EFFECT OF SUBOPTIMAL TEMPERATURES, LOW CARBON DIOXIDE LEVELS, AND RELATIVE HUMIDITIES ON INTRASPECIFIC AND INTERSPECIFIC INTERACTIONS OF *CRYPTOLESTES FERRUGINEUS* (STEPHENS) AND *TRIBOLIUM CASTANEUM* (HERBST)

By

Rajshekhar Hulasare

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

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Department of Biosystems Engineering

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ABSTRACT

The main objective of the thesis research was to experimentally investigate the effect of low temperatures, CO_2 concentrations, and relative humidities on the population dynamics of two of Canada's most common and economically important stored-product insect species, *Cryptolestes ferrugineus* (Stephens) and *Tribolium castaneum* (Herbst), in isolation (intraspecific) and in combination (interspecific) with each other.

An experimental unit was designed and fabricated to conduct the tests in a controlled temperature chamber. The data for adult survival of each species in single and mixed-species combination were collected in the laboratory for various combinations of temperature (15, 20, and 25°C), CO_2 level (ambient, 2, 5, and 10%), relative humidity (50 and 70%), and exposure time (2 to 8 wk). The food source for all the treatments was hard red spring wheat No. 1 cv. 'AC Barrie' with 5% dockage added to it. The adult population densities for all single-species and mixed-species combinations of each species were 1000 and 2000 insects/kg, respectively.

The data of adult survival obtained from all the experimental tests were appropriately transformed using logarithmic, square root, or arcsin transformations for analyses of variance (ANOVA) using the general linear model (GLM) of SAS (2000). Procedures REG and MIXED were used to fit data into predictive equations for each species and to compare adult survival in various treatments.

All the variables: moisture content, temperature, CO_2 concentration, species combination, and time of exposure significantly affected the adult survival of both the species in single as well as mixed-species combinations. The adult survivals of both species,

singly and together were significantly higher at a higher relative humidity (wet grain at 15% moisture content, wet basis) compared with a lower humidity (dry grain at 12% moisture content, wet basis) in all treatments at various temperature and CO_2 levels. For both species and their combinations, the temperature had a significant and positive correlation effect on the adult survival at constant CO_2 levels and a negative correlation with increasing CO_2 levels at constant temperature. Similarly, the CO_2 concentration had a significant and negative correlation with adult survival i.e. it decreased with increasing CO_2 levels. The species effect, being alone or in combination with other species, also affected adult survival. *Cryptolestes ferrugineus* had a dominant and population-suppressing effect on *T. castaneum* adults in mixed-species combinations in both dry and wet wheat. Seed germination was affected significantly in mixed-species combinations of both the species and single-species controls of *T. castaneum* at 25 °C.

The adult survival at all treatments for various species combinations was compared with adult survival at ideal conditions of 30 °C and 70% relative humidity. All the variables: temperature, CO_2 level, and relative humidity are stress conditions resulting in lower adult populations compared with ideal conditions. Regression analysis was performed for the entire data, and two models one for each species, were fitted to predict the adult populations for all the ranges of variables in this study over an exposure time of 8 wk.

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Dedicated
to my mother *'Akkä'*
and
In memory of my father *'Appä'*

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LIST OF ABBREVIATIONS AND SYMBOLS

am	ambient CO_2 concentration of 0.03%
ANOVA	analysis of variance
CA	controlled atmosphere
cf	*Cryptolestes ferrugineus*
cfad	*Cryptolestes ferrugineus* alone in single-species controls in dry grain at 12% m.c. wb
cfaw	*Cryptolestes ferrugineus* alone in single-species controls in wet grain at 15% m.c. wb
cfcd	*Cryptolestes ferrugineus* with *T. castaneum* in mixed-species combination in dry grain at 12% m.c. wb
cfcw	*Cryptolestes ferrugineus* with *T. castaneum* in mixed-species combination in wet grain at 15% m.c. wb
C, CO_2	carbon dioxide in percent
cv.	cultivar
ERH	equilibrium relative humidity
GIU	grain-insect exposure unit
GLM	general linear model
LSURVCF	predicted logarithmic transformed adult population of *C. ferrugineus*
LSURVTC	predicted logarithmic transformed adult population of *T. castaneum*
M, m.c.	moisture content on wet basis

PSURVCF	predicted back-transformed adult population of *C. ferrugineus* from LSURVCF
PSURVTC	predicted back-transformed adult population of *T. castaneum* from LSURVTC
PVC	poly vinyl chloride
REG	regression
RH	relative humidity in percent
S	species effect factor
T	temperature in °C
tc	*Tribolium castaneum*
tcad	*Tribolium castaneum* alone in single-species controls in dry grain at 12% m.c. wb
tcaw	*Tribolium castaneum* alone in single-species controls in wet grain at 15% m.c. wb
tccd	*Tribolium castaneum* with *C. ferrugineus* in mixed-species combination in dry grain at 12% m.c. wb
tccw	*Tribolium castaneum* with *C. ferrugineus* in mixed-species combination in wet grain at 15% m.c. wb
W	time in weeks
wb	wet basis

1. INTRODUCTION

A stored grain bulk is a man-made ecological system in which qualitative and quantitative deterioration results from interactions among physical, chemical, and biological variables. Insects, mites, and fungi are the main agents that contaminate and destroy the stored grain. Stored-product pests are major contributors to post-harvest food losses ranging from 9% in the USA to about 50% in some parts of the developing nations (Sinha 1995). Monetary costs in Canada related to stored grain and oilseeds are estimated at 162 to 475 M$/yr (White 1993) due to stored-product pests and microorganisms (prevention and control losses) and do not include the potential loss of markets in highly competitive international markets.

