kingfisher and Crescent were analyzed separately for deep cups in 1993 (Tables 11, 12). Kingfisher sample data only showed temperature to have a highly significant ($p=0.0004$) effect and a significant ($p=0.0437$) three-way interaction among direction, distance from wall, and depth (Fig. 12). *C. ferrugineus* populations clustered near the center of the bin (Fig. 15). The Crescent data did not show any significant effects by the independent variables (Table 13), although the insects tended to congregate in the center of the bin (Fig. 16). Again, most of the temperature readings all

fell in the <75°F range. The early morning moderate temperatures probably do not provide an indication of insect temperature preference with respect to maximum daily temperatures in the region. The three-way interaction tells us that *C. ferrugineus* populations sampled vary at each level of depth and distance from wall in all cardinal directions, most likely due to large, variable *C. ferrugineus* populations.

C. waterstoni captured in deep cup probes in 1994 showed significant depth ($p=0.0000$) and distance from wall ($p=0.0103$) main effects on insect populations as well as a location by temperature interactive effect ($p=0.0067$) (Table 13). Most of the variation is probably due to the differing numbers of *C. waterstoni* captured at each location and their central accumulation tendency (Figs. 17, 18).

The *C. ferrugineus* deep cup catch in 1994 showed no significant effects of any type (Table 14). The sample capture by location and distance from wall is outlined in Figures 15 and 16 and shows that the populations tended to clump in the center of the bin at Kingfisher but not at Crescent.

The expected trend of insects migrating deeper into the grain mass over time only occurred consistently in samples removed from Kingfisher in 1993 (Fig. 19). No other sampling location or year displayed this inclination, which may be due to the instantaneous sampling nature of the deep cup coupled with the locomotory abilities inherent in each species of insect. The small size of *C. waterstoni* allowed them to follow *C. ferrugineus* down into the grain, indicating an excellent grain penetration capability.

Vacuum Probes: During the entire two-year study, we removed approximately 180 vacuum probe samples of ≈1-2 kg. each in which there were found 160 *C. ferrugineus*

and *C. waterstoni* total, usually in the samples at 3.0 and 6.0m (Table 15). Clearly, this is strong evidence that no insects are entering the structure through the bottom of the bin. Any insects found at this depth are most likely emigrants of the existing populations on the grain surface that have migrated deeper in to the grain mass. This data reinforces the concept that stored grain insects generally confine their activities to the upper regions of large bulks of grain.

Correlation coefficients associating temperature, moisture content, and insects captured by trap type with one another are shown in Tables 16-21. There are no obvious trends, so only highlights will be elucidated. The largest positive coefficient of 0.64915 related *C. ferrugineus* and *C. waterstoni* capture in flight traps at Kingfisher in 1993. The largest negative coefficient of -0.38851 related *C. waterstoni* capture in pitfall traps to temperature. Both values are significantly ($p < 0.05$) different from zero. There was a moderate correlation trend (positive) with respect to each insect species' capture frequency in one trap type versus another (Tables 16-19). The correlation coefficients were typically strongest when relating *C. ferrugineus* and *C. waterstoni* capture in the various trapping/sampling devices (Tables 20, 21). The most negative coefficients occur when correlating insect catch with grain temperature or moisture, possibly due to the cooler temperatures when sampling and the highly variable moisture readings.

Discussion

Our results demonstrate that *C. ferrugineus* were the most numerous stored grain insect, and *C. waterstoni* typically closely paralleled their population fluctuations often peaking one or two weeks after *C. ferrugineus*. Both species are highly mobile and have a

short generation time. They seemed to thrive in the conditions found in the commercial storages during the course of the study. The parasitoid *C. waterstoni* was most abundant in flight traps and was not captured in as large numbers in pitfall traps or deep cup probe samples. This could be due to the fact that they follow larval *C. ferrugineus* through the grain mass and are not attracted to adults trapped in the pitfall probes. *C. ferrugineus* were most abundant in pitfall probe traps, but were also captured in large numbers in flight traps, particularly in the cap.

Flight traps placed in the outer eaves, inner eaves, vents, and cap typically caught more insects because the top of the bin is accessible to immigrating insects. Insects were detected in small numbers before grain was binned, indicating their presence in the area, probably due to random interception of flying insects or insects being carried by the wind. Flight traps were placed interiorly in each bin after harvest and immediately began detecting greater numbers of insects, demonstrating the rapid immigration of insects into the facility after binning (July 6, June 21, 1993; June 28, 21, 1994 for Crescent and Kingfisher, respectively). The *C. ferrugineus* probably migrated toward grain volatile emanations while *C. waterstoni* followed its host into the bin, most likely in response to kairomonal cues produced by increasing *C. ferrugineus* larval populations in the grain mass.

Different insect species exhibited dissimilar trapping frequencies based on trap location. Because the flight traps were unbaited, the insects captured were not responding to the trap attractiveness. The factors affecting trap catch were probably the orientation of the insects toward the grain mass, distance of insect populations from the facility,

characteristic flight behavior of each species, wind speed and direction, and weather conditions. *C. ferrugineus* and *C. waterstoni* immigration was detected interiorly in greater numbers. These insects have a high locomotory behavior and appeared to continually redistribute themselves within the bin during the course of the trapping period each year. Perhaps the *C. ferrugineus* were constantly moving within the bin in response to temperature and moisture gradients, more favorable food sources, or a less crowded area to inhabit. *C. waterstoni* were moving widely also, possibly searching for readily accessible mates and tracking ambulatory host larvae to parasitize. Additionally, the confined space within the bins is likely to have a more homogeneous density of insects in flight than open areas outside the bin (Leos-Martínez et al. 1986).

Pitfall traps detected insects during the first week of placement in the grain mass at Crescent on August 2, 1993 and June 28, 1994 and at Kingfisher on June 28, 1993 and June 21, 1994. Usually, *C. ferrugineus* was captured first, followed by *C. waterstoni*. As time progressed, the numbers of insects captured increased until peaking in August or September, depending on the facility. Definite trends are discernible with respect to the insects trapped at different trap distances from the bin wall, although these trends aren't consistent for each insect species for each bin location and trapping year. The response of the parasitoid populations in response to host are typical parasite/host curves with the host peaking concurrently with or just before the parasitoid.

C. ferrugineus and *C. waterstoni* trap catch varied considerably with respect to trap location. At both Crescent in 1993 and at Kingfisher in 1994, *C. ferrugineus* populations were most abundant in the centers of the bin where fines and easily

consumable broken kernels accumulate. At Kingfisher in 1993, the traps near the bin wall captured the most insects and close parallels between both species at every trap distance from wall were apparent. *C. waterstoni* displayed consistent trends both years at Kingfisher, with the majority being captured in the center of the bin. The trend was consistent both years at Crescent as well.

Commonly, the trap catch of *C. ferrugineus* exceeded that of *C. waterstoni* at each level of trap distance from wall by a large margin. This is due to the shorter developmental time and greater fecundity of *C. ferrugineus* over *C. waterstoni* which resulted in large *C. ferrugineus* populations. When examining the trap catch of these insects by direction no consistent trends are evident, which may signify that the insects don't prefer one direction over another when initially infesting the grain.

Insect counts for deep cup probe samples indicate that insects tend to congregate in the center of the grain mass and usually restrict themselves to the surface of the grain mass, at least initially. Population trends in these samples mirrored trends seen in the pitfall traps almost exactly. *C. waterstoni* populations rose with increasing *C. ferrugineus* populations, particularly in the center of the bin. Although average sample catch was low, the trend was prominent. Temperature and moisture are influential in insect distribution (Surtees 1965) and affect insect capture (Loschiavo 1983, Fargo et al. 1989). The temperature and moistures did differ from other regions in the grain in this investigation. The temperature usually varied slightly, but consistently, by distance from wall and depth over the course of time, while the moistures varied at virtually every level of depth, direction, and distance from wall during the course of the study.

Every correlation coefficient relating deep cup catch with pitfall trap catch was positive (with one exception), and many were significantly different from zero. This provides evidence that the number of insects caught in deep cups and pitfall traps are related to some extent. One consistent trend appeared when correlating deep cup or pitfall trap catch with flight trap capture during both years at both locations - both *C. ferrugineus* and *C. waterstoni* had positive coefficients. This demonstrates that flight trap catch might be an indicator of the relative population level of these two insects within the grain mass as shown by the deep cup and pitfall captures. When correlating both species captured in flight traps, it is clear that there is a moderate relationship there as well, even though it may be unexpected because no larvae were captured in flight traps for obvious reasons.

C. ferrugineus are present in the area well before grain harvest, either in natural reservoirs or in on-site infestations in uncleaned grain spillage, seed plants, etc. These populations may be supporting *C. waterstoni*, which follow them into the storage structure in response to emigration depleting natural reservoirs and/or attraction to host larvae present in the grain. Once the grain is binned, these insects are attracted by the aromatic volatiles of the grain and/or aggregation pheromones exuded by insects that arrived very early in the grain storage process. The sticky flight traps were useful in detecting the relative abundance of insects as they immigrated into the structure and for monitoring population trends in and around the bin. The pitfall probes traps provided an early indication of insect populations and their interactions in the grain mass because they are sensitive to low insect densities. The deep cup probe was useful because, although not

responsive to low insect populations, it provided a measure of density which facilitated the determination of relative infestation levels as populations grew. All sampling/trapping techniques used displayed the classic parasitoid/host response curves where both populations increased and decreased coincidentally. As parasitization rates peaked, *C. ferrugineus* populations typically dropped precipitously in response and *C. waterstoni* shortly thereafter. Obviously, *C. waterstoni* are present naturally in sufficient numbers to affect *C. ferrugineus* populations detrimentally. It can be said with certainty that *C. waterstoni* decrease *C. ferrugineus* populations to some extent as evidenced in the figures displaying trap/sample capture rates for the two species.

According to Hagstrum (1995), there is a 15:1 ratio of *C. ferrugineus* larvae to adults in a population with a stable age distribution. Since only adults were captured and observed trends of increase and decrease were followed by a similar peak of the *C. waterstoni* adult populations, the assumption is that the larval population reserves are being depleted by the parasitoid, resulting in a population crash of the adults. This rapid decrease may also be aided by the fact that the remaining adults redistribute themselves at a lower density, and few or no *C. ferrugineus* immigrants arrive to renew the populations, particularly later in the storage season.

Although the natural parasitoid populations are present, they would need augmentation in order to reduce insect pest levels to a tolerable density. The fact that little or no protectant is applied in commercial storage may enable parasitoids and predators to affect pest populations. *C. waterstoni* is definitely a viable candidate for biocontrol in large commercial facilities and could reduce reliance on pesticides.

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Table 1 . Total and average number of beneficial insects captured by trap type for Kingfisher and Crescent in 1993-1994

Species	Flight traps			Pitfall traps			Deep cup probes		
	N[a]	Avg.[b]	Total[c]	N	Avg.	Total	N	Avg.	Total
Kingfisher 1993									
C. waterstoni	160	96.2	1539	23	125.6	1633	53	8.3	116
X. flavipes	0	0	0	10	0.8	10	0	0	0
Kingfisher 1994									
C. waterstoni	90	9.2	166	23	5.0	65	6	0.6	9
X. flavipes	0	0	0	4	0.3	4	0	0	0
Crescent 1993									
C. waterstoni	40	12.6	151	25	55.9	391	31	8.4	67
X. flavipes	0	0	0	18	3.4	24	0	0	0
Crescent 1994									
C. waterstoni	41	7.2	101	10	5.5	44	23	0.02	26
X. flavipes	0	0	0	1	0.3	2	0	0	0

[a] Number of times each insect was detected

[b] Average number of insects captured per sampling date

[c] Total number of insects captured during the sampling period

Table 2. Maximum likelihood analysis of variance of *C. waterstoni* captured in flight traps at Kingfisher and Crescent in 1993

Source	df	χ^2	*P*
Location	1	22.59	0.0000
Direction	3	13.08	0.0045
Location * Direction	3	2.84	0.4167
Height	6	25.09	0.0003
Location * Height	6	11.11	0.0849
Direction * Height	18	66.73	0.0000
Loc * Dir * Height	12	60.85	0.0000
Likelihood ratio	0	.	.

Table 3. Maximum likelihood analysis of variance of *C. ferrugineus* captured in flight traps at Kingfisher and Crescent in 1993

	Source								
		Location			Direction		Location * Direction		
Height	df	$\chi 2$	*P*	df	$\chi 2$	*P*	df	$\chi 2$	*P*
Base	1	5.05	0.025	3	32.70	0.0000	3	11.29	0.0103
¼ bin	1	2.69	0.1011	3	51.95	0.0000	3	1.99	0.5749
½ bin	1	5.62	0.0000	3	29.63	0.0000	3	28.47	0.0000
¾ bin	1	15.67	0.0001	3	69.91	0.0000	3	20.64	0.0001
O. eave	1	4.44	0.035	3	80.55	0.0000	3	11.84	0.0079
I. eave	1	3.69	0.0548	3	4.03	0.2579	3	3.23	0.3571
Cap	1	155.9	0.0000	3	27.85	0.0000	3	83.5	0.0000

Table 4. Maximum likelihood analysis of variance of *C. waterstoni* captured in flight traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	8.03	0.0046
Direction	3	5.38	0.1458
Height	7	111.76	0.0000
Loc * Dir	3	5.60	0.1329
Loc * Height	7	9.42	0.2242
Dir * Height	21	33.38	0.0422
Likelihood ratio	21	24.21	0.2832

Table 5. Maximum likelihood analysis of variance of *C. ferrugineus* captured in flight traps at Kingfisher and Crescent in 1994

Source	df	$\chi 2$	*P*
Location	1	0.00	0.9828
Direction	3	5.32	0.1497
Height	7	367.88	0.0000
Loc * Dir	3	2.90	0.4076
Loc * Height	7	61.37	0.0000
Dir * Height	21	34.14	0.035
Likelihood ratio	21	26.78	0.1784

Table 6. Maximum likelihood analysis of variance of *C. waterstoni* captured in pitfall traps at Kingfisher and Crescent in 1993

By group	Source	df	χ^2	*P*
DFW1-K	Direction	3	58.24	0.0000
DFW2-K	Direction	3	117.21	0.0000
DFW3-K	Direction	3	240.08	0.0000
DFW1-C	Direction	3	14.18	0.0027
DFW2-C	Direction	3	64.02	0.0000
DFW3-C	Direction	3	102.52	0.0000

Table 7. Maximum likelihood analysis of variance of *C. ferrugineus* captured in pitfall traps at Kingfisher and Crescent in 1993

By group	Source	df	$\chi 2$	*P*
DFW1-K	Direction	3	158.02	0.0000
DFW2-K	Direction	3	63.74	0.0000
DFW3-K	Direction	3	122.41	0.0000
DFW1-C	Direction	3	535.27	0.0000
DFW2-C	Direction	3	240.05	0.0000
DFW3-C	Direction	3	32.81	0.0000

Table 8. Maximum likelihood analysis of variance of *C. waterstoni* captured in pitfall traps at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	6.72	0.0096
Direction	3	5.68	0.128
Loc * Dir	3	14.97	0.0018
Dist. from Wall	2	3.74	0.1543
Loc * DFW	2	17.42	0.0002
Dir * DFW	6	12.35	0.0546
Likelihood ratio	6	5.83	0.4422

Table 9. Maximum likelihood analysis of variance of *C. ferrugineus* captured in pitfall traps at Kingfisher and Crescent in 1994

By group	Source	df	χ^2	*P*
DFW1-K	Direction	3	232.91	0.0000
DFW2-K	Direction	3	163.68	0.0000
DFW3-K	Direction	3	490.94	0.0000
DFW1-C	Direction	3	536.1	0.0000
DFW2-C	Direction	3	313.22	0.0000
DFW3-C	Direction	3	54.11	0.0000

Table 10. Maximum likelihood analysis of variance for *C. waterstoni* captured in deep cup probes at Kingfisher and Crescent in 1993

Source	df	χ^2	*P*
Location	1	1.09	0.2973
Direction	3	3.29	0.3493
Dist. from wall	1	3.68	0.0550
Depth	2	7.19	0.0274
Temperature	2	22.25	0.0000
Loc * Dir	3	14.98	0.0018
Loc * Temp	2	5.06	0.0795
DFW * Depth	2	4.89	0.0869
Likelihood ratio	90	59.65	0.9943

Table 11. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Crescent in 1993

Source	df	χ^2	*P*
Dist. from wall	1	3.34	0.0675
Depth	2	3.62	0.1633
Temperature	2	3.45	0.0633
Temp * Depth	2	2.44	0.2945
Likelihood ratio	39	24.85	0.9620

Table 12. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Kingfisher in 1993

Source	df	χ^2	*P*
Temperature	2	15.89	0.0004
Direction	3	4.65	0.1996
Temp * Dir	4	5.90	0.2065
Dist. from wall	1	0.88	0.3493
Temp * DFW	2	2.17	0.3385
Dir * DFW	3	4.27	0.2338
Temp*Dir*DFW	3	4.90	0.1795
Depth	2	3.66	0.1601
Temp*Dir*Depth	12	13.57	0.3291
DFW * Depth	2	4.24	0.1198
Dir*DFW*Depth	6	12.96	0.0437
Likelihood ratio	12	3.64	0.9891

Table 13. Maximum likelihood analysis of variance for *C. waterstoni* captured in deep cup probes at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	0.23	0.6288
Dist. from wall	2	9.15	0.0103
Depth	2	41.60	0.0000
Temperature	1	1.04	0.3076
Loc * Temp	1	17.60	0.0000
Temp * Dir	3	12.20	0.0067
Temp * DFW	2	9.21	0.0100
Dir * DFW	6	12.87	0.0451
Likelihood ratio	106	41.72	1.0000

Table 14. Maximum likelihood analysis of variance for *C. ferrugineus* captured in deep cup probes at Kingfisher and Crescent in 1994

Source	df	χ^2	*P*
Location	1	1.83	0.1758
Temperature	1	2.85	0.0913
Loc * Temp	1	1.40	0.2361
Loc * DFW	2	5.47	0.065
Temp * DFW	2	4.16	0.1247
Likelihood ratio	117	54.24	1.0000

Table 15. Total and average insect capture in vacuum probe samples at Kingfisher and Crescent in 1993-1994

	RGB			CEPH		
	N	Avg	Tot	N	Avg	Tot
Kingfisher '93						
June 21	0	0	0	0	0	0
August 9	4	0.4	11	0	0	0
September 2	8	0.4	11	5	0.2	5
Kingfisher '94						
June 21	0	0	0	0	0	0
July 26	1	0	1	0	0	0
September 13	4	0.2	6	0	0	0
Crescent '93						
July 6	0	0	0	0	0	0
August 9	11	3.2	96	0	0	0
Crescent '94						
June 28	0	0	0	0	0	0

Table 15. Total and average insect capture in vacuum probe samples at Kingfisher and Crescent in 1993-1994

July 26	2	0.2	5	0	0	0
August 16	11	0.7	22	1	0.1	3

Table 16. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Kingfisher, 1993

Parameters	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	0.13573*	0.24288*
Deep cup/pitfall trap[b]	0.15552*	0.24072*
Pitfall trap/flight trap[c]	0.22417*	0.11684
Pitfall trap/temperature[d]	-0.0133	-0.22345
Deep cup/Temperature[e]	-0.21043*	-0.21412*
Pitfall trap/grain moisture[f]	0.17961*	0.06159
Deep cup/grain moisture[g]	0.07207	-0.01848

[a-g] df = 864, 720, 277, 69, 224, 335, 359 respectively for each set of correlation parameters

* Coefficient is significantly different from zero

Table 17. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Crescent, 1993

Parameters	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	0.37695*	0.08736
Deep cup/pitfall trap[b]	0.21934*	0.05044
Pitfall trap/flight trap[c]	0.12376	0.3393*
Pitfall trap/temperature[d]	-0.38266*	-0.38851*
Deep cup/Temperature[e]	0.1909	-0.17169
Pitfall trap/grain moisture[f]	0.00622	-0.28438*
Deep cup/grain moisture[g]	-0.2286	-0.1922

[a-g] df = 432, 282, 112, 31, 46, 191, 69 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Table 18. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Kingfisher, 1994

Parameters	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	0.07966*	0.16748*
Deep cup/pitfall trap[b]	0.10337*	0.34228*
Pitfall trap/flight trap[c]	0.22401*	0.15424*
Pitfall trap/temperature[d]	-0.0587	-0.22368*
Deep cup/Temperature[e]	0.03097	-0.01271
Pitfall trap/grain moisture[f]	0.03692	0.04468
Deep cup/grain moisture[g]	0.09759*	0.04882

[a-g] df =936, 936, 416, 96, 647, 336, 647 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Table 19. Correlation coefficients comparing each insect species' capture against trapping type, temperature, and moisture for Crescent, 1994

Parameters	*C. ferrugineus*	*C. waterstoni*
Deep cup/flight trap[a]	0.14571*	0.29108*
Deep cup/pitfall trap[b]	0.13443*	0.39051*
Pitfall trap/flight trap[c]	0.00902	0.19801*
Pitfall trap/temperature[d]	0.34016*	0.21859
Deep cup/Temperature[e]	-0.12509	-0.31600*
Pitfall trap/grain moisture[f]	0.03467	0.04761
Deep cup/grain moisture[g]	0.15424*	0.21127*

[a-g] df = 527, 479, 157, 43, 165, 159, 191 respectively for each set of correlation parameters

* Coefficient significantly different from zero

Table 20. Correlation coefficients comparing *C. ferrugineus* and *C. waterstoni* captured in each trap type for Kingfisher, 1993-94

Parameters	Correlation coefficient
1993	
RGBD/CEPHD[a]	0.21741*
RGBP/CEPHP[b]	0.52501*
RGBF/CEPHF[c]	0.64915*
1994	
RGBD/CEPHD[d]	0.0107
RGBP/CEPHP[e]	-0.05676
RGBF/CEPHF[f]	0.34536*

[a-f] df = 359, 119, 371, 647, 155, 527 respectively for each set of correlation parameters; RGB = rusty grain beetle, CEPH = *C. waterstoni*, D = deep cup, P = pitfall trap, F = flight trap

* Coefficient significantly different from zero

Table 21. Correlation coefficients comparing *C. ferrugineus* and *C. waterstoni* captured in each trap type for Crescent, 1993-94

Parameters	Correlation coefficient
1993	
RGBD/CEPHD[a]	0.42475*
RGBP/CEPHP[b]	0.27583*
RGBF/CEPHF[c]	0.23983*
1994	
RGBD/CEPHD[d]	0.13968
RGBP/CEPHP[e]	0.17374
RGBF/CEPHF[f]	0.40476*

[a-f] df = 69, 47, 233, 191, 83, 397 respectively for each set of correlation parameters; RGB = rusty grain beetle, CEPH = *C. waterstoni*, D = deep cup, P = pitfall trap, F = flight trap

* Coefficient significantly different from zero

Fig. 1. Average grain temperature at both sampling locations from June 21 to September 20, 1993.