More than 100 species of insects and over 350 species of mites have been recorded in stored products with 54 species from stored flour worldwide (White 1995). Only a few species cause serious damage to grains; the rest are fungus feeders, scavengers, predators, and parasites. Many insect species are cosmopolitan in nature and are found in different regions of the world. Evolutionary adaptations in morphology, physiology and behavior by insects, in addition to movement of grain by transportation across the world have facilitated their widespread presence. Successful exploitation of relatively dry human food by stored-product insects is due to their original and present reservoirs, range of tolerance for physical factors (temperature and relative humidity) in their environment, range of food habits, rate of reproduction and related population characteristics, adult survival in absence of food, and morphological adaptations (White 1995).

Qualitative or quantitative (or both) losses in stored grains are due to a number of factors, out of which the three major factors are (Sode et al. 1995):

1) selection of cultivars susceptible to insect attack or shattering;

2) delayed harvesting after crop maturity - resulting in shattering, spillage, and damaged kernels; and

3) improper care during the operations from harvesting to milling.

Delayed harvesting and improper care during various operations from harvesting to milling can be attended in various ways. For the purpose and scope of my research, emphasis is on the insect infestation and interactions in the stored grain.

Grain infested with insects can have nutrient loss (change in vitamins, lipids, proteins, and carbohydrates), functional property losses (germinability, milling and baking characteristics), and aesthetic changes (discoloration, caking, odors) (White 1995). Aesthetic changes can downgrade the grain and lower its marketing value. Similarly, nutrient losses (like proteins) can render the grain unsuitable for its intended use such as high-protein wheat for baking breads or low-protein wheat for noddles and flat breads. The Canada Grain Act (1994) defines a 'zero tolerance' for grain feeding insects in export grains and therefore the stored grain must be free of insects. All these factors make it essential that insect populations be controlled or eliminated from the stored grain.

Grain spoilage can be monitored by periodic grain sampling and isolating the insects by sifting (Loschiavo 1975) or using the Berlese funnel (Sinha et al. 1962). Another method to measure the grain spoilage is the use of permanently or temporarily installed electrical sensors (sound, temperature, insect movement) placed at strategic points in the storage structure. Elevated carbon dioxide concentrations in the intergranular air in grain bins are also an indicator of biological activity (molds, insects, mites, or grain respiration) causing grain spoilage (Muir et al. 1985).

Disinfestation using insecticides that are grain protectants or fumigants has been successful in controlling populations of insects and thus reducing the deterioration of stored grain. A widespread increase in resistance to chemicals by insects, chemical residues in grain and concerns about human health and the environments(Champ and Dyte 1976, Bailey and Banks 1980, White and Loschiavo 1985, Bond 1987, Conway 1987).

Controlled atmospheres, a technique that involves altering the normal composition of atmospheric gases in the storage structure to make it inimical to insect pests, does not have the perils associated with chemically-based methods. A considerable amount of work (AliNiazee 1971, Bailey and Banks 1980, Jay 1980, Annis 1986, White et al. 1988, Rameshbabu et al. 1991) has been conducted on the use of elevated carbon dioxide (CO_2) levels for achieving the highest insect mortality in the shortest time.

In the Canadian prairies, the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) and the red flour beetle, *Tribolium castaneum* (Herbst) are the two most common and economically important insect species found in stored grain on the farm (Sinha and Watters 1985, Madrid et al. 1990). Both species have been found together in stored grain on the Canadian prairies (White and Loschiavo 1985, Madrid et al. 1990). Considerable work has been done on these two species at higher temperature ranges, as well as in the area of bioenergetics. The aspect of population fluctuations due to interaction between these two species at low CO_2 concentrations of 2-10% and temperatures of 15 to 25°C has not been investigated. These temperature ranges are generally observed in stored grain in the Canadian prairies in autumn (except at harvest when grain temperatures might reach 35 °C). The low CO_2 concentrations of 2 to 10% are biologically producible concentrations observed due to respiration by grains, insects, molds and microorganisms (Muir et al. 1985, Sinha et al. 1986). The aspect of interspecific and intraspecific competition for these two species has not been investigated for cool temperatures (15 to 25 °C) and low CO_2 concentrations (2 to 10%) and the knowledge gained will assist in understanding the biology of these insects.

A number of ecological and pest management models have been developed. Similarly, a number of moisture, gas, heat transfer models have been developed which simulate the field conditions and predict the conditions that are likely to occur in bulk grain. Essentially, all the models are approximations of the real system. All these models are influenced by the insect populations that alter the balance of temperature, CO_2, and moisture by their biological activity. For a pest management model, an insect population dynamics model is a necessity. The pest management models however, are not extensively available because of the lack of basic biological data for many pest species especially near unfavorable conditions (Throne 1995). The role of cannibalism and predation in these two beetles as a population regulator (Lloyd 1967) has not been investigated at the proposed test temperatures and CO_2 levels in the present study. Incorporating the results of the present study into an integrated, comprehensive simulation model will improve detection of insect populations.

2. OBJECTIVES

The objectives of my research involving laboratory experiments with the two most common and economically important beetle species of *C. ferrugineus* and *T. castaneum* were:

i) to measure effect of suboptimal temperatures (15, 20, and 25°C) on adult survival and reproduction;

ii) to measure the effect of sublethal CO_2 concentrations (2, 5, and 10%) on adult survival and reproduction;

iii) to measure the effect of two relative humidities (50 and 70%) i.e. in dry [12% wet basis (wb)] and damp (15% wb) grains on adult survival and reproduction;

iv) to investigate the effect of predation or cannibalism in the interspecies (mixed) combination, on the overall adult survival of two insect species reared singly and together at various combinations of temperature, CO_2 concentrations, and moisture contents ;

v) to measure the effects on germination from insect damage at low temperatures and CO_2 levels in dry and damp grains (12 and 15% moisture content wb, respectively);

vi) to develop equations on the basis of experimental data to describe and predict the adult survival for two species in single and mixed populations; and

vii) to analyze the stress effect of moisture content, suboptimal temperatures, sublethal CO_2 levels, and species combination compared to ideal conditions.

3. REVIEW OF LITERATURE

3.1 Major Stored-product Insect Pests

Western Canada is the major grain producing region in Canada with a continental climate consisting of a mid-latitude humid zone and a semi-arid zone. The stored grain on farms in Western Canada is often infested by two major granivorous pests: the rusty grain beetle, *Cryptolestes ferrugineus*, and the red flour beetle, *Tribolium castaneum* and numerous fungus-feeding insects. These are the most common and economically important stored-product insects on Canadian prairie farms (Madrid et al. 1990).

My research focuses on the adult stage of both *C. ferrugineus* and *T. castaneum*. Both species are cosmopolitan and differ in terms of range of food habits, range of tolerance for physical factors, and rates of reproduction and population characteristics (Howe 1965). Adult *C. ferrugineus* have a dry mass of 0.1 mg and *T. castaneum* has a dry mass of 1.0 mg (White and Sinha 1987). A few important characteristics of both the species are highlighted in Table 3.1. White (1995) has summarized the estimates of optimal and minimal conditions for insect pests of stored-products.

3.1.1 *Cryptolestes ferrugineus*

Cryptolestes ferrugineus has a wide geographical distribution, occurring both in the temperate and tropical zones of the world. It is known to infest oilseeds, brans and cowpeas in tropical and subtropical regions of Africa, and it is a most common pest in southern parts of Canada and the northern USA in North America. *Cryptolestes ferrugineus* became a major pest of stored grain in Western Canada during the years 1939-1944 (Rilett 1949). It

Table 3.1 Physical parameters for *Cryptolestes ferrugineus** (Stephens) and *Triboliu castaneum* (Herbst)**.

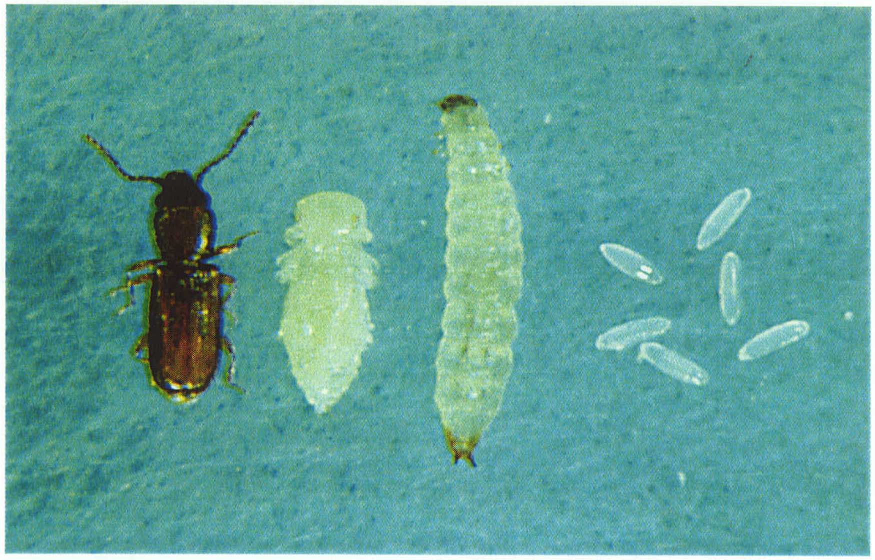
Species	Minimum*** temp. for development/ oviposition (°C)	Optimum Range (°C)	Minimum RH (%)	Dev. time (d)†	Rate of increase (every 4 wk)	Climatic Plasticity Index (*I*p)
1. *ferrugineus* Cold hardy and tolerant of low relative humidity	18	32-35	10	21	60	570
2. *Tribolium castaneum* Cold susceptible and tolerant of low relative humidity	18	32-35	1	20-30	70	700

† Time from egg to adult stage.
* *Source*: Sinha and Watters (1985)
** *Source*: Howe (1965)
*** *Source*: Fields and White (1997)

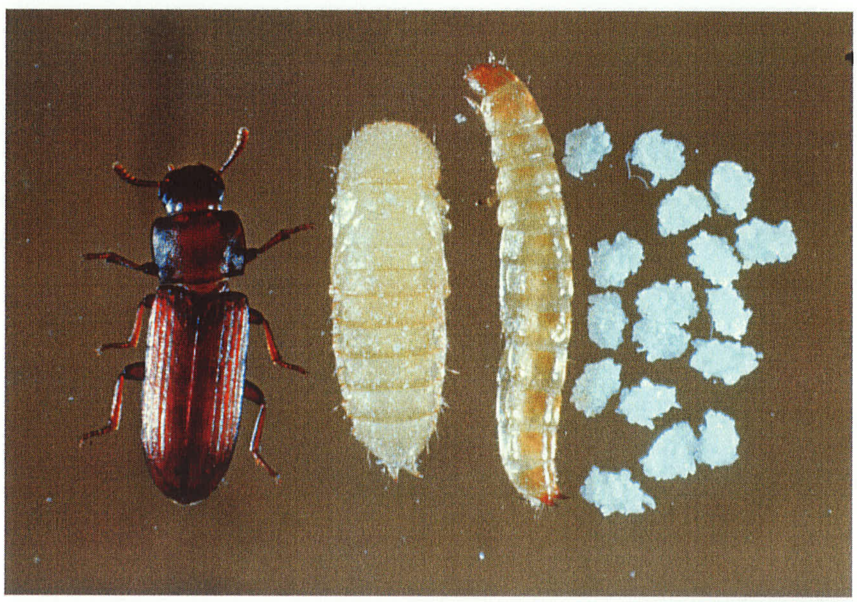
is cold hardy, tolerates low relative humidities and when acclimatized can survive at -15 °C for several weeks (Fields 1992) but prolonged exposure at -5 °C can kill it. It is a germ feeder, relying on broken or damaged seed coat (bran layer) and cannot penetrate sound grain (Rilett 1949).