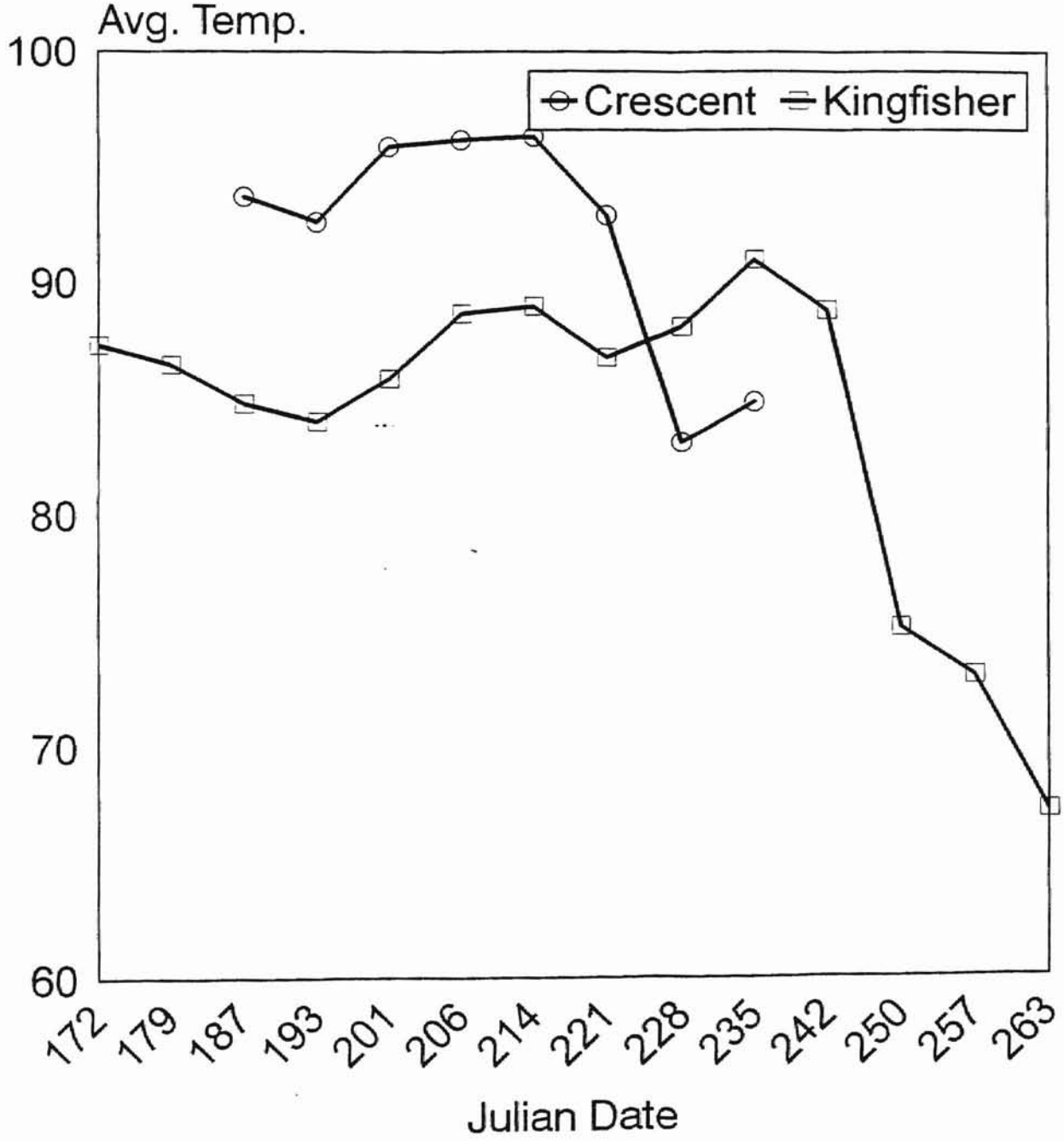

Avg. Temp.
100
90
80
70
60
Crescent
Kingfisher
172
179
187
193
201
206
214
221
228
235
242
250
257
263
Julian Date

Fig. 2. Average grain temperature at both sampling locations from June 21 to September 20, 1994.

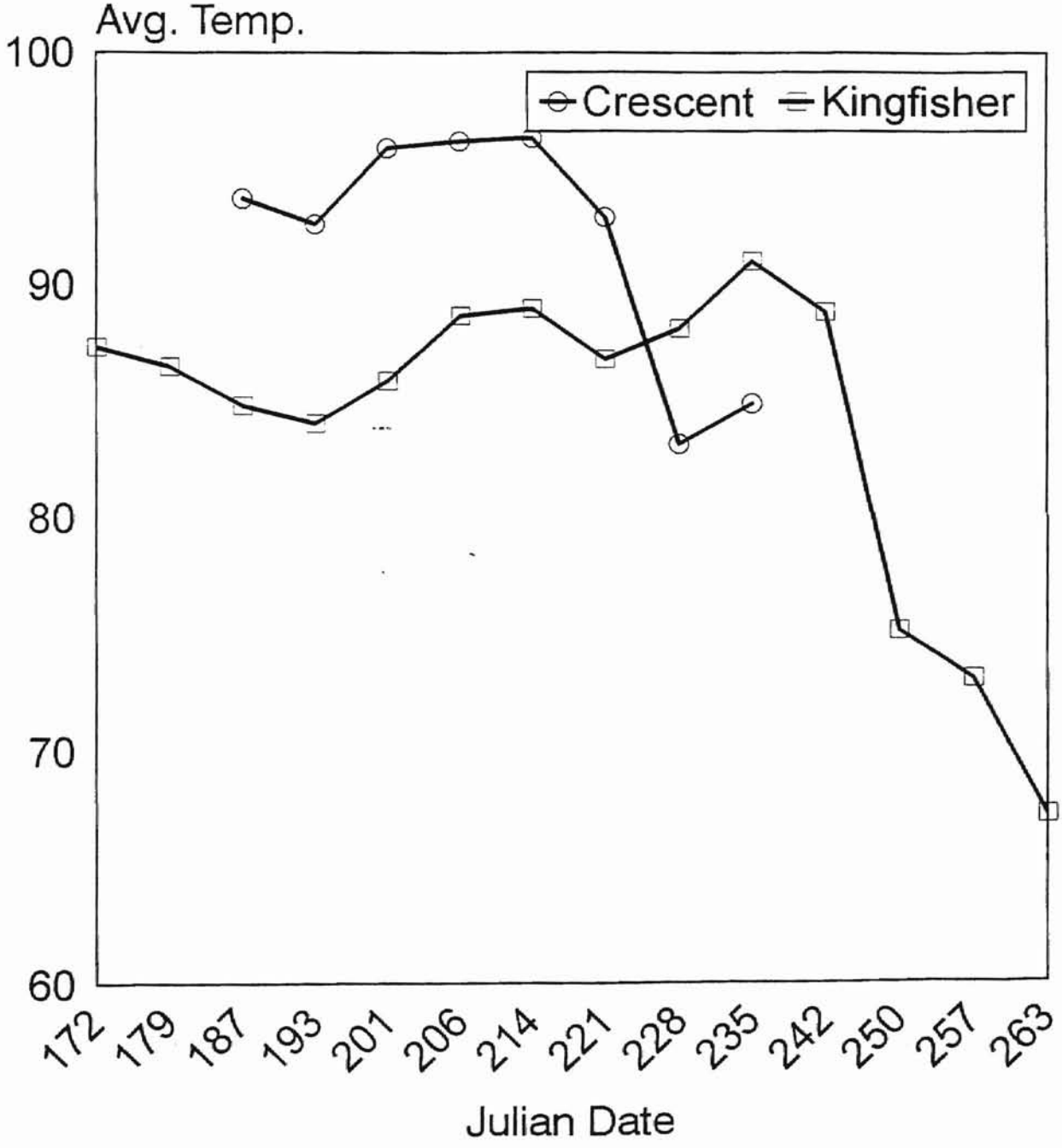
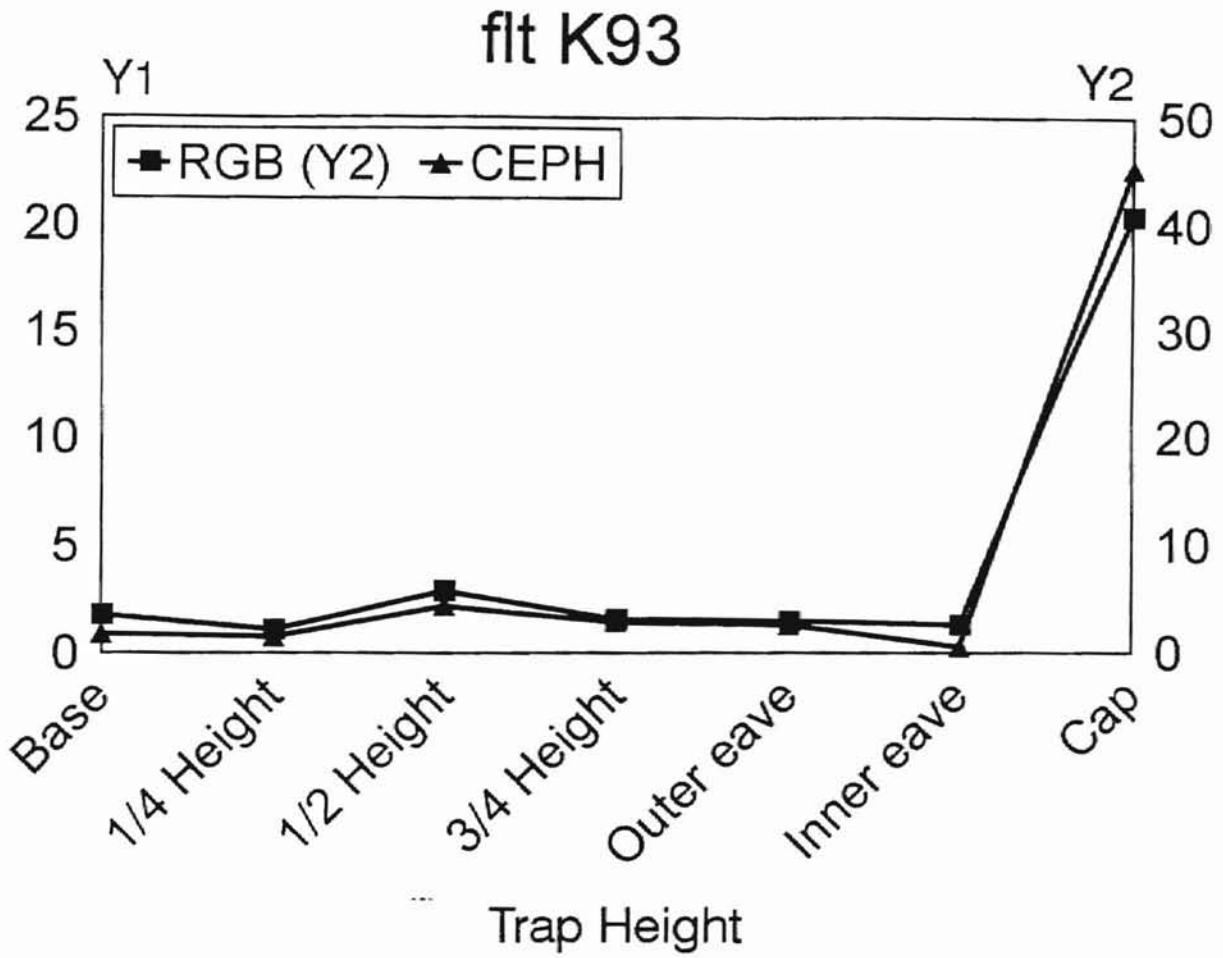

Avg. Temp.
100
90
80
70
60
Crescent
Kingfisher
172
179
187
193
201
206
214
221
228
235
242
250
257
263
Julian Date

Fig. 3. Average number of adult insects captured in flight traps by trap height at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in flight traps by trap height at Kingfisher in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps by trap height at Kingfisher in 1994; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)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Y1
Y2
25
20
15
10
5
0
50
40
30
20
10
0
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Cap
Trap Height

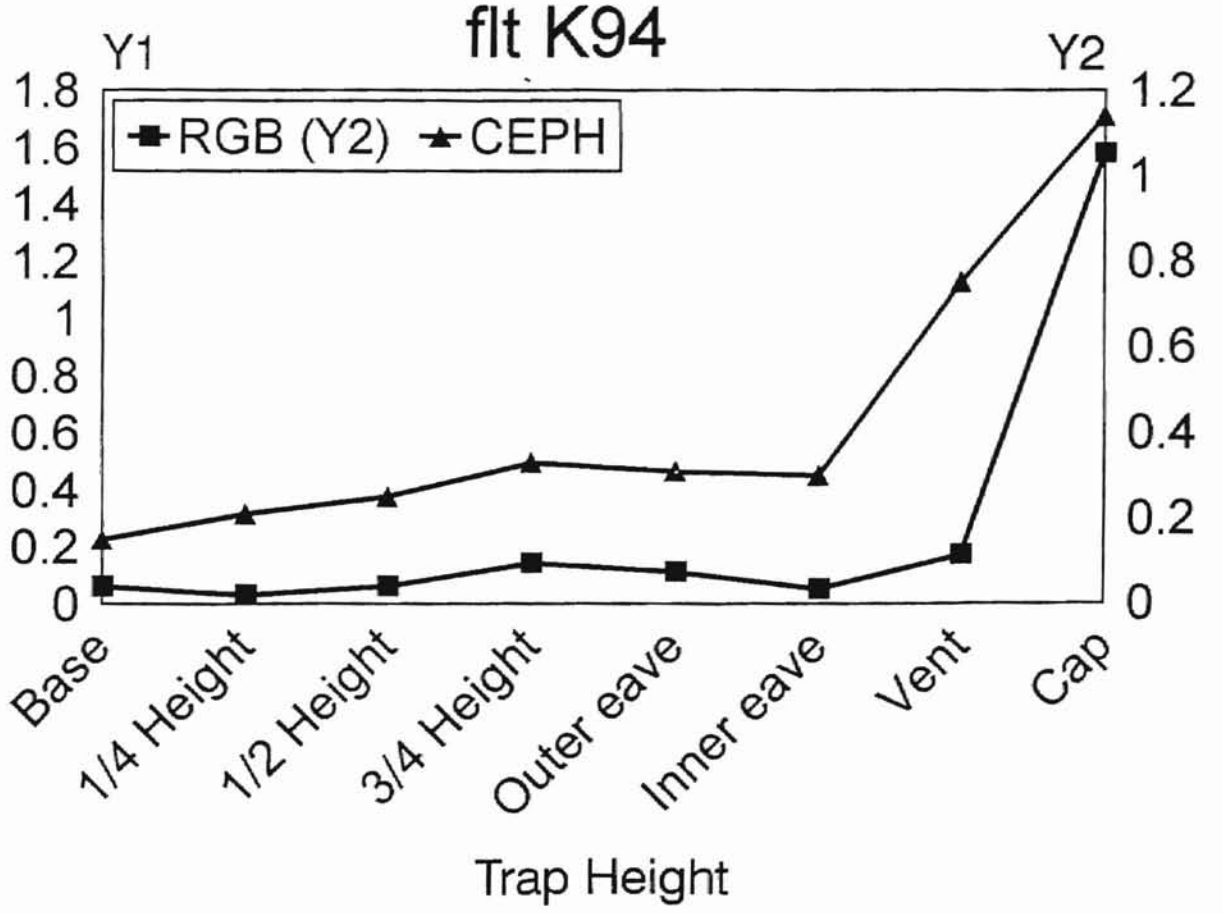
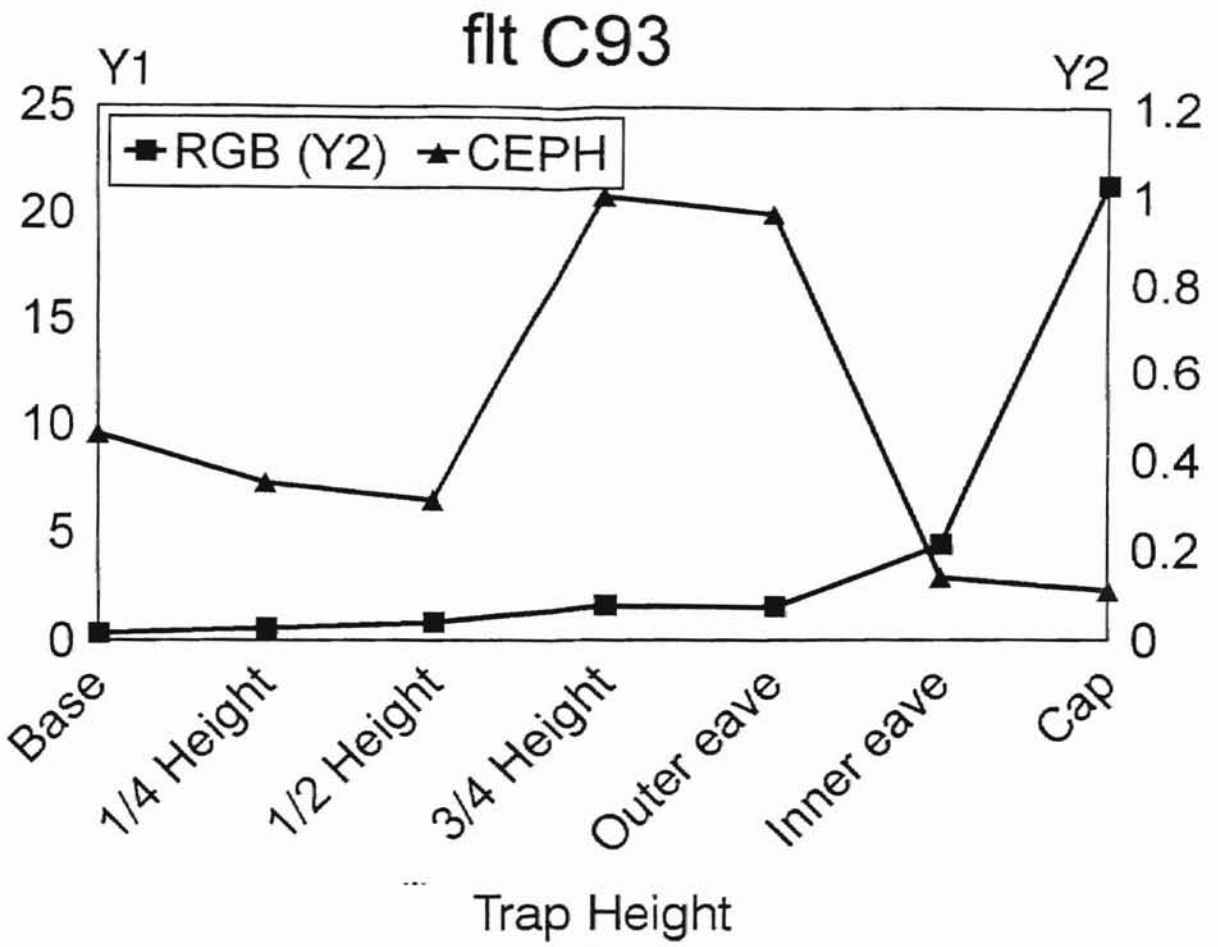

flt K94
Y1
Y2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.2
1
0.8
0.6
0.4
0.2
0
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 4. Average number of adult insects captured in flight traps by trap height at Crescent in 1993-1994

Key: A) Average number of adult insects captured in flight traps by trap height at Crescent in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps by trap height at Crescent in 1994; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


flt C93
Y1
Y2
25
20
15
10
5
0
1.2
1
0.8
0.6
0.4
0.2
0
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Cap
Trap Height

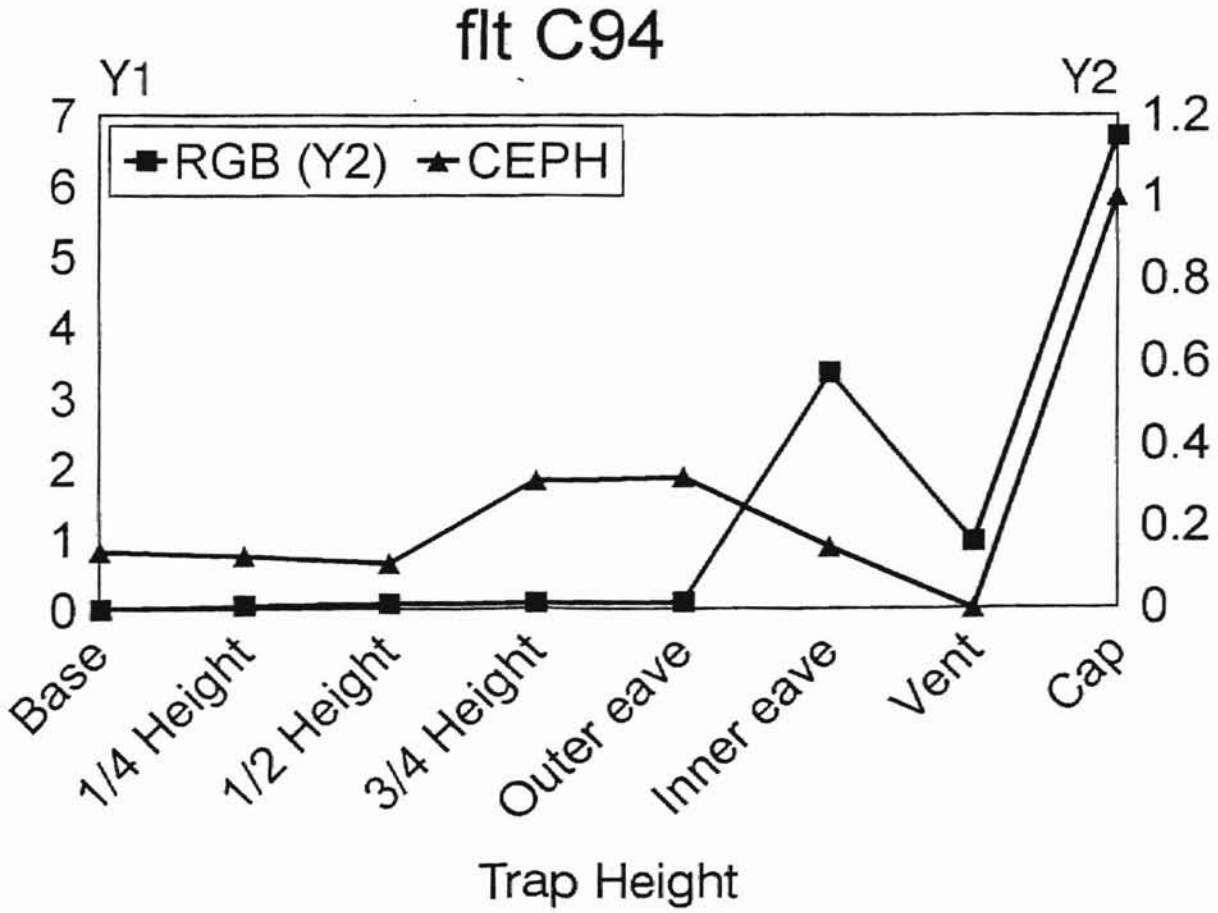
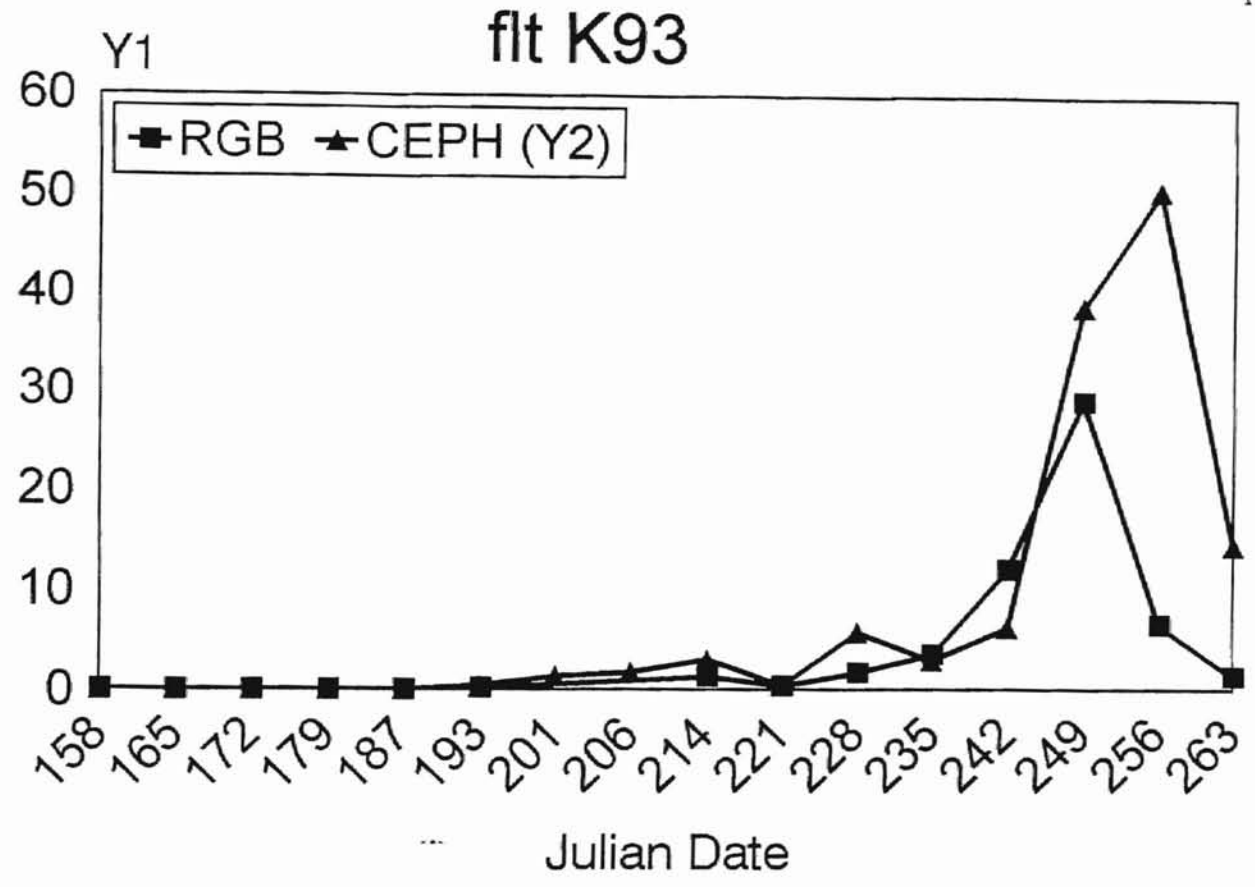

flt C94
Y1
Y2
7
6
5
4
3
2
1
0
1.2
1
0.8
0.6
0.4
0.2
0
RGB (Y2)
CEPH
Base
1/4 Height
1/2 Height
3/4 Height
Outer eave
Inner eave
Vent
Cap
Trap Height

Fig. 5. Average number of adult insects captured in flight traps at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in flight traps from June 7 to September 20 at Kingfisher in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y1); CEPH, *C. waterstoni* (Y2); B) Average number of adult insects captured in flight traps from May 17 to September 13 at Kingfisher in 1994; RGB, rusty grain beetle, *C. ferrugineus* ; CEPH, *C. waterstoni*


flt K93
Y1
RGB
CEPH (Y2)
60
50
40
30
20
10
0
158
165
172
179
187
193
201
206
214
221
228
235
242
249
256
263
Julian Date

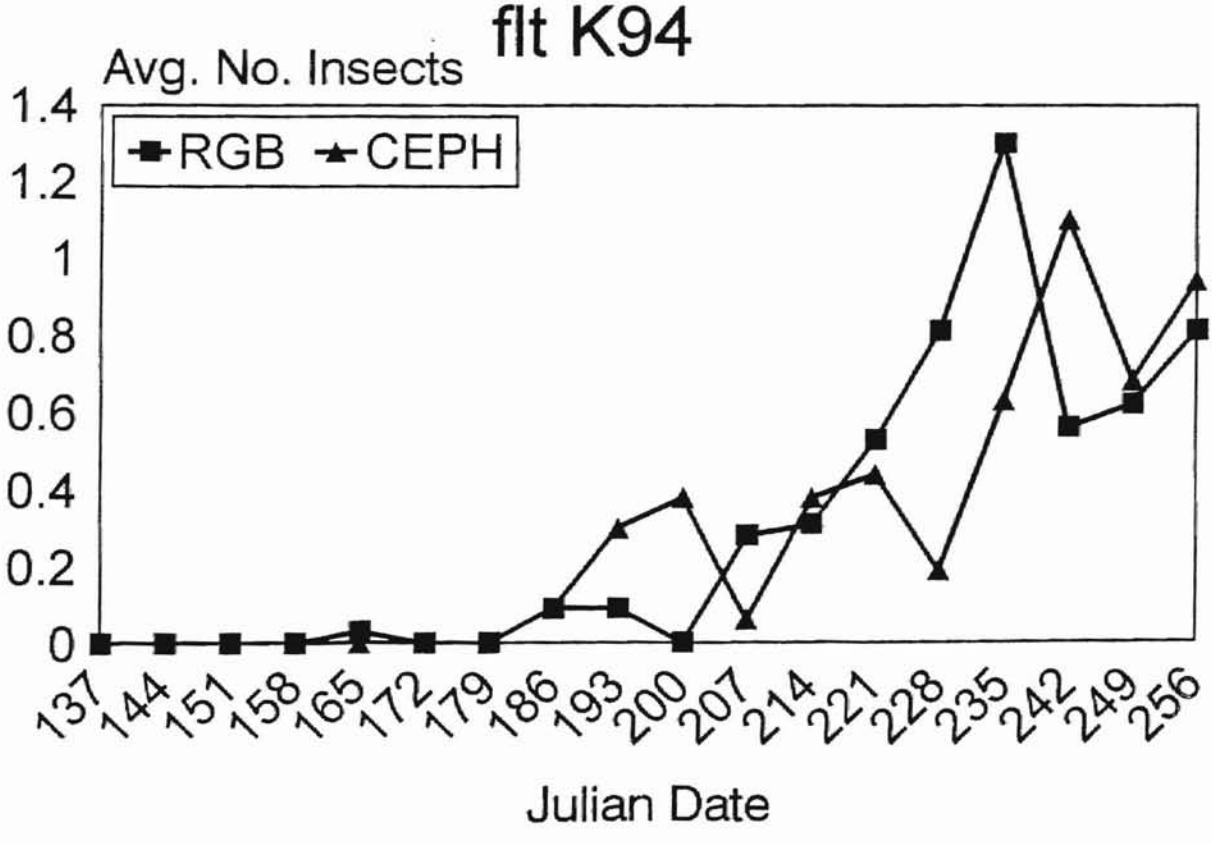
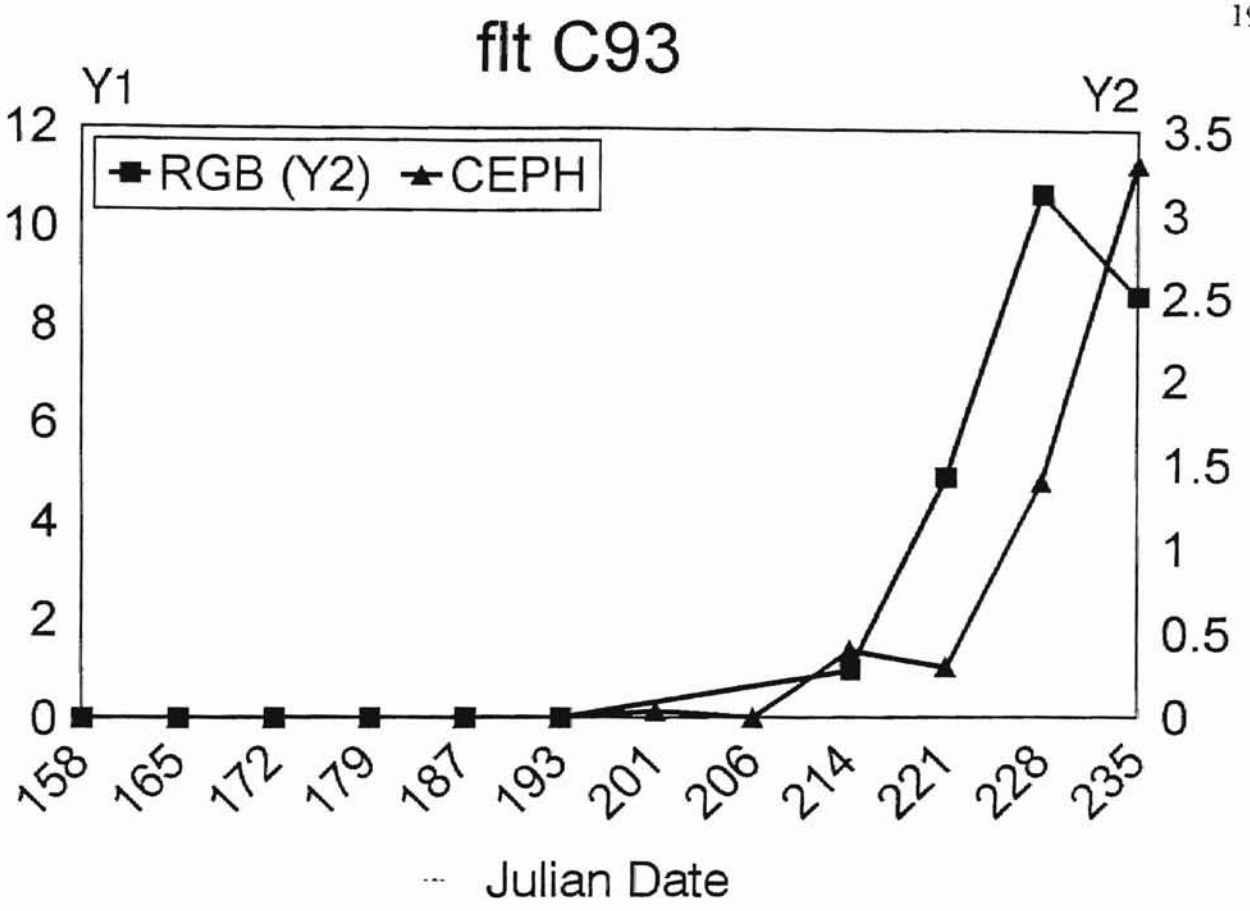

flt K94
Avg. No. Insects
RGB
CEPH
1.4
1.2
1
0.8
0.6
0.4
0.2
0
137
144
151
158
165
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 6. Average number of adult insects captured in flight traps at Crescent in 1993-1994

Key: A) Average number of adult insects captured in flight traps from June 7 to August 23 at Crescent in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in flight traps from May 17 to August 16 at Crescent in 1994; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


flt C93
Y1
Y2
RGB (Y2)
CEPH
12
10
8
6
4
2
0
3.5
3
2.5
2
1.5
1
0.5
0
158
165
172
179
187
193
201
206
214
221
228
235
Julian Date