The adults of *C. ferrugineus* are flattened and red brownish in color and 1.5 - 2.5 mm long (Fig. 3.1a). Large populations can build up quickly when grain is harvested warm, causing grain heating and spoilage. Insect-infested grain is likely to cake, become moldy and musty, sprout and undergo loss in germination, milling and baking quality. Typical damage to a grain kernel can be recognized by the presence of a distinct burrowing hole in the germ area made by the emerging adult. Large populations can generate enough heat and moisture to create hot spots in bulk grain under favorable conditions even in cold weather. The adults of species exhibit positive geotropism (tendency to move down) in bins and also moves towards areas of high moisture content (m.c.) (Loschiavo 1983) or high CO_2 concentration (White et al. 1993). The ability to acclimatize to low temperatures enables it to survive severe winters in Canada. It has a climatic plasticity index (*I*p) of 570, which ranks it amongst the highest for stored-product insects. Only *T. castaneum*, another cosmopolitan, primary pest in the Canadian prairies has a higher plasticity index at 700 and a tolerance to a wider range of humidity than *C. ferrugineus* (Sinha and Watters 1985) (Table 3.1).

Smith (1985) reported detection of rusty grain beetles in samples of 46% of the railcars that were being loaded at primary elevators in southern Manitoba. *Cryptolestes ferrugineus*, was detected in residues of empty granaries in 35% of 296 farms in western Canada (Smith and Barker 1987). *Cryptolestes ferrugineus* was found in 45% of farm



(a)



(b)

Fig. 3.1 Life stages (adult, pupa, larva and eggs; left to right) of *Cryptolestes ferrugineus* (Stephens) (a) and *Tribolium castaneum* (Herbst) (b).

granaries filled with cereals in Manitoba within a few months after harvest in one year but at low rates the previous year (Madrid et al. 1990). *Cryptolestes ferrugineus* is known to infest rye, wheat, pulse, cocoa, rice, bran, cereal products, pulse products, corn, barley, and millet. The surveys and reports indicate that the insect species is endemic and a serious threat to maintaining the insect-free, high quality of Canadian grain (Madrid et al. 1990).

3.1.2 *Tribolium castaneum*

Climatically, *T. castaneum* is one of the world's most well-adapted and successful insect pests of stored grain. The red flour beetle is a strong flier and shows distinct dispersal behavior. It is a well established, major pest in the Canadian prairies since 1955 (McKay 1955). It is cold susceptible but can survive at very low relative humidities (minimum 1%) and hence prevails in semiarid regions such as Egypt and Sudan and also in middle latitude humid regions of Western Europe, former USSR, China and Japan (Sinha and Watters 1985).

The adults are 2.3 - 4.5 mm long and reddish in color (Fig. 3.1b) The last three antennal segments of the adult of the red flour beetle are abruptly larger as opposed to a gradual increase in that of the sibling species, *Tribolium confusum* J. du Val. Larvae have two pointed projections (urogomphi) on the end of the abdomen. The adults thrive on broken kernels, dockage, and flour. The adults reproduce faster when some fine material and chaff is present in bulk-stored cereal. The red flour beetle cannot feed on undamaged, dry grain with less than 12% moisture content (wb). It prefers grain dust, broken grain and milled stocks. Grain with large numbers of these insects has a pungent, undesirable odor. Adults and larvae are omnivorous and cannibalistic, particularly in crowded situations, where they feed on specific eggs and pupae. Heavily infested flour turns grayish and contains cast skins and frass. In some cases, the flour may turn pink, giving out a disagreeable taste and odor caused by benzoquinone secretion of the adults. Germ destruction of the infested wheat by these beetles causes rapid germination loss. Under optimum environmental conditions (33 °C and 70% RH) it can feed and multiply well on dockage-free wheat (Sinha and Watters 1985). Sinha and Watters (1985) stated that out of 1,019 inspections of Canadian flour mills over many years, 69% reported insect infestation. The red flour beetle was the most common species occurring in 25% of all the reports. They also reported predominance of red flour beetle over all insect species in feed mills and warehouses in Canada.

3.2 Methods of Insect Control

The common method of controlling insects in stored grain is using chemically-based control techniques like contact insecticides, grain protectants, and fumigants. Chemically-based techniques, though fast and effective for insect control, are being discouraged because they pose environmental hazards like depletion of the ozone layer (i.e. the fumigant methyl bromide), leave chemical residues in grain, targeted insects are developing insecticide resistance (Champ and Dyte 1976), and consumers are demanding pesticide-free food. Use of fumigants and contact insecticides also results in toxic and potentially carcinogenic residues in the treated product (Bailey and Banks 1980). Stored product pests are developing resistance to pesticides throughout the world (White and Loschiavo 1985, Subramanyam and Hagstrum 1996).

Use of physical control methods like sun drying, controlled atmospheres (CA), admixture of rock and ash, winnowing, sieving, thermal disinfestation, cooling, and irradiation to control pests in stored-products were in use before or in conjunction with the use of synthetic chemicals (Banks and Fields 1995). Controlled atmosphere is a technique to eliminate or control infestation by manipulating the natural storage gases (introducing CO_2 or N_2 from an external source) CO_2, O_2, and N_2 for lethal effect on the insect populations (Banks and Fields 1995). Controlled atmosphere technology has limitations such as high initial cost of air-tight storage structures or making the existing structures air-tight and the cost of the generation and transportation of gas to a site (Annis 1986). Insect mortality is delayed in CAs compared to chemical methods but CAs do not adversely affect the functional characteristics of grains and they help in maintaining seed germination and viability, and prevent mold growth (White and Jayas 1993).