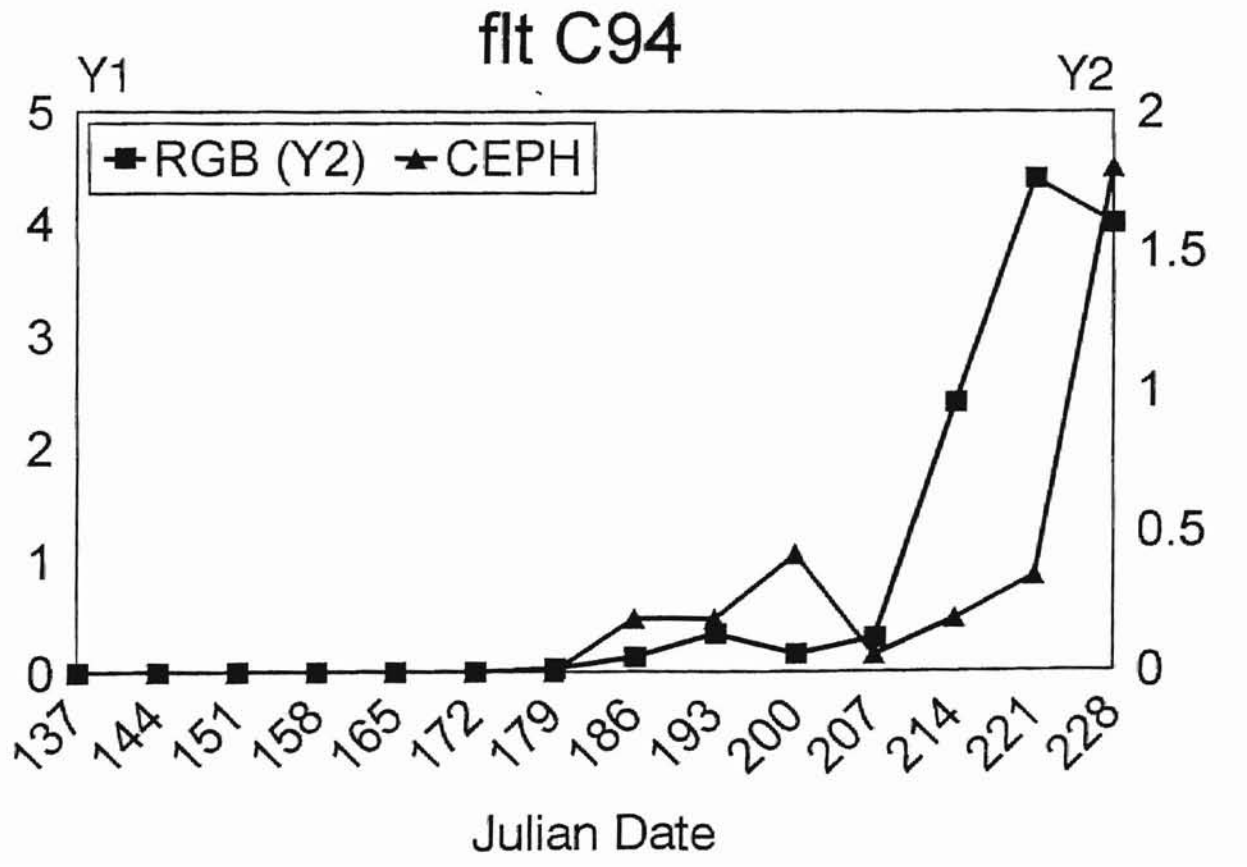
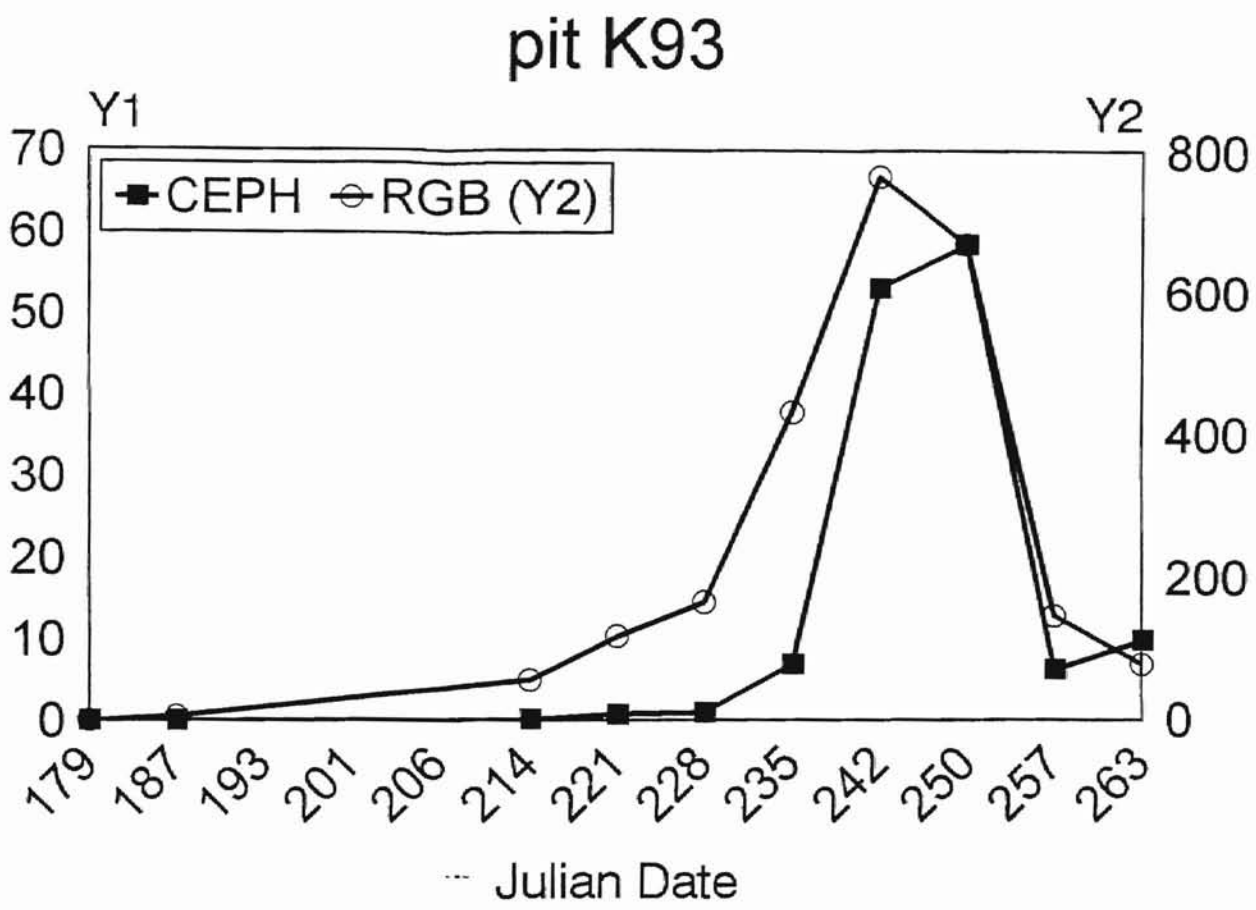

flt C94
Y1
Y2
RGB (Y2)
CEPH
5
4
3
2
1
0
2
1.5
1
0.5
0
137
144
151
158
165
172
179
186
193
200
207
214
221
228
Julian Date

Fig. 7. Average number of adult insects captured in pitfall probe traps at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in pitfall probe traps from June 28 to September 20 at Kingfisher in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in pitfall probe traps from June 21 to September 13 at Kingfisher in 1994; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)


pit K93
Y1
Y2
CEPH
RGB (Y2)
70
60
50
40
30
20
10
0
800
600
400
200
0
179
187
193
201
206
214
221
228
235
242
250
257
263
Julian Date

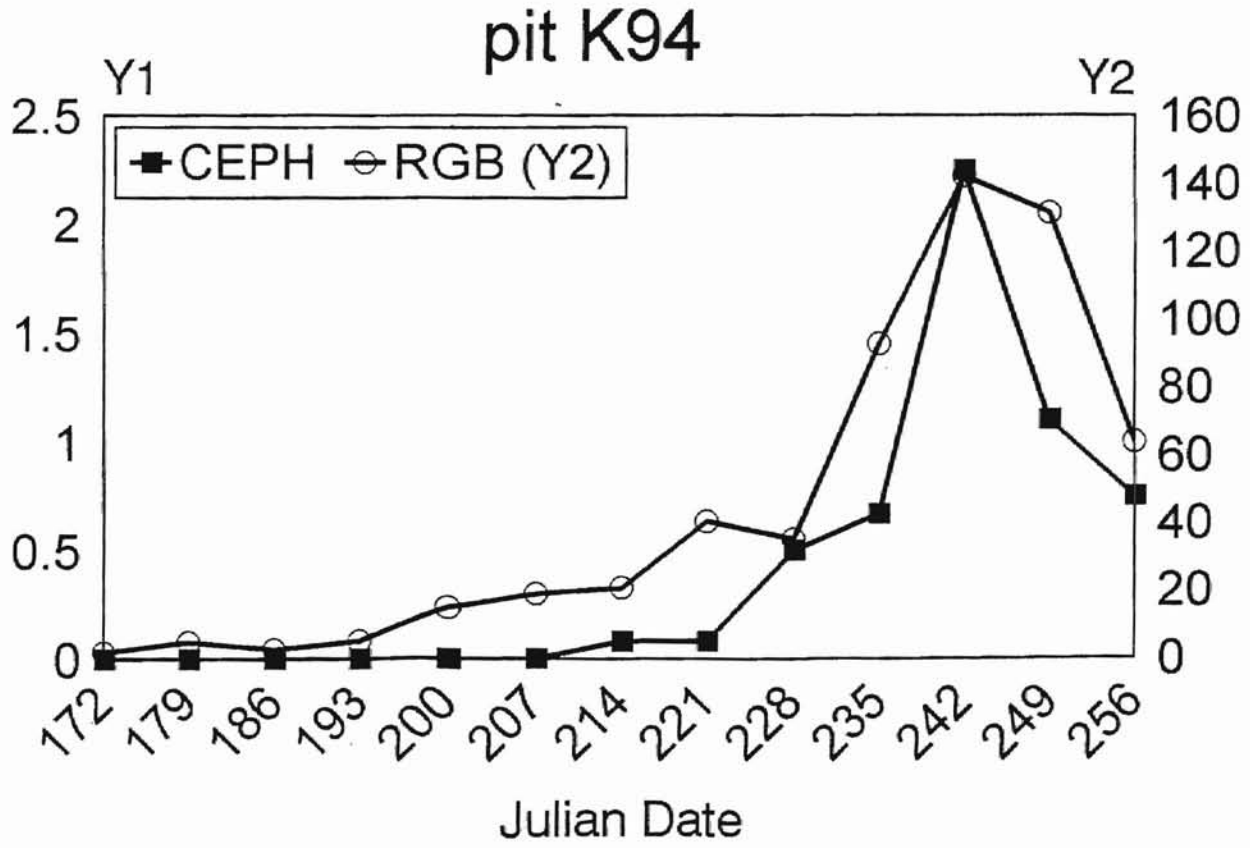

pit K94
Y1
Y2
CEPH
RGB (Y2)
2.5
2
1.5
1
0.5
0
160
140
120
100
80
60
40
20
0
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 8. Average number of adult insects captured in pitfall probe traps at Crescent in 1993-1994

Key: A) Average number of adult insects captured in pitfall probe traps from August 2 to August 23 at Crescent in 1993; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1); B) Average number of adult insects captured in pitfall probe traps from June 28 to August 23 at Crescent in 1994; RGB, rusty grain beetle, *C. ferrugineus* (Y2); CEPH, *C. waterstoni* (Y1)

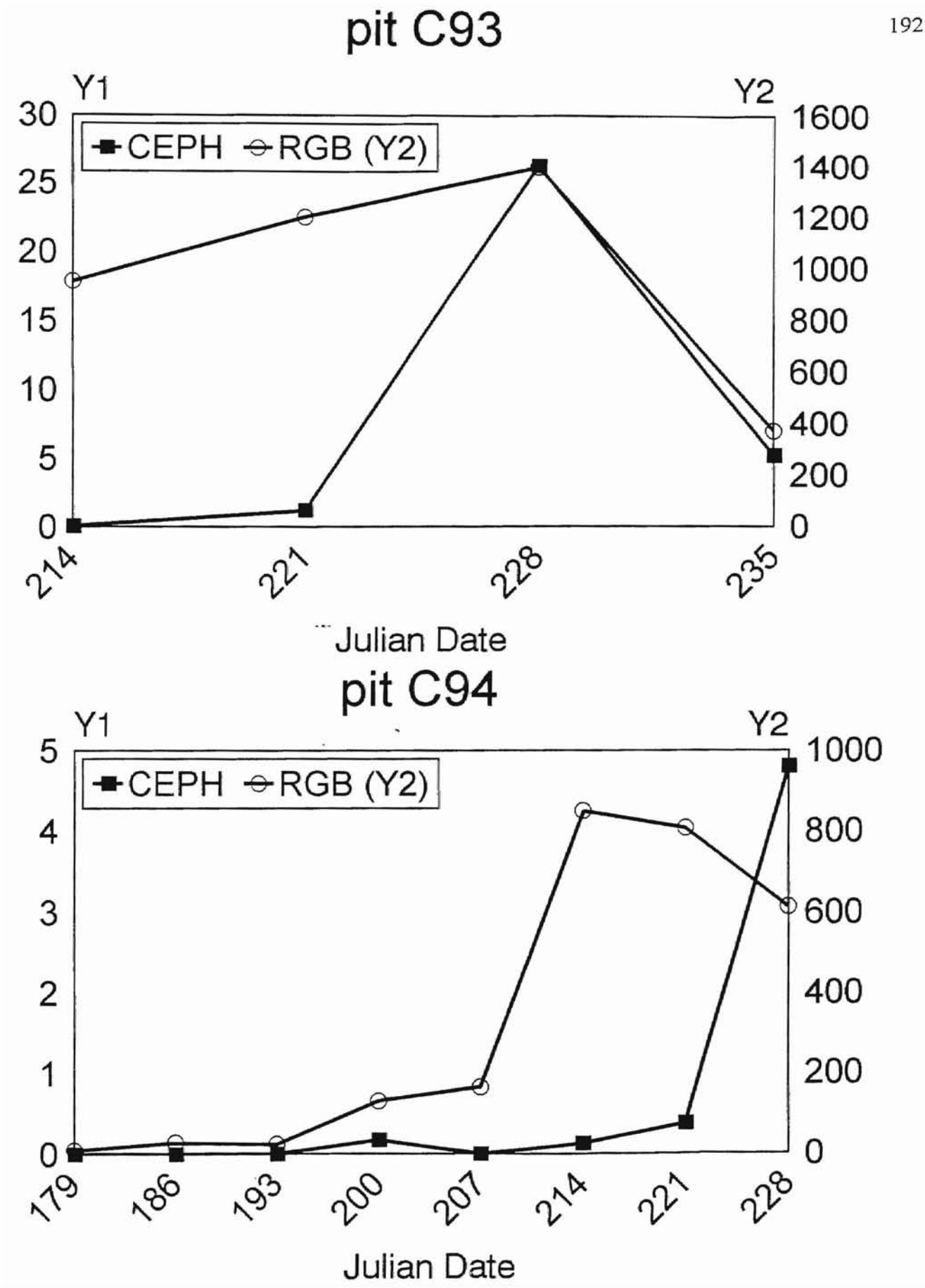
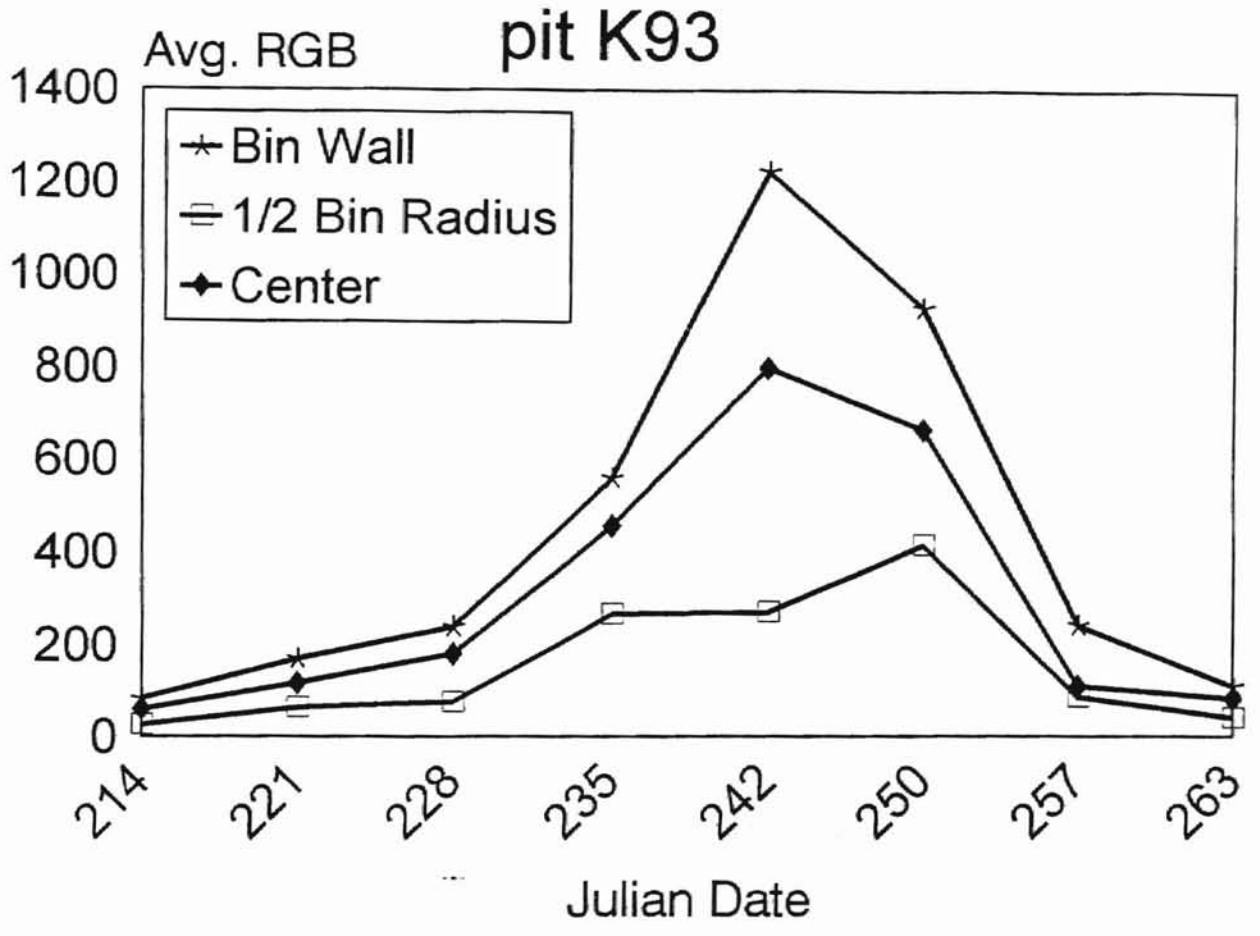

pit C93
Y1
Y2
CEPH
RGB (Y2)
30
25
20
15
10
5
0
1600
1400
1200
1000
800
600
400
200
0
214
221
228
235
Julian Date
pit C94
Y1
Y2
CEPH
RGB (Y2)
5
4
3
2
1
0
1000
800
600
400
200
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 9. Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 20 at Kingfisher in 1993; B) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from June 21 to September 13 at Kingfisher in 1994


pit K93
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
1400
1200
1000
800
600
400
200
0
214
221
228
235
242
250
257
263
Julian Date

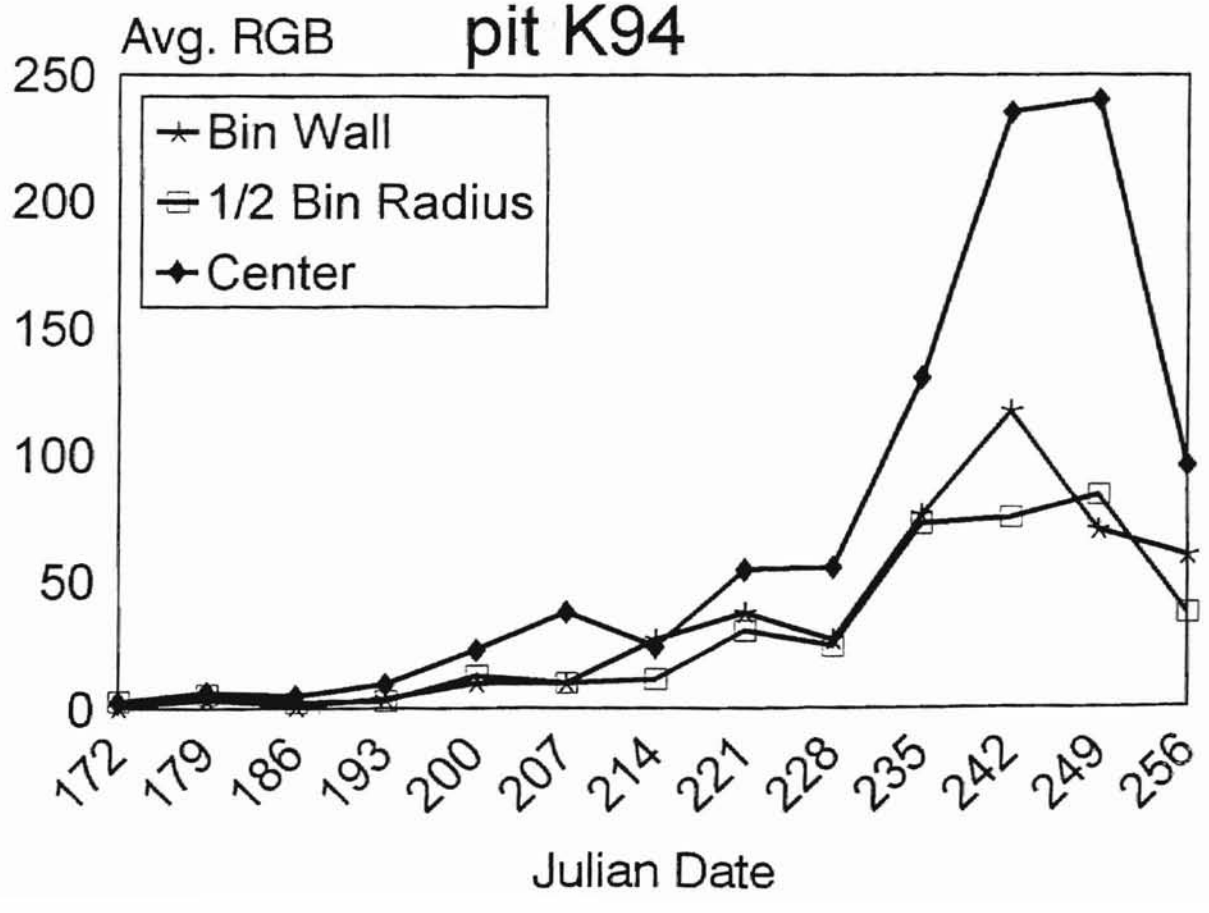
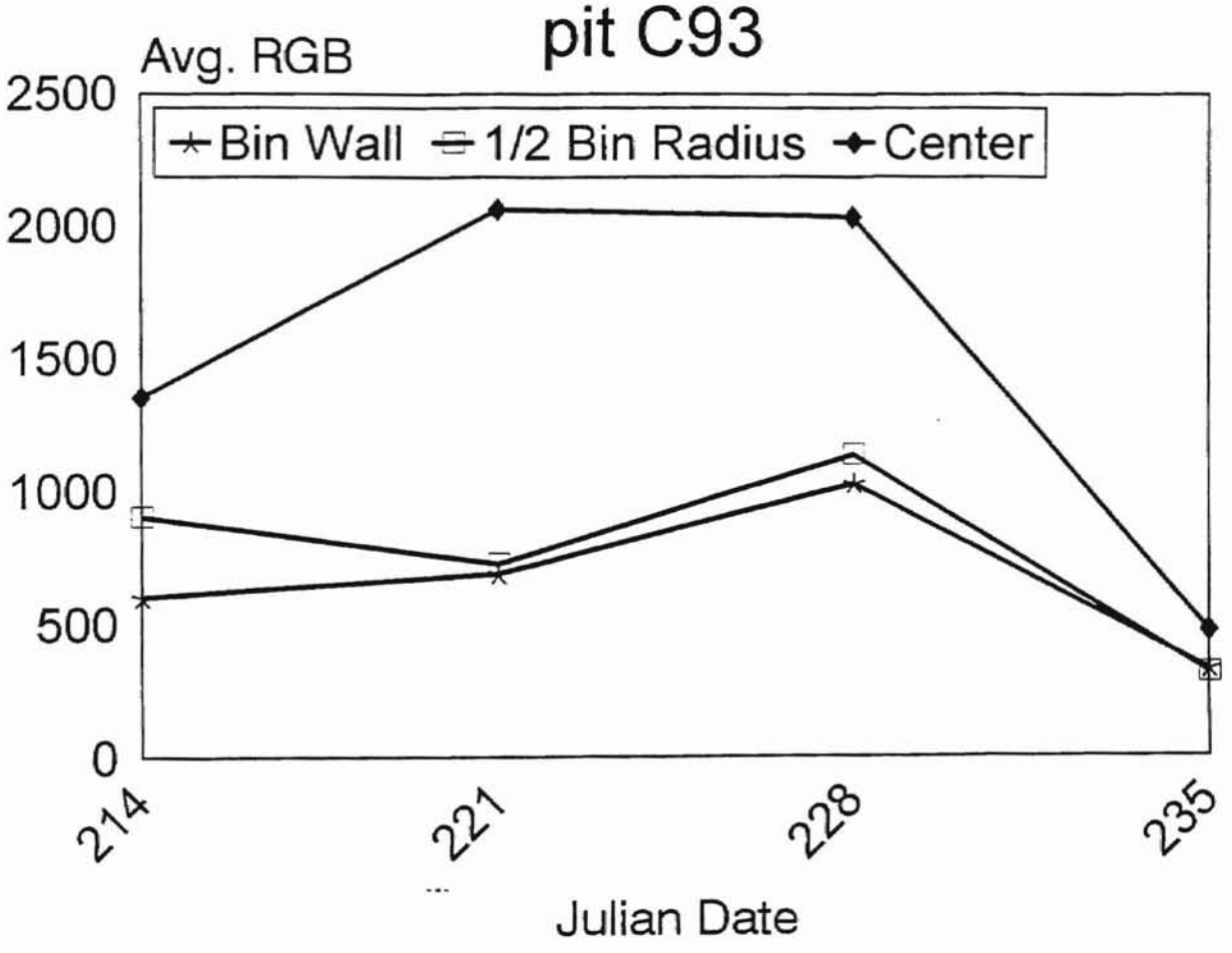

pit K94
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
250
200
150
100
50
0
172
179
186
193
200
207
214
221
228
235
242
249
256
Julian Date

Fig. 10. Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. ferrugineus* captured in pitfall probe traps by trap distance from bin wall from June 28 to August 16 at Crescent in 1994


pit C93
Avg. RGB
2500
2000
1500
1000
500
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
Julian Date

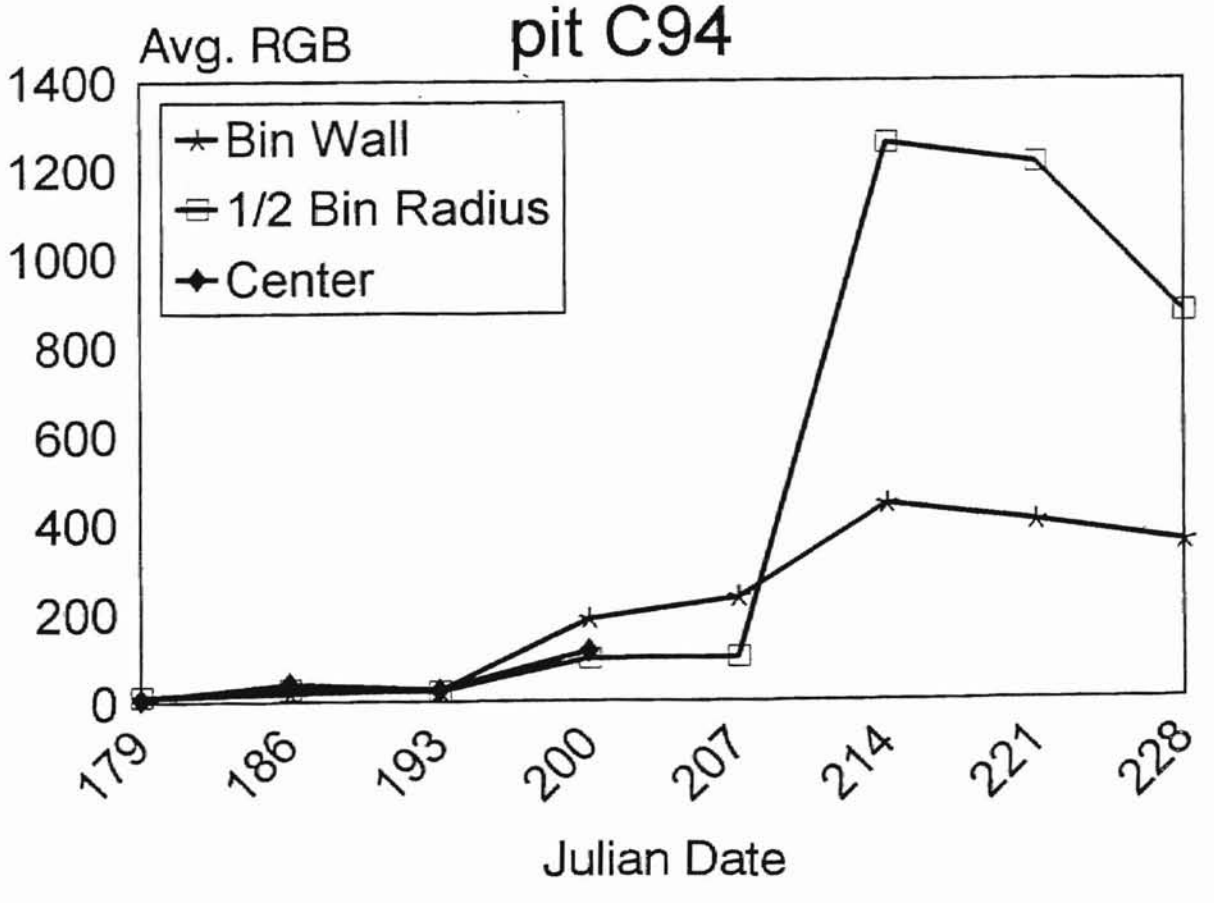
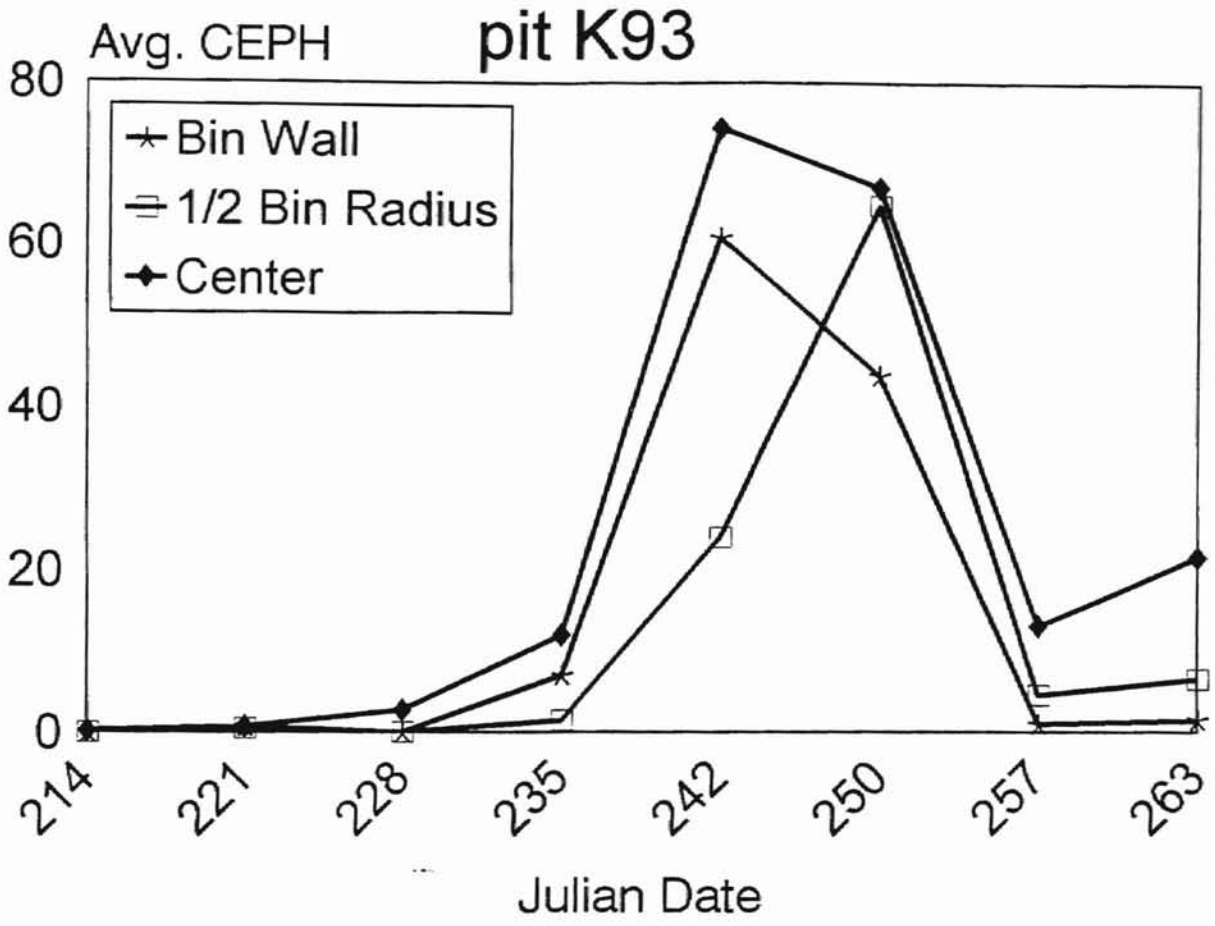

pit C94
Avg. RGB
1400
1200
1000
800
600
400
200
0
Bin Wall
1/2 Bin Radius
Center
179
186
193
200
207
214
221
228
Julian Date

Fig. 11. Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 20 at Kingfisher in 1993; B) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to September 13 at Kingfisher in 1994


Avg. CEPH
pit K93
80
60
40
20
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
242
250
257
263
Julian Date

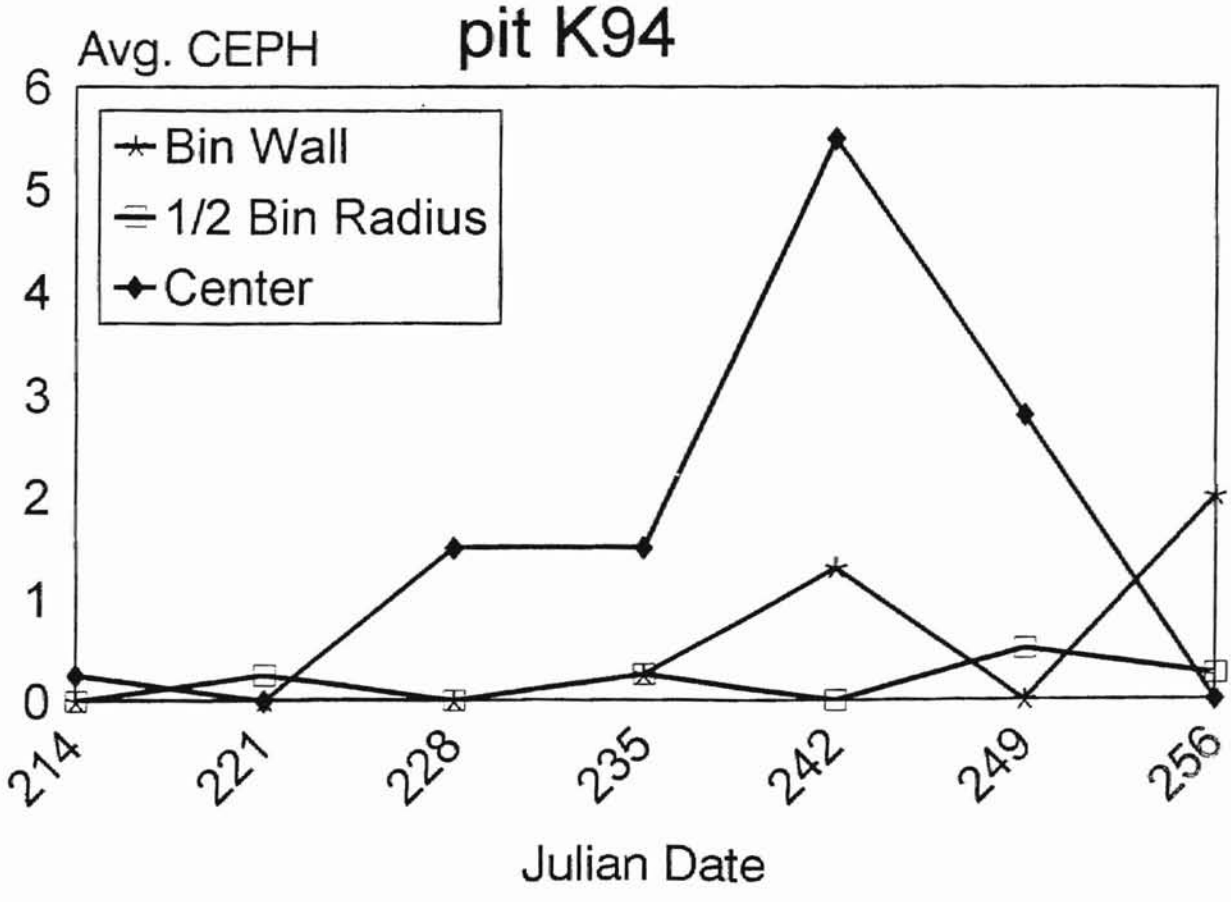
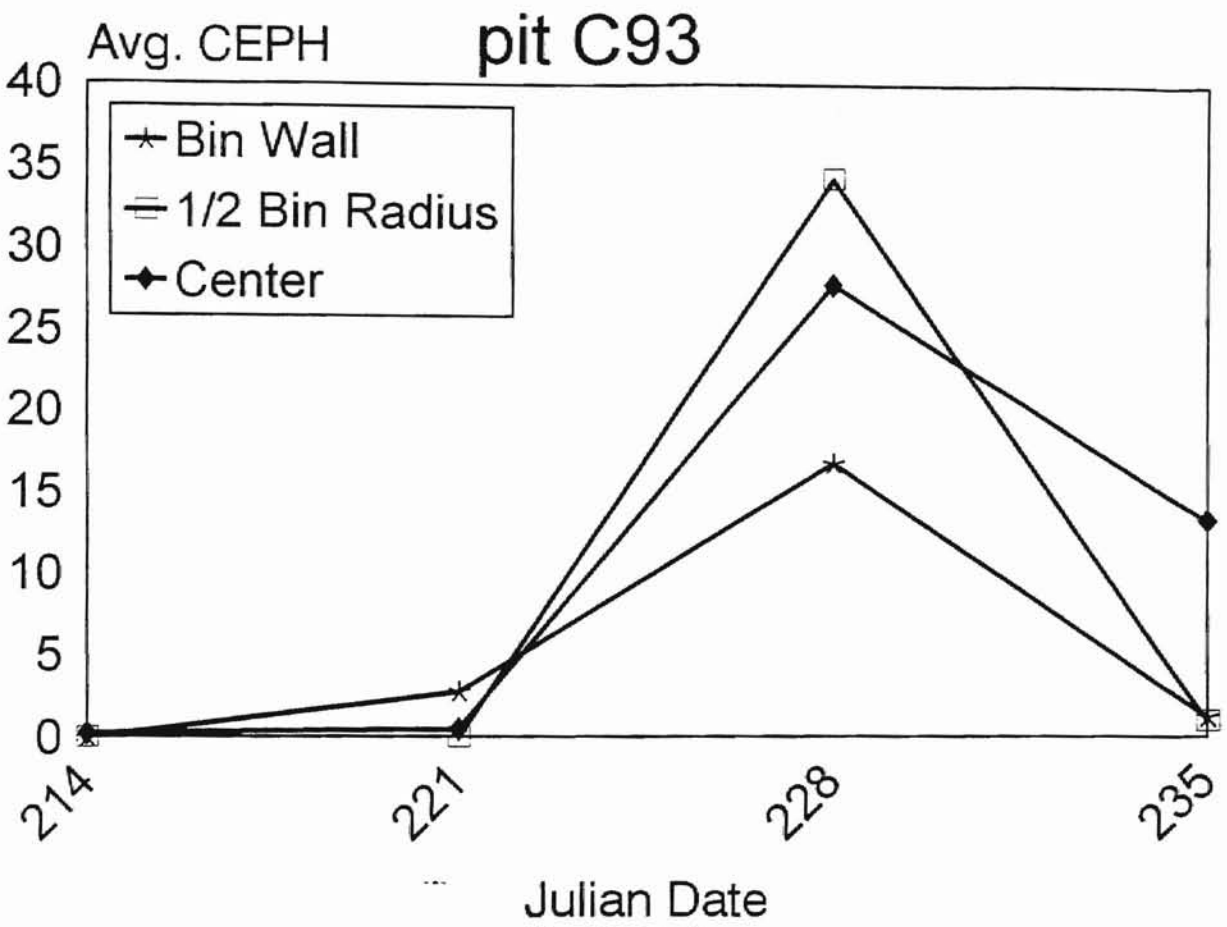