3.3 Factors Affecting Insect Mortality in CAs

3.3.1 Identification of factors

The effectiveness of CAs in controlling insect populations is dependent on various biotic and abiotic factors. Biotic factors include species, life stage, and size and distribution of infestation, predation, parasitism, success in life cycle etc; and abiotic factors are gaseous composition, relative humidity, temperature, food-type, length of exposure, and gas pressure (Jayas et al. 1991). The population dynamics of insects in stored grain is regulated by various density-dependent [or biotic (for example: high mortality of immature stages or cannibalism in *Tribolium* spp., limited food, combination of food and predation)] and density-independent [or abiotic (for example: temperature, gaseous composition)] factors (White 1995). The effect of most important abiotic and biotic factors on population dynamics of stored-grain insects is briefly reviewed in the following sections.

3.3.2 Temperature

Temperature plays a major role in determining actual rate of increase and longevity of insect pests (White 1995). Stored-product insects have a wide range of tolerance for the physical factors of the environment such as temperature and relative humidity. Some insect species may be susceptible to particular temperatures while others may be more tolerant. Several researchers (Howe 1965, Sinha and Watters 1985, and White 1995) have summarized the estimates of optimal and minimal conditions for various insects of stored-products.

Insects of stored-products multiply over a narrow range of temperature (Howe 1965, White 1995). Difference of about 5 °C above the optimum for population increase, can cause mortality in insects (Table 3.2). Fields (1992) classified the response of stored-products insects in three temperature zones: optimum, where the species have the greatest rate of development and multiplication; suboptimum, where temperatures are above or below the optimum zone but species still complete their life cycle; and lethal, where temperatures are above or below the suboptimum zone and cause mortality over time. The range of temperatures in which stored-product insects can normally survive lies between 8 to 41 °C (Sinha and Watters 1985) and generally development and multiplication is optimal near 30 °C and 50-70% relative humidity (Howe 1965). Canadian grain is generally stored below 20 °C except immediately after harvest when it can reach temperatures of 30 °C or more (Kawamoto et al. 1991) and can be stored for several months and up to 2 years in large non-aerated grain bulks (Jayas et al. 1990).

Table 3.2 Response of stored-product insects to temperature.

Zone	Temperature range (°C)	Effects
Lethal	> 62	Death in less than 1 min
	50-62	Death in less than 1 h
	45-50	Death in less than 1 d
	35-42	Populations die out, mobile insects seek cooler environment
Suboptimum	35	Maximum temperature for population increase
Optimum	32 to 35	Maximum rate of population increase
Near Optimum	25 to 32	Near-optimum population increase
Suboptimum	13 to 25	Slow population increase, development slows
	13 to 20	Slowly lethal, development stops
Lethal	5	Movement stops
	-10 to -5	Death in weeks, or months if acclimated
	-25 to -15	Death in less than 1 h

Source: Banks and Fields (1995) with modifications.

Both *C. ferrugineus* and *T. castaneum* require high temperatures to develop and multiply and have very high growth rates at optimal conditions (Table 3.1). Insects requiring high temperature to develop have been classified as cold-hardy, moderately cold-hardy, and cold susceptible. The rusty grain beetle, *C. ferrugineus* is cold hardy and tolerant of low relative humidities, whereas the red flour beetle, *T. castaneum*, is cold susceptible and tolerant of low relative humidities (Table 3.1).

Fields (1992) reviewed the research on survival of stored-product beetles at low temperatures under laboratory conditions. The review covers survival of various stages of beetles in a temperature range from -9 to 15°C for 50% survival and relates duration of exposure for this survival. Kawamoto et al. (1990) observed the effect of temperature from 15 to 35°C on egg development of *C. ferrugineus* and reported that mortality of eggs was higher at 15 and 19°C than at 25, 30, and 32°C and that no eggs hatched at 15°C. They developed a linear relationship between development rate and temperature and concluded that relative humidity had no effect on egg mortality and development rate. Smith (1963) investigated the effect of temperature from 20 to 40°C (at 70% RH) on oviposition of *C. ferrugineus* and reported that oviposition increased from 20 to 35°C and was reduced at 40°C. Kawamoto et al. (1989a) investigated the effect of temperatures from -9 to 40°C on adult survival and fecundity of rusty grain beetles and reported that at -9°C, more females survived than males initially (4 to 6 wk) and mortality was identical after 7 wk. They also reported that at the lower and upper thermal limit of development and survival, *C. ferrugineus* populations start declining sharply after 3 wk at -9°C and after 4 wk at 40°C and observed that males survived longer than females at a temperature of 35°C. At either high

CO_2 or low O_2 concentrations, increasing temperature augments the rate of mortality of stored-product insects.

A review of research done on survival of various life stages of *T. castaneum* at low temperatures (-6.5 to 13.5°C) and the exposure period required for survival is summarized by Fields (1992). Unlike *C. ferrugineus, T. castaneum* is a cold-susceptible species (Howe 1965) and cannot withstand lower temperatures for a long time. Fields and White (1997) observed the survival and multiplication of *C. ferrugineus*, *Rhyzopertha dominica*, and *T. castaneum* in temperatures declining from 25 to 0°C and concluded that *T. castaneum* was the least cold hardy of the three species as it did not survive once the temperatures were below 10°C. They also observed that in five naturally infested granaries in Manitoba, all *T. castaneum* were dead by February, confirming that *T. castaneum* is unlikely to overwinter in the prairies of western Canada although it could survive in large, non-aerated bulks of grain or in heated structures. The effect of high temperatures on the fecundity and development of *T. castaneum* was investigated by Park and Frank (1948). They observed oviposition rate, fecundity, and development rate at three constant temperatures: 24, 29, and 34°C (at 70 to 75% RH). At these temperatures, they observed that rate of oviposition (per female per 72 h for a 30 d period) increased with increasing temperature and was 19.1, 50.5, and 57.2 eggs for 24, 29, and 34°C, respectively. The fecundity and the rate of development for eggs, larvae, and pupae also increased with temperature. Donahaye et al. (1996) investigated the combined effect of temperature (26, 30, and 35°C) with modified atmospheres on *T. castaneum* and found that the effect of temperature on mortality was significant at low O_2 concentrations (1, 2, and 3%).