Avg. CEPH
pit K94
6
5
4
3
2
1
0
Bin Wall
1/2 Bin Radius
Center
214
221
228
235
242
249
256
Julian Date

Fig. 12. Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. waterstoni* captured in pitfall probe traps by trap distance from bin wall from June 28 to August 16 at Crescent in 1994


Avg. CEPH
pit C93
Bin Wall
1/2 Bin Radius
Center
40
35
30
25
20
15
10
5
0
214
221
228
235
Julian Date

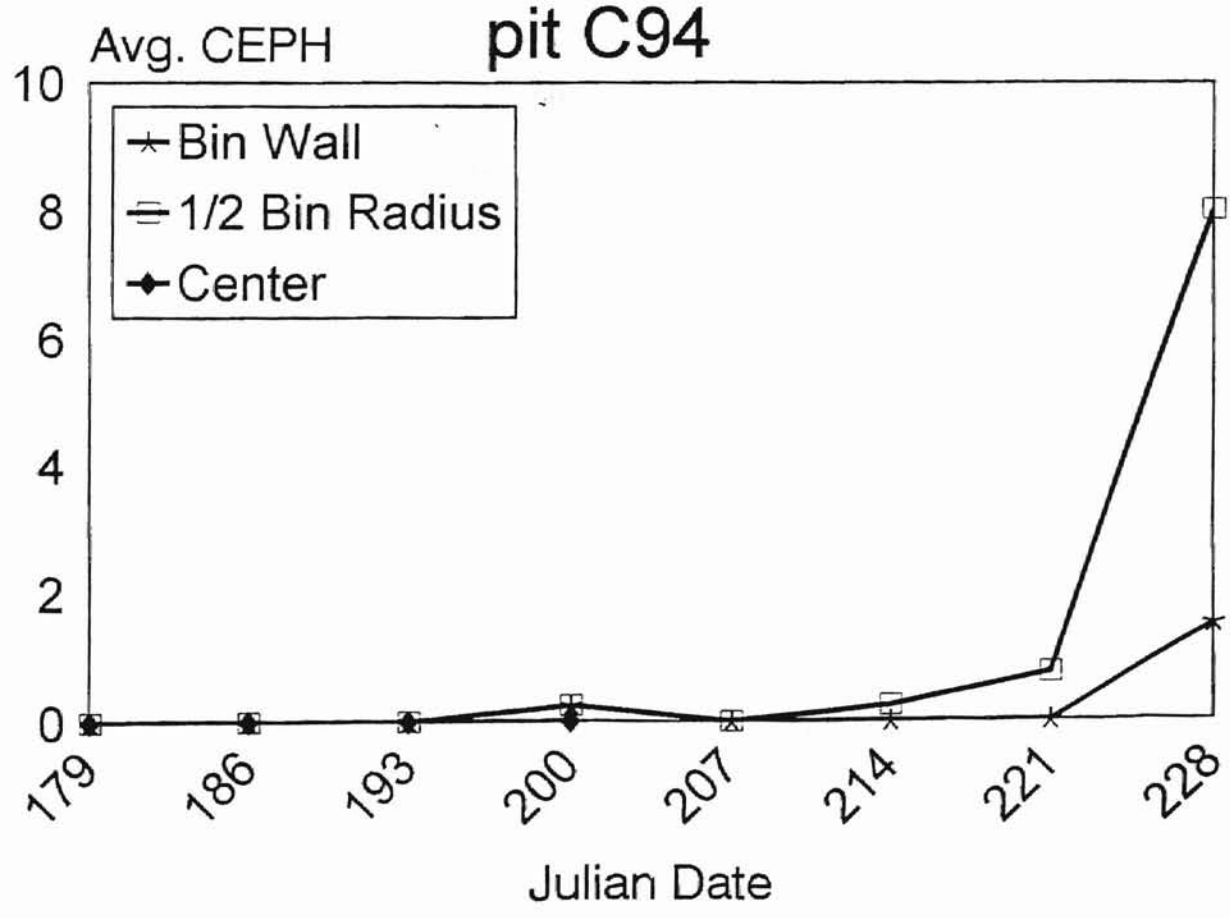
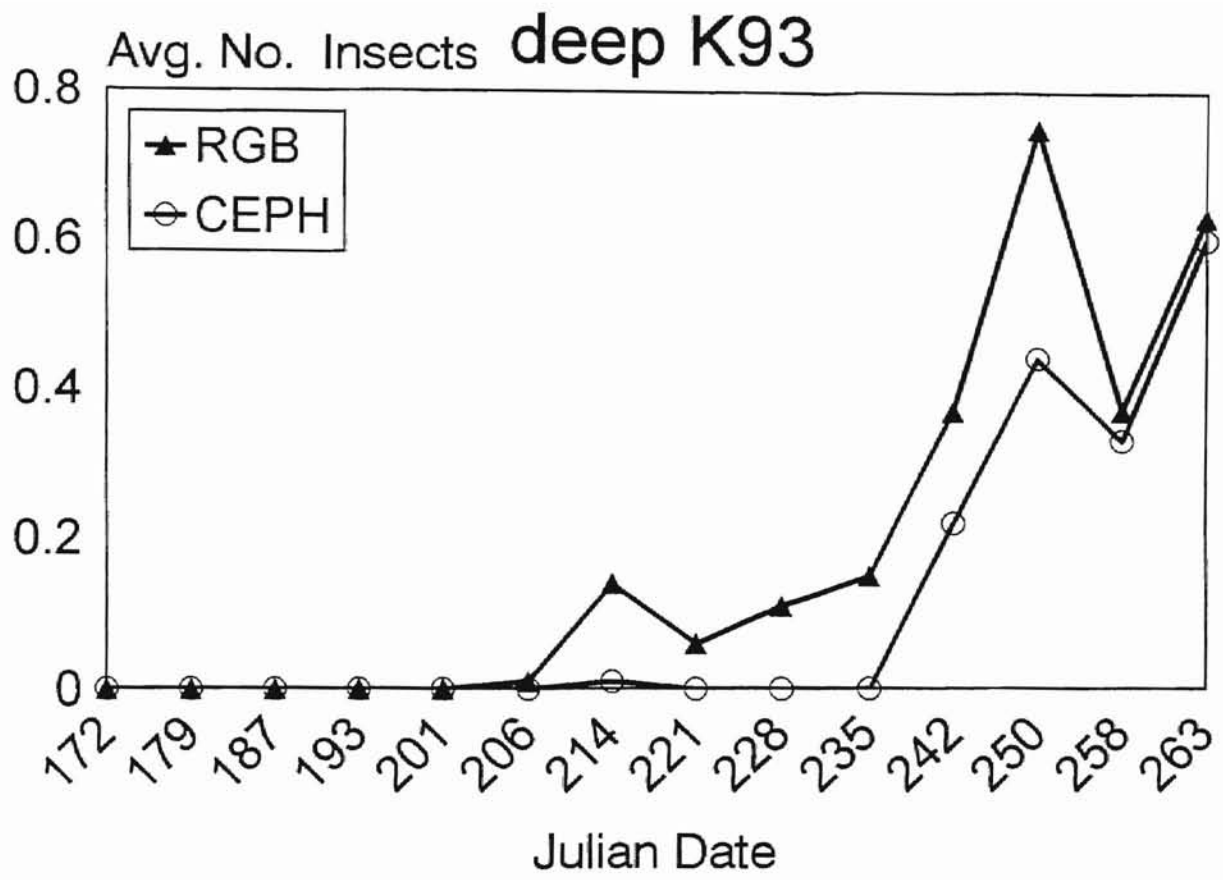

Avg. CEPH
pit C94
Bin Wall
1/2 Bin Radius
Center
10
8
6
4
2
0
179
186
193
200
207
214
221
228
Julian Date

Fig. 13. Average number of adult insects captured in deep cup probe samples at Kingfisher in 1993-1994

Key: A) Average number of adult insects captured in deep cup probe samples from June 21 to September 20 at Kingfisher in 1993; RGB, rusty grain beetle, *C. ferrugineus*; CEPH, *C. waterstoni* ; B) Average number of adult insects captured in deep cup probe samples from June 21 to September 20 at Kingfisher in 1994; RGB, rusty grain beetle, *C. ferrugineus*; CEPH, *C. waterstoni*


deep K93
Avg. No. Insects
RGB
CEPH
0.8
0.6
0.4
0.2
0
172
179
187
193
201
206
214
221
228
235
242
250
258
263
Julian Date

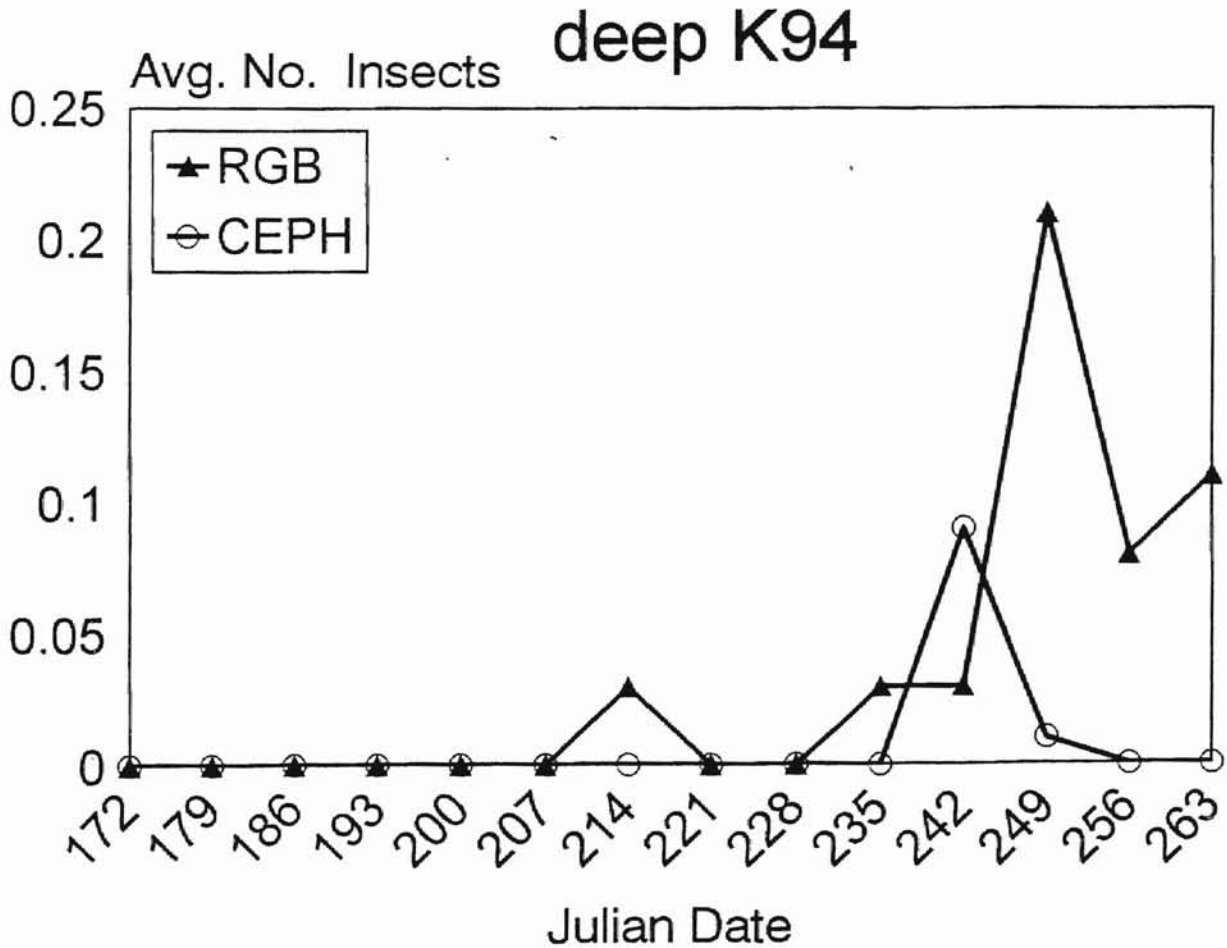
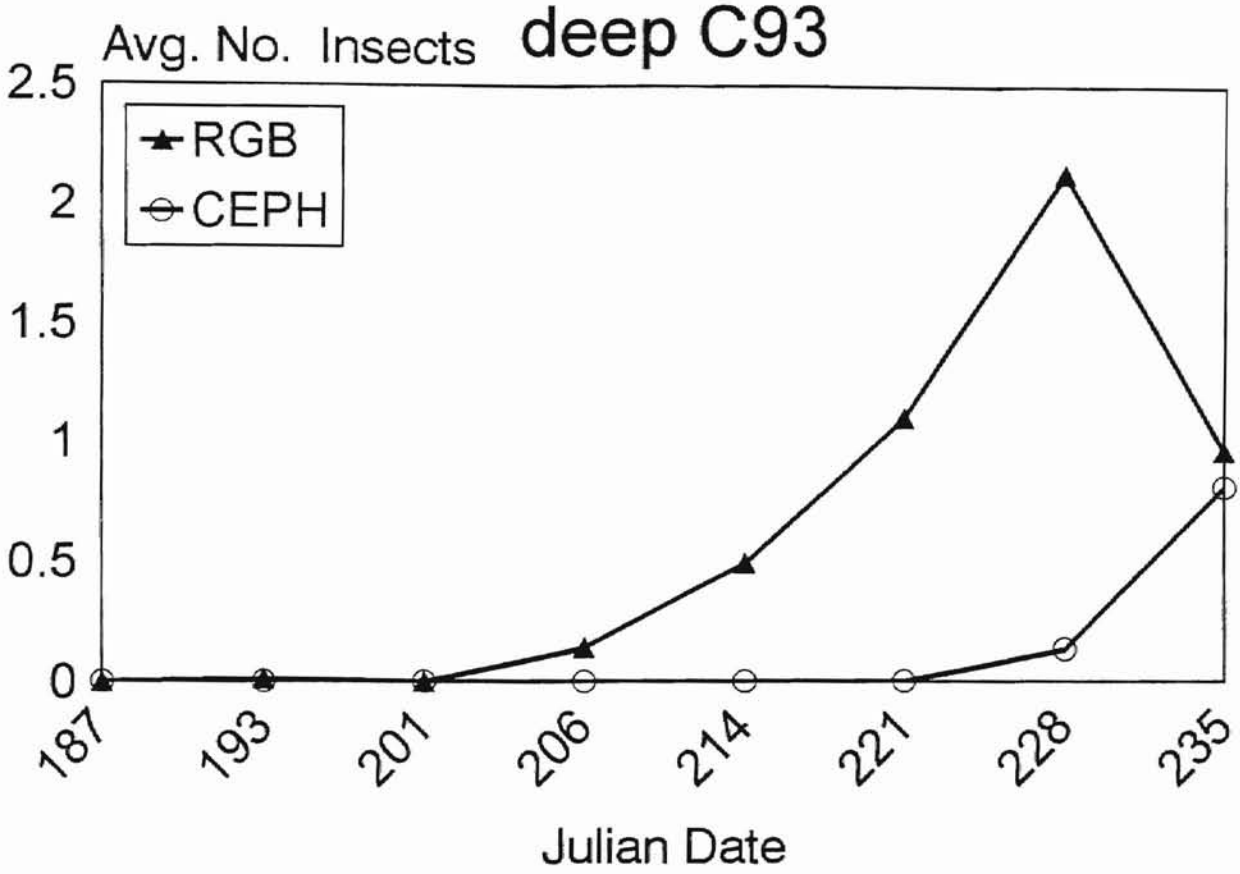

deep K94
Avg. No. Insects
RGB
CEPH
0.25
0.2
0.15
0.1
0.05
0
172
179
186
193
200
207
214
221
228
235
242
249
256
263
Julian Date

Fig. 14. Average number of adult insects captured in deep cup probe samples at Crescent in 1993-1994

Key: A) Average number of adult insects captured in deep cup probe samples from July 6 to August 23 at Crescent in 1993; RGB, rusty grain beetle, *C. ferrugineus*; CEPH, *C. waterstoni*; B) Average number of adult insects captured in deep cup probe samples from July 5 to August 23 at Crescent in 1994; RGB, rusty grain beetle, *C. ferrugineus*; CEPH, *C. waterstoni*


deep C93
Avg. No. Insects
2.5
2
1.5
1
0.5
0
RGB
CEPH
187
193
201
206
214
221
228
235
Julian Date

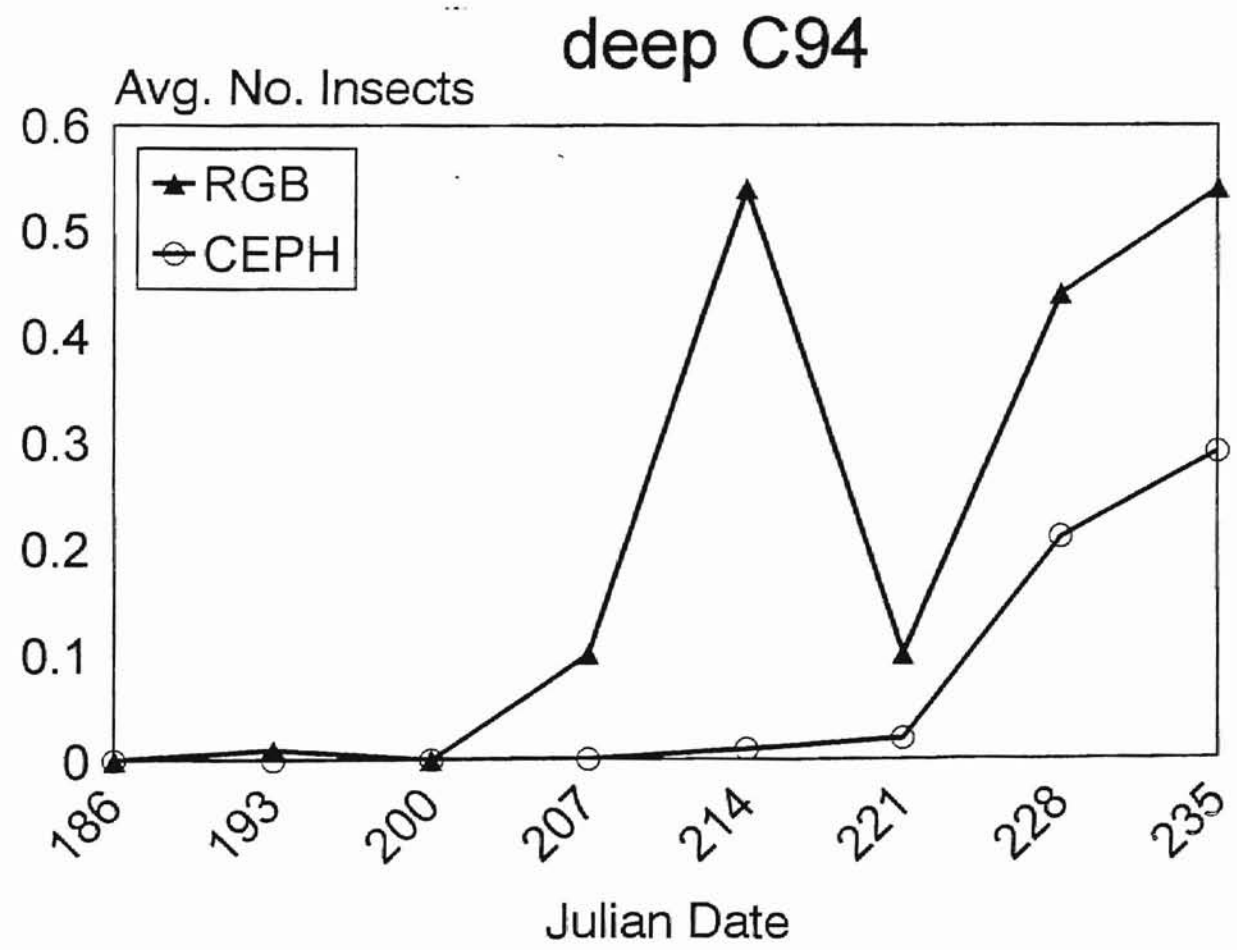
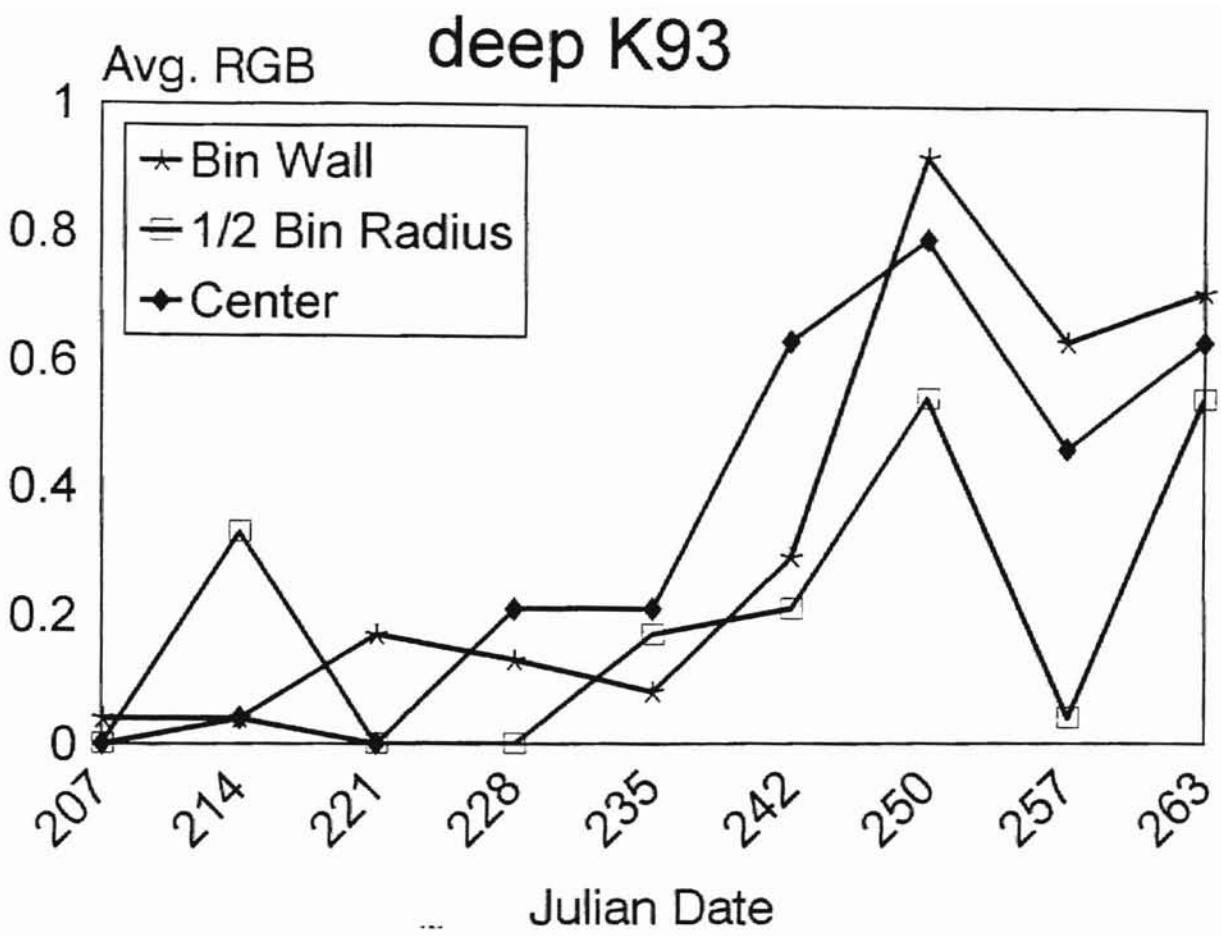

deep C94
Avg. No. Insects
0.6
0.5
0.4
0.3
0.2
0.1
0
RGB
CEPH
186
193
200
207
214
221
228
235
Julian Date

Fig. 15. Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of *adult C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1993; B) Average number of *adult c. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1994


deep K93
Avg. RGB
1
0.8
0.6
0.4
0.2
0
Bin Wall
1/2 Bin Radius
Center
207
214
221
228
235
242
250
257
263
Julian Date

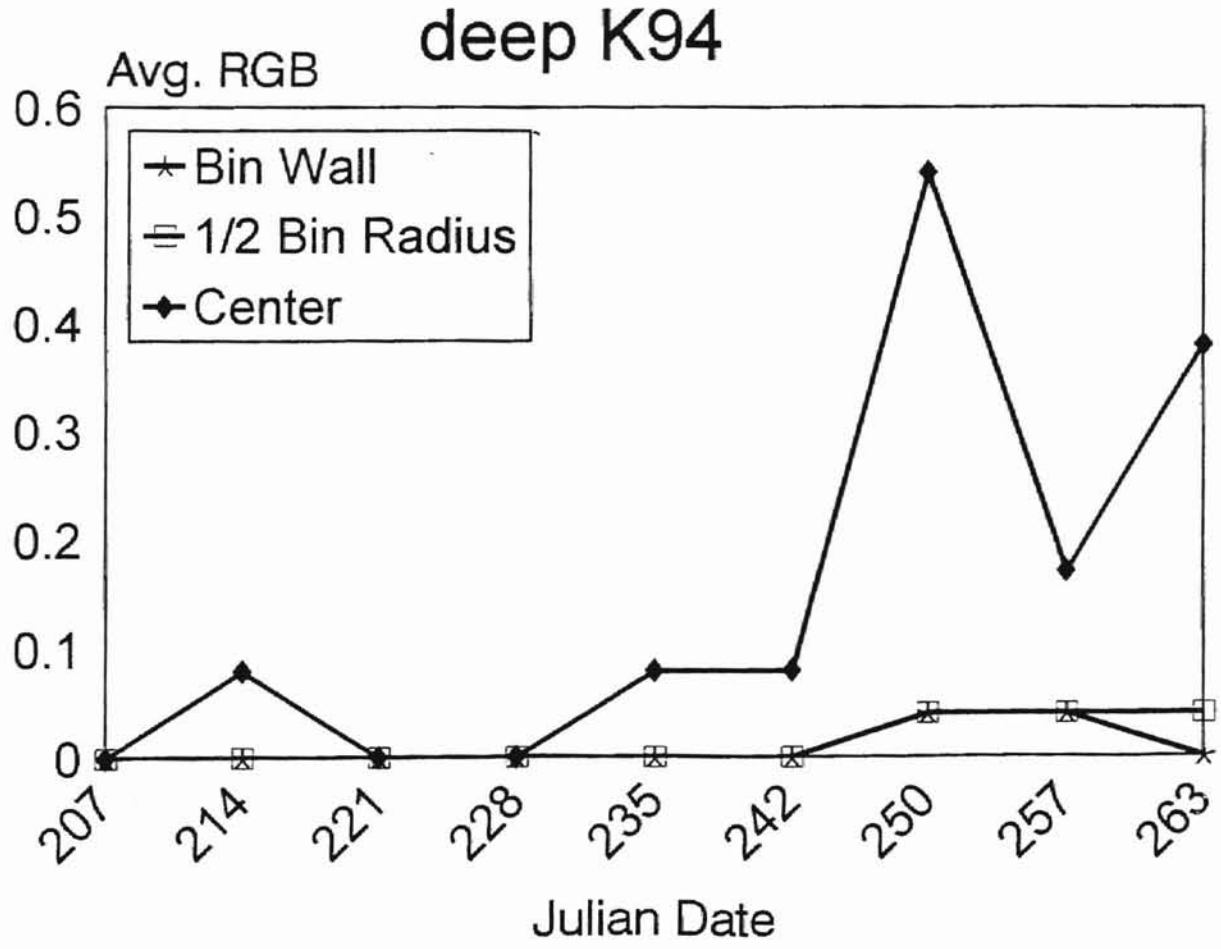
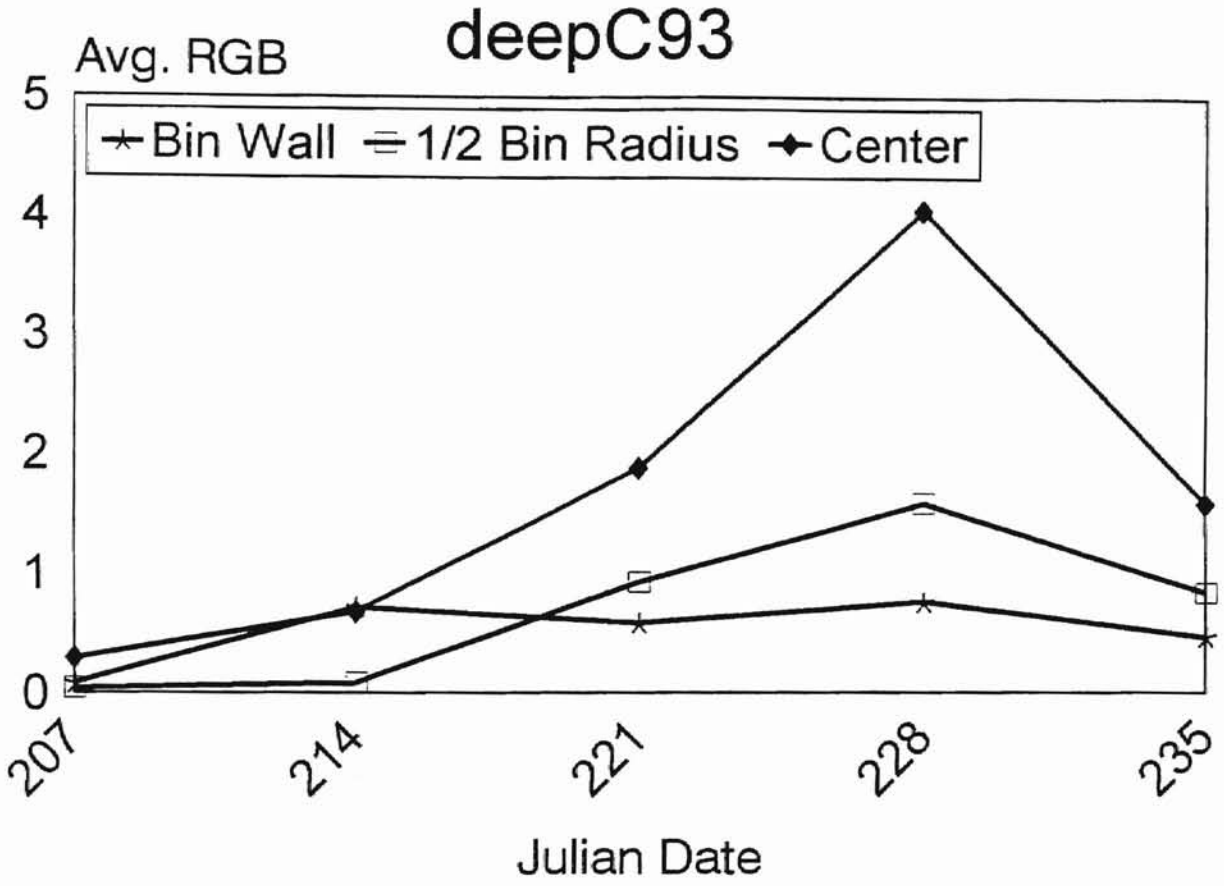

deep K94
Avg. RGB
0.6
0.5
0.4
0.3
0.2
0.1
0
Bin Wall
1/2 Bin Radius
Center
207
214
221
228
235
242
250
257
263
Julian Date

Fig. 16. Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1994


deepC93
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
5
4
3
2
1
0
207
214
221
228
235
Julian Date

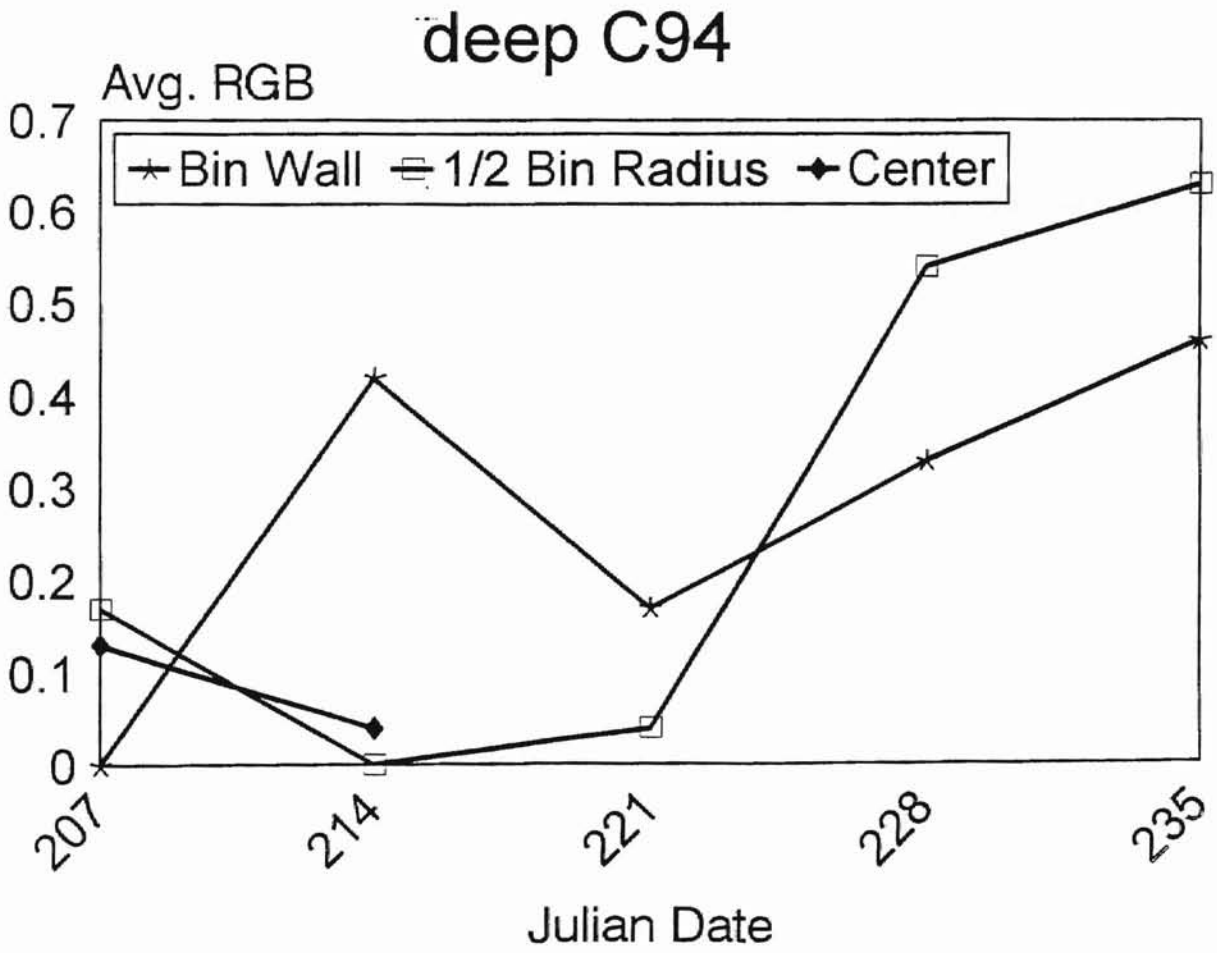
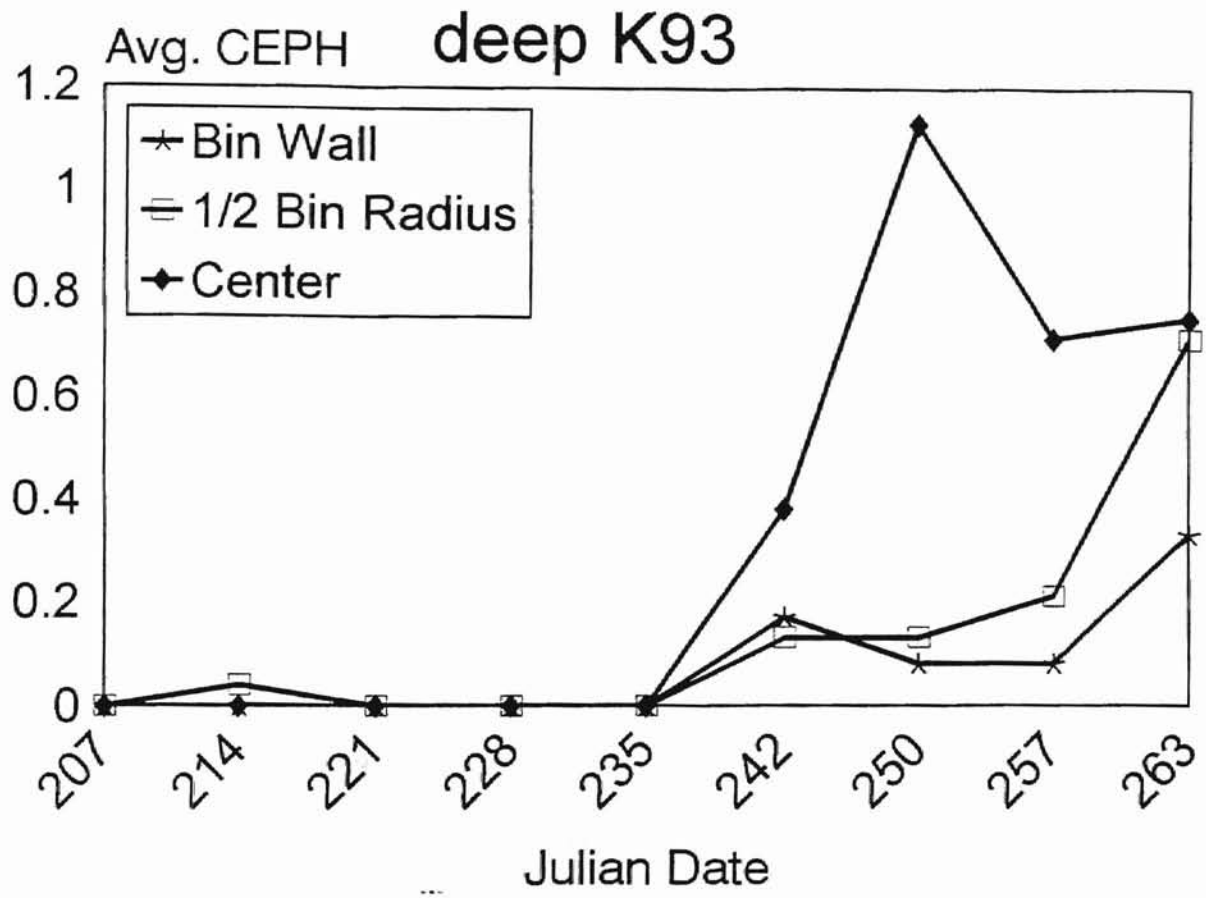

deep C94
Avg. RGB
Bin Wall
1/2 Bin Radius
Center
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
207
214
221
228
235
Julian Date

Fig. 17. Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall at Kingfisher in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1993; B) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from July 26 to September 20 at Kingfisher in 1994


deep K93
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
1.2
1
0.8
0.6
0.4
0.2
0
207
214
221
228
235
242
250
257
263
Julian Date