Numerous laboratory studies (Kabir 1966, Lefkovitch 1968, White and Sinha 1980, Hagstrum and Throne 1989) have been done on interaction among various species of beetles. Kabir (1966) reported laboratory interactions among *Sitophilus oryzae* (L.), *R.dominica*, and *T. castaneum* on sorghum and found that *R. dominica* and *S. oryzae* mutually inhibited development whereas *T. castaneum* benefitted by the presence of either or both species. Lefkovitch (1968) reported laboratory interactions among *S. oryzae*, *Lasioderma serricone* (F.), *T. castaneum* and *C. ferrugineus* at 30°C and 60% RH. The four species in various combinations were raised on hard spring wheat or crushed wheat, and the effect of food type and species interactions was studied. For the species combination of *C. ferrugineus* and *T. castaneum*, he reported that on both wheat and crushed wheat, *C. ferrugineus* inhibited the *T. castaneum* population and that *C. ferrugineus* was the most likely species to persist of all four species. White and Sinha (1980) determined the implications of infesting bulk-stored wheat with multiple species of insects for 60 wk at 30 ± 2°C and 45 ± 5% RH. One of the several combinations of insect species was the COT (*C. ferrugineus*, *Oryzaephilus surinamensis* (L.), and *T. castaneum*) system and variables such as CO_2, O_2, temperature, grain moisture content, insect numbers, seed damage, germination, dust weight and volume, and microflora were determined. In this system, *C. ferrugineus* was the dominant species, although *T. castaneum* reached population levels higher than those when it was reared alone and *O. surinamensis* became extinct after 10 wk. However, contrary to the work of Lefkovitch (1968), *C. ferrugineus* did not have an inhibitory effect on *T. castaneum* populations. Hagstrum and Throne (1989) observed single-species population trends of *T. castaneum* and *R. dominica* in the laboratory (at 27°C and 70% RH or 14% moisture content on wheat) and multiple-species populations of *C. ferrugineus*, *T. castaneum*, and *R. dominica* on farms. The average initial temperatures at two sampling locations (at 0.9 and 3 m depth in the center of two metal bins of 6.4m diameter) in bins were 33 and 36.3 °C and decreased by 0.7 and 0.8 °C respectively, per week over 16 wk. A population dynamics model was developed based on the biotic conditions and by developing equations for egg production and development rate (temperature-developmental time) of various insect species. The simulation model predicted 87, 93, and 96% of changes in mean measured densities of *C. ferrugineus*, *R. dominica*, and *T. castaneum*, respectively.

3.3.3 Relative humidity

Stored-product insects exhibit a wide range of tolerance to moisture content (relative humidity) (White 1995). *Cryptolestes ferrugineus* is a cold hardy, facultative fungivore (it is attracted to moldy grain) and *T. castaneum* is cold susceptible, but both are tolerant of low relative humidities (Table 3.1). Holdway (1932) showed that density of adults was positively correlated with humidities by observing the *Tribolium confusum* populations at constant temperature of 27 °C and at 25, 50, and 75% RH. He concluded that cannibalism increased with decreasing moisture content, resulting in lower population and the converse was also true. Jay et al. (1971) reported the importance of RH in CAs in their experiments with *T. castaneum, O. surinamensis*, and *T. confusum* at four RH and binary mixtures of O_2 and N_2 or ternary mixtures of O_2, N_2, and CO_2. They observed increased mortality of all three species with decreasing RH in binary mixtures of O_2 and N_2 (O_2 less than 1%). Similar results were obtained with ternary mixtures of CO_2, O_2, and N_2; the mortality increased with decreasing RH. They concluded that low humidities used together with modified atmospheres would cause higher insect mortality for fixed exposure time than either of the two used alone. Kawamoto et al. (1990) reported the effects of temperature and RH on egg development of *C. ferrugineus* and concluded that RH did not have a significant effect on mortality and development rate of eggs of *C. ferrugineus* and excluded the effect of RH in their model since the species can withstand RH as low as 10%. The toxic effect of CO_2 varies with RH as reported by AliNiazee (1971) when he observed 100% mortality of *T. castaneum* adults in 18 h exposure time to 100% CO_2 at 26.7°C and 38% RH whereas the exposure time to achieve the same mortality was 30 h at 100% RH. Annis (1986) comprehensively reviewed the data on lethal response of stored-product insect and mite pests to CAs above 20°C and formulated broad dosage regimes of CAs that would be effective against all stages of common stored-product insects. However, the effect of RH was not included in the dosage regime for CAs. As reported by AliNiazee (1971) and other researchers (Navarro 1978, Navarro and Calderon 1973), RH affects insect mortality and hence an allowance in the form of greater exposure time or increased gas concentration may have to be made if equilibrium RH is above 70% (optimal for growth and multiplication). For RH below 70%, an adjustment is not necessary because low RH can provide an additional factor of safety.

Tribolium castaneum survives over a wider range of relative humidities compared to *C. ferrugineus* due to physiological differences. Roth and Willis (1951) conducted experiments with *T. castaneum* in dry and moist air (near 0% to 100 relative humidity) using whole-meal wheat flour and also by starving the beetles in dry and moist air. They concluded that *T. castaneum* adults sense and respond to gradients in moisture content and possess the remarkable attribute of retaining a relatively constant proportion of water in their bodies while being starved in dry air. The adults of *Tribolium castaneum* is capable of absorbing water from unsaturated air and conserves the metabolically produced water by drying out the air before it is expired from the spiracles. They can also retain water that is produced as a by-product of respiration. Hygroreceptors have been found on the antennae of adult *T. castaneum* signifying the morphological adaptation and sensitivity to moisture content. Water uptake by insects is effected by various absorption sites and structures in their bodies. For example, a rectal uptake system referred to as a crypto-nephridial complex is responsible in Tenebrionidae for removal of water from the fecal matter leaving behind a dry solid excreta, anal valves close off the rectum from the atmosphere when ambient relative humidity goes below 88% and open only for occasional defecation (Hadley 1994).

The moisture content of a stored product determines the RH and in the case of grains the RH for a particular moisture content of grain can be determined from the sorption relationships for a given crop (ASAE 1998a).

3.3.4 CO_2 concentration

Adult beetles normally keep their spiracles (respiratory openings along the sides of the body) closed, opening them just enough to satisfy their oxygen (O_2) requirements (Jay et al. 1971). The frequency of opening and closing the spiracles is influenced by a number of factors including concentration of CO_2 and O_2 in the environment. Mellanby (1934) found that a 2% concentration of CO_2 is sufficient to produce sustained opening of the spiracles in adult flea *Xenopsylla cheopis* (Rothschild) and in larval *Tenebrio molitor* (L.), and the moth *Tineola bisselliella* (Hummel). The same effect can be achieved if the O_2 concentration is reduced below 1%. Stored-grain insects and their life stages are affected differentially by CO_2; these effects can be physiological (Annis 1986) and behavioral (White et al. 1993). During exposure to high CO_2 concentrations, insect mortality is by dessication and exhaustion of triglyceride (TG) energy reserves, and not by a prolonged narcotic effect of anaesthesia, or the accumulation of toxic end-products (Donahaye 1990).

AliNiazee (1971) reported the effect of CO_2 alone or in combinations with other gases (He, N_2, O_2) on mortality of *T. castaneum*. He observed that the only toxic mixture for adults of *T. castaneum* was a 80% CO_2, 20% O_2 mixture at 26.7°C and 38 ± 6% RH. Similar results were obtained with 90:10 CO_2 and N_2 and 95:5 He and O_2 mixtures, indicating that at high CO_2 concentrations, it is the specific action of CO_2 that has the lethal effect and variation in O_2 concentration had little influence on insect mortality. Experiments with 2 and 4 % O_2 indicated little change in the toxicity of CO_2. The adults were the most susceptible stage followed by larvae, eggs, and pupae when exposed to 100% CO_2 and the insect mortalities increased with increased temperature (15.6 to 26.7°C). Spratt (1984) investigated population dynamics of *T. castaneum* and *T. confusum* in atmospheres containing 5-20% O_2 with or without 10% CO_2. At constant temperature (30°C) and 70% RH conditions, the egg production was about 60% higher in the presence of CO_2 at O_2 concentrations of 5, 7.5, and 10%.

Most of the adult *T. castaneum* (95%) are killed in 5 d at 20% CO_2 or 1.5 d at 60% CO_2 in the temperature range of 20 to 29°C (Annis 1986). As a general rule, increased CO_2 concentrations at constant temperature and RH conditions result in higher mortality with decreased exposure time and the efficacy of CO_2 is reduced with decreasing temperature

(Banks and Fields 1995).

Cryptolestes ferrugineus is susceptible to CO_2 toxicity and adults are the most tolerant life stage (Shunmugam et al. 1993). Adults of *Cryptolestes ferrugineus* are probably more tolerant to CO_2 than those of *T. castaneum* because insects less than 3 mm in length can respire by diffusion alone, whereas larger insects such as *T. castaneum* must supplement diffusion with convective ventilation of the trachea using abdominal musculature (Hadley 1994). Elevated CO_2 levels could stimulate the active ventilation in *Tribolium* leading to more rapid intoxication. Adult *C. ferrugineus* exhibits positive geotropism (tendency to move downward in storage) and have a tendency to be attracted to high CO_2 levels along a gradient (White et al. 1993). The positive geotropism of adult *C. ferrugineus* and behavior of CO_2 to accumulate at the bottom of structures (the CO_2 gas being heavier than air) can increase the effectiveness of CA fumigation to control this pest.

White et al. (1995) investigated the toxic effect of CO_2 at biologically producible levels (7.5 to 19.2%) at 22 ± 2°C and 50 ± 5% RH, on oviposition of adult *T. castaneum*, *Cryptolestes pusillus* (Schonherr) and *C. ferrugineus*. Compared to controls, *T. castaneum*, *C. pusillus*, and *C. ferrugineus*, exposed to 7.5% CO_2 for 1 wk had the number of offspring reduced by 43, 94, and 50%, respectively and total population at 6 wk was reduced by 53, 84, and 19%, respectively. Insect development was similar at 7.5 and 8.6% CO_2 with mean mortality of 43, 62, and 30% greater than controls for *T. confusum*, *T. castaneum*, and *C. ferrugineus*, respectively. They also observed that mean levels of 5.8 to 8.3% CO_2 for 7 wk reduced populations of *T. confusum* by 85%, *T. castaneum* by 99%, *C. pusillus* by 68%, and *C. ferrugineus* by 54% on all the combined sampling dates and concluded that species in order of increasing sensitivity to CO_2 are *C. ferrugineus*, *C. pusillus*, *T. confusum*, and *T. castaneum*.

Stored-product insects are sometimes exposed to elevated but nonlethal concentrations of CO_2 due to various reasons such as inefficient or nonairtight fumigation which may extend a CO_2 fumigation period to a week or more (Alagusundaram et al. 1993), or increased CO_2 concentrations caused by insect, mold, and grain metabolism in hot spots. It is therefore, essential to know the interaction between two species at low temperatures ($< 25\,^{\circ}C$) and lower CO_2 concentrations (2 to 10%) so that the sublethal effect of CO_2 on these species, can be determined and incorporated in a comprehensive simulation model that would predict insect populations at given environmental conditions.