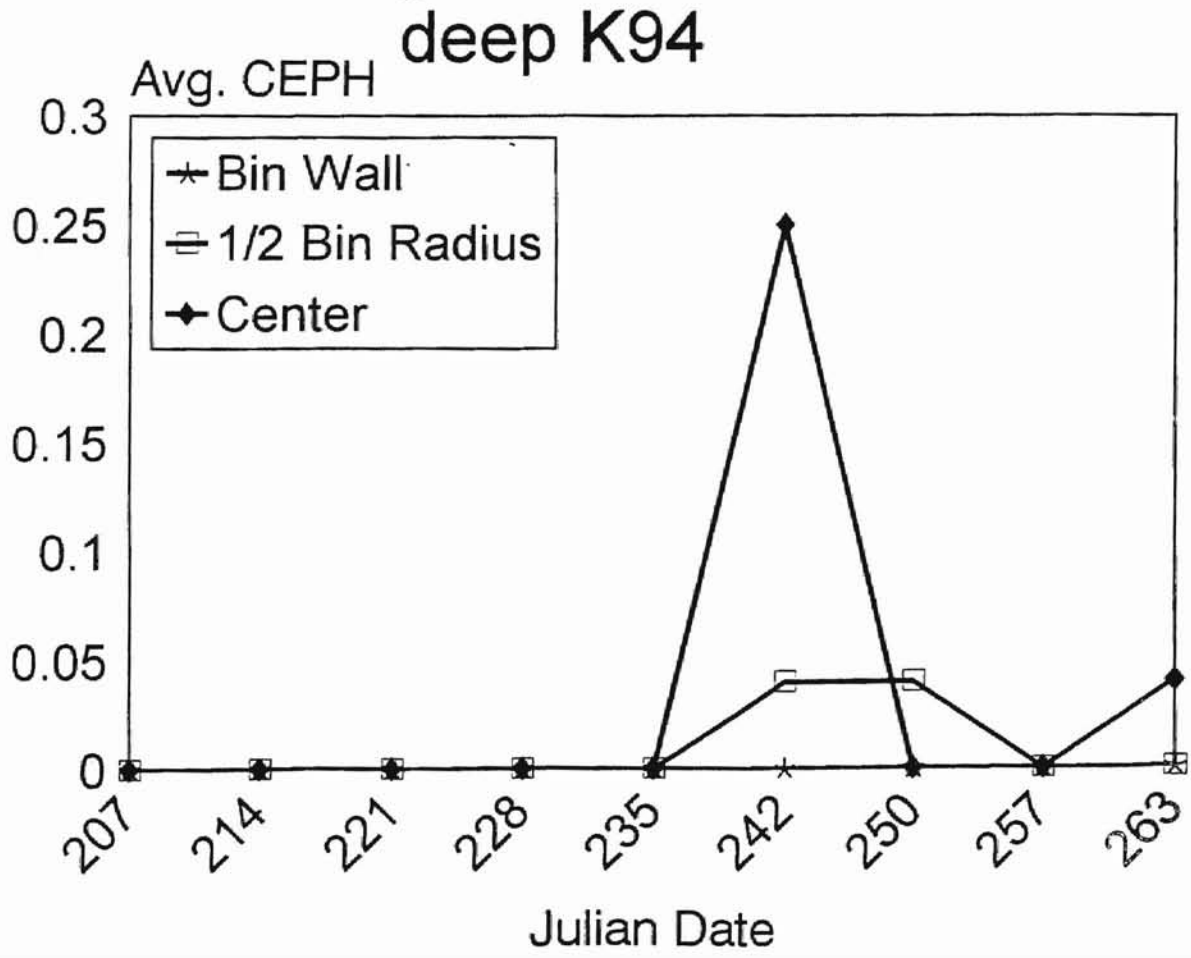
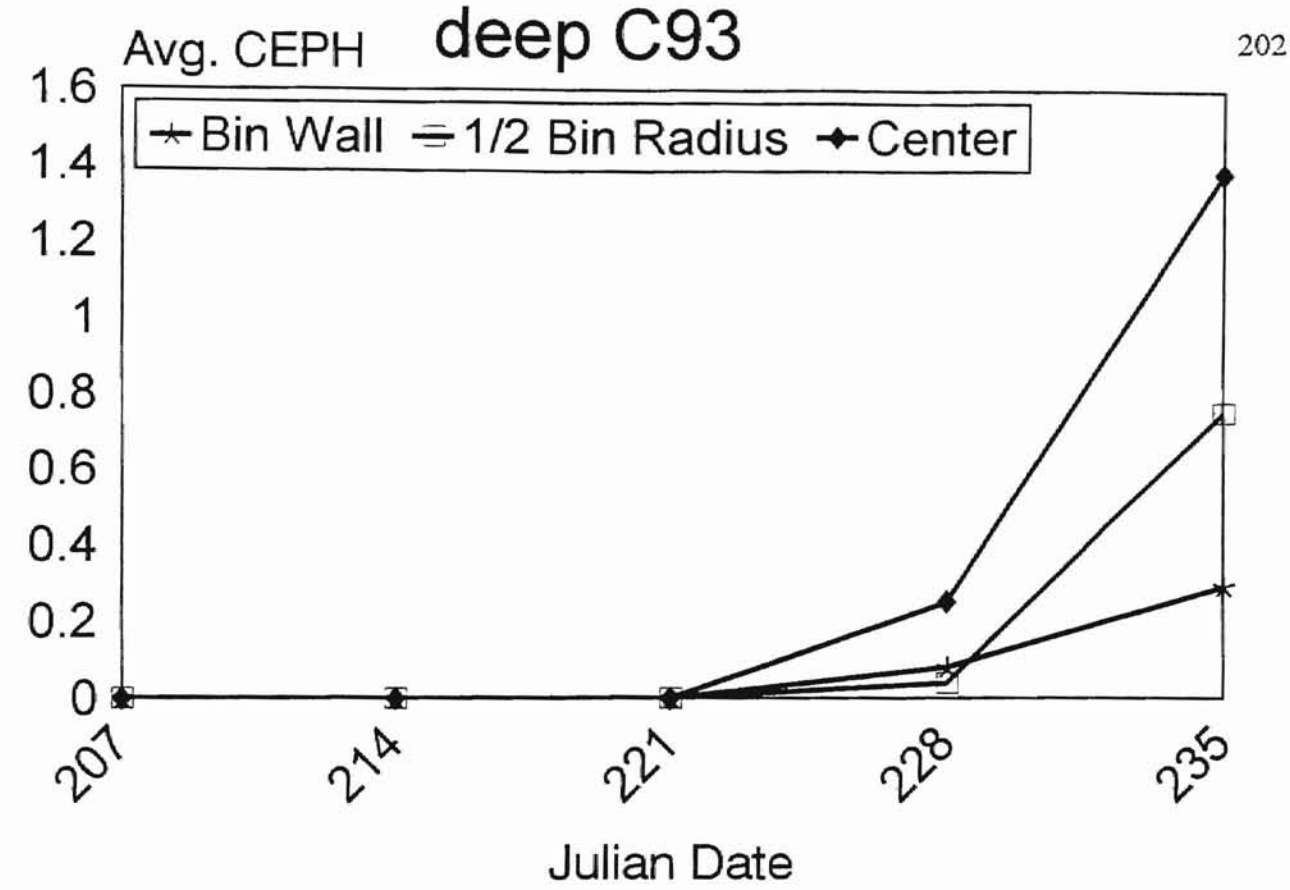

deep K94
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
0.3
0.25
0.2
0.15
0.1
0.05
0
207
214
221
228
235
242
250
257
263
Julian Date

Fig. 18. Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall at Crescent in 1993-1994

Key: A) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1993; B) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample distance from bin wall from August 2 to August 23 at Crescent in 1994


deep C93
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
207
214
221
228
235
Julian Date

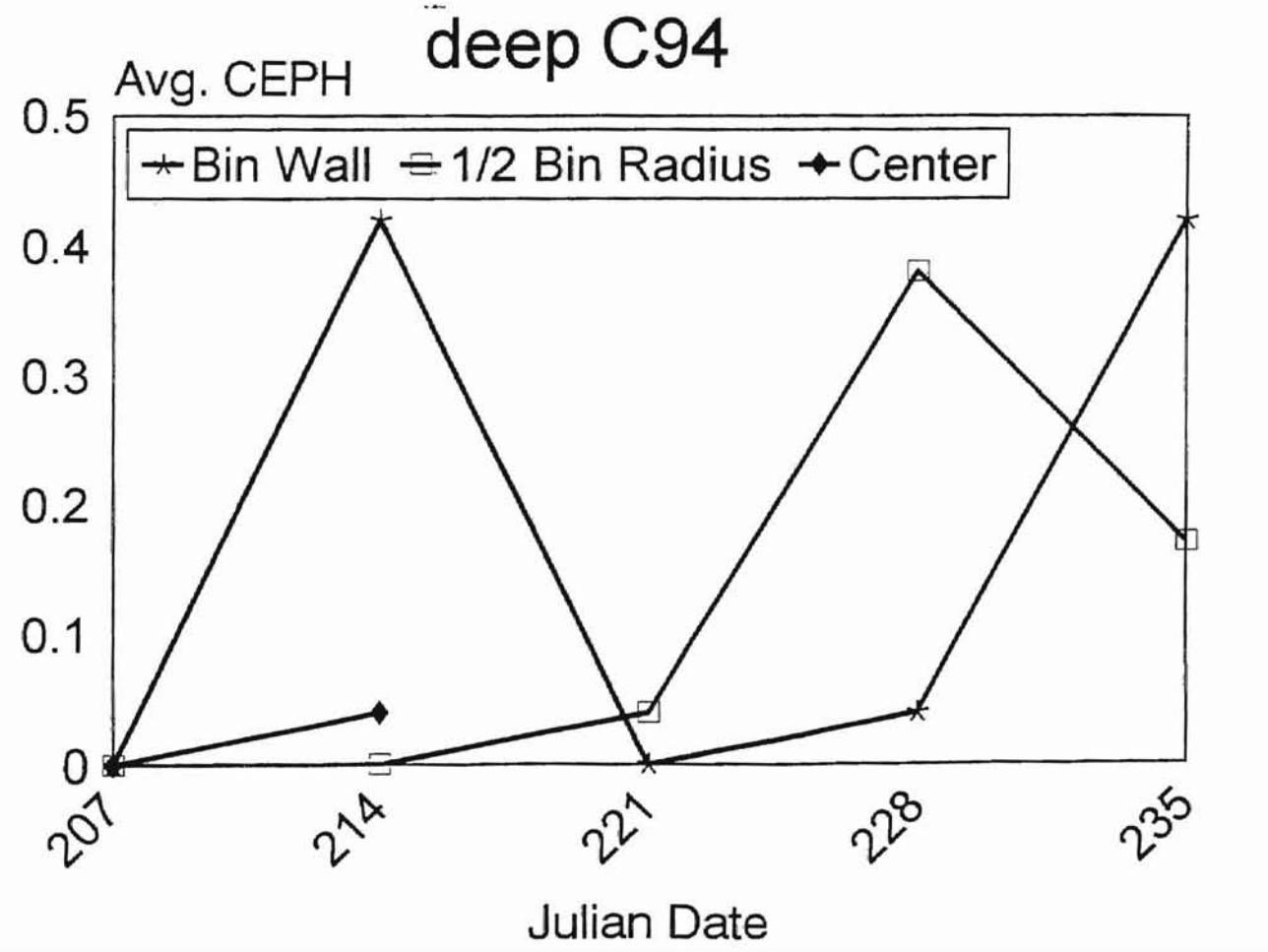
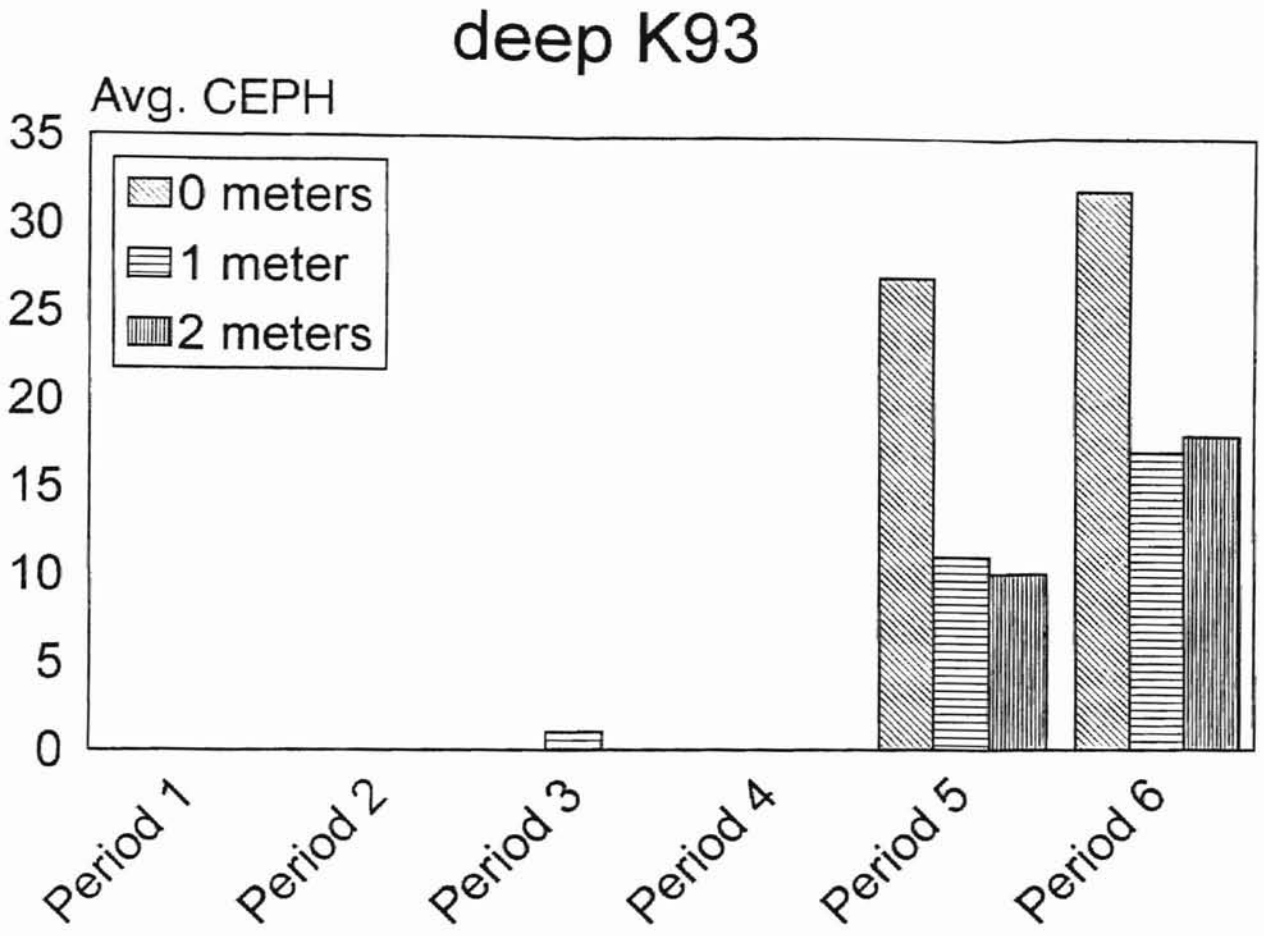
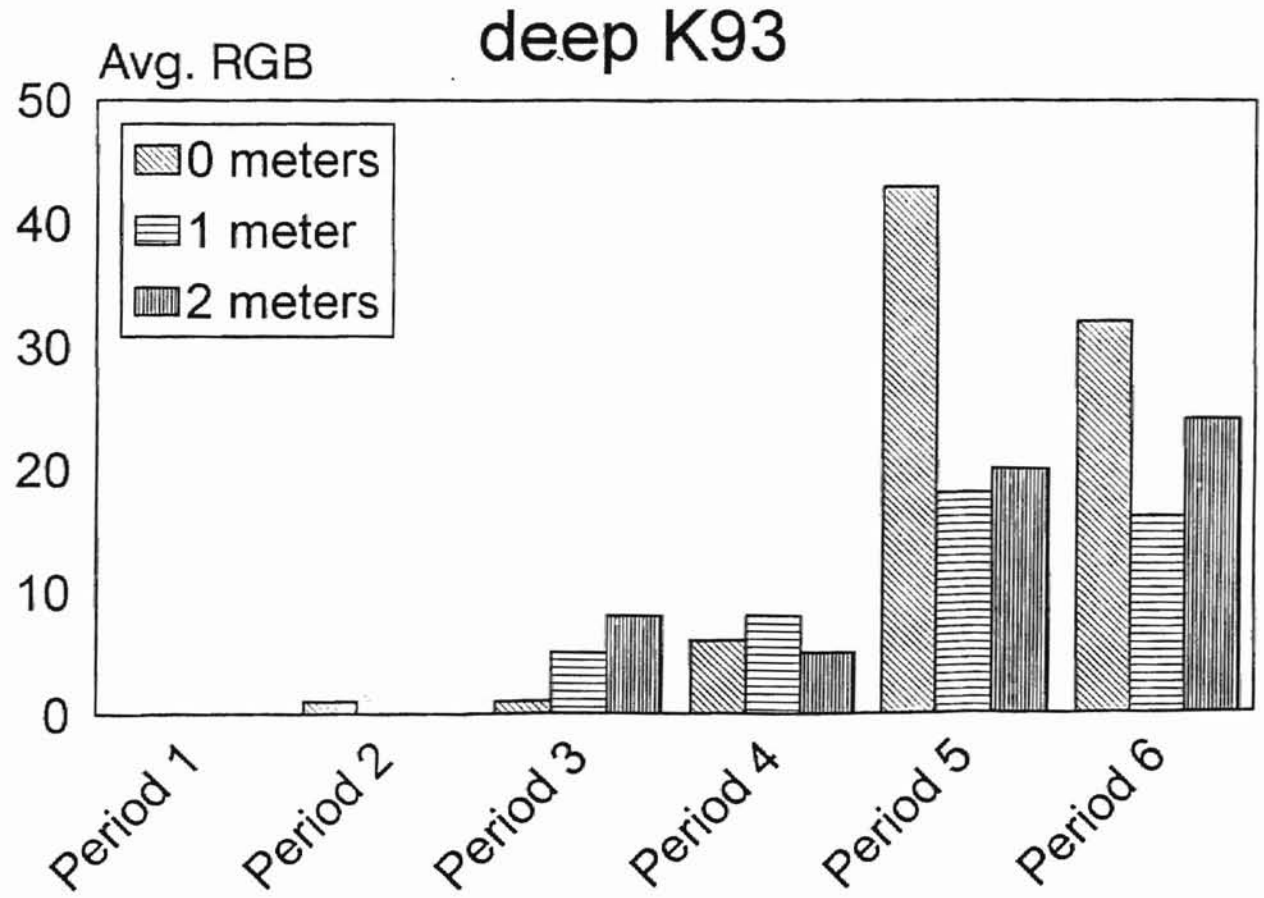

deep C94
Avg. CEPH
Bin Wall
1/2 Bin Radius
Center
0.5
0.4
0.3
0.2
0.1
0
207
214
221
228
235
Julian Date

Fig. 19. Average number of adult insects captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993

Key: A) Average number of adult *C. ferrugineus* captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993; B) Average number of adult *C. waterstoni* captured in deep cup probe samples by sample depth from July 26 to September 20 at Kingfisher in 1993; Period 1, July 5 & 12; Period 2, July 19 & 26; Period 3, August 2 & 9; Period 4, August 16 & 23; Period 5, August 30 and September 7; Period 6, September 14 & 20


deep K93
Avg. CEPH
35
30
25
20
15
10
5
0
0 meters
1 meter
2 meters
Period 1
Period 2
Period 3
Period 4
Period 5
Period 6


deep K93
Avg. RGB
50
40
30
20
10
0
0 meters
1 meter
2 meters
Period 1
Period 2
Period 3
Period 4
Period 5
Period 6

VITA

Michael William Gates

Candidate for the Degree of

Master of Science

Thesis: POPULATION DYNAMICS OF LESSER GRAIN BORER, RUSTY GRAIN BEETLE, AND *CEPHALONOMIA WATERSTONI* IN COMMERCIAL ELEVATORS

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Experience: Worked as a crop scout for Missouri Valley Agri-Services and as a laborer at a grain Co-op in Norborne, Missouri during the summer/fall of 1992; employed by Oklahoma State University as a graduate research assistant; Oklahoma State University, Department of Entomology, 1993 to present.

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