3.3.5 Range of diets

Stored-product insects have a wide range of diets and feed on most of the dry food products of plant and animal origin (White 1995). Stored-grain is the primary source of food (or diet) for many insects but susceptibility to insect infestation also depends on factors such as cultivar, extent of grain damage, moisture content (or RH), dockage, and molds associated with the grain (White 1995).

Both *C. ferrugineus* and *T. castaneum* are crushed-grain feeders and cannot feed easily on sound whole kernels but can feed on whole kernels with a damaged bran layer. *Cryptolestes ferrugineus* is primarily a germ feeder whereas *T. castaneum* is an omnivorous and cannibalistic insect thriving on the embryo of seed, dockage, broken kernels, grain dust and insect eggs and pupae (Sinha and Watters 1985). Adults of *Cryptolestes ferrugineus* move rapidly on warm days and can fly when temperature is above $23\,^{\circ}C$ and hence the freshly harvested crop left in open piles or in poorly sealed granaries on farms is prone to infestation by these insects.

Rilett (1949) investigated the effect of different diets on various life stages of *C. ferrugineus*. The effects such as suitability for the larval stage, susceptibility of grain and oilseeds to damage, and suitability of damaged and sound grains for development of *C. ferrugineus* were investigated. He observed that wheat germ was the best larval food compared to white flour, bran, and wheat without germ; and that whole wheat or rye is a better diet than damaged kernels due to the fact that development was faster on germ than on endosperm of damaged kernels. Mukerji and Sinha (1953) investigated the effect of food on the life history of *T. castaneum* by using four different diets: arrowroot, barley, whole wheat flour, and refined wheat flour at 25 to 31 °C and 66 to 92% RH. They observed that the number of eggs laid per female was the highest in whole wheat flour followed by refined wheat flour, barley, and arrowroot and was related to the chemical content of the diet. Whole wheat flour had the maximum protein content (12.1%) and vitamin B_1, whereas vitamin B_1 was absent in arrowroot and it had a lower protein content (0.2%). Sinha (1969) investigated reproduction of five cosmopolitan species of insects (*R. dominica* , *S. granarius*, *C. ferrugineus, T. castaneum,* and *T. confusum*) on varieties of wheat, oats, and barley and observed the resistance and susceptibility of varieties to specific species. Sinha (1975) also investigated the effect of dockage on development and multiplication of nine species of insects including *C. ferrugineus* and *T. castaneum* at dockage levels of 0, 5, and 10%. He observed that *C. ferrugineus* (number of adults emerging) was adversely affected by increasing the dockage level, i.e., the number of adults emerging was higher on dockage-free wheat than on wheat with dockage. For *T. castaneum*, it was observed that increasing dockage level to 5% did not have any effect whereas at a level of 10%, egg production yielded significantly more adults. White and Bell (1994), using two strains of *C. ferrugineus* [inbred strain (SS) and outbred strain (GV)], observed that both strains lived longer on ground wheat plus wheat germ than on whole kernels that had seed coats over the germs removed. The extra energy required for feeding on whole kernels shortened their life span.

3.3.6 Species and stage of development of beetles

Beetle species and the stage of development (egg, larvae, pupae, or adult) influence the response to CAs. Storey (1977) investigated the effect of low O_2 atmosphere (with O_2 < 1.0%, CO_2 9.0 to 9.5%, and balance N_2) on mortality of *T. castaneum* and *T. confusum* at 18 ± 1 and 27 ± 1 °C at 50% RH. He observed that except for the egg stage, *T. castaneum* were consistently more tolerant than *T. confusum* at 18 °C but there was little difference between species at 27 °C. At 18 °C, the general order of tolerance for *T. castaneum* was pupae > eggs >larvae > adults, whereas for *T. confusum* it was eggs > pupae > larvae > adults. At 27 °C, the order of tolerance was the same for both species: pupae > eggs > adults > larvae. He also observed that exposure period for the LT_{95} (lethal time to achieve 95% mortality) at 18 °C was significantly longer than at 27 °C. Banks and Fields (1995) have compiled the exposure times for developmental stages of 14 insect species for 95% or greater mortality at high CO_2 (50-70%) and low O_2 (< 1%) atmospheres at 14-17 and 20-29 °C. Many researchers (Bailey 1965, Spratt 1984, Nicolas and Sallans 1989, White et al. 1990, Rameshbabu et al. 1991, Shunmugam et al. 1993, White et al. 1995) have investigated the effect of different CAs for control of either *C. ferrugineus* or *T. castaneum* and have observed the differential response of developmental stages when exposed to the same CA. For example, Shunmugam et al. (1993) investigated the effect of CA on all life stages of *C. ferrugineus* at 30, 40, and 60% CO_2 levels at 30°C and observed 100% mortality of all life stages at 60% CO_2 in 3 d whereas, at 30 and 40% CO_2 levels all adults were killed in 8 d compared to 4 d for all pupae, larvae, and eggs indicating that adults were the most tolerant stage.

3.3.7 Acclimation of beetle species

Insects that are acclimated by gradual exposure to cool temperatures (20-10°C) increase their cold-hardiness by two to ten-fold at lower temperatures (Fields 1992). With the exception of *S. granarius* (Robinson 1926), all the beetles demonstrate increased cold-hardiness when exposed to cooler temperatures before being exposed to cold temperatures. Augmented cold-hardiness by acclimation can be of importance in laboratory experiments, so that the cold-hardiness of a species is not underestimated due to inadequate acclimation. Fields (1992) has mentioned several acclimation regimes and observed that the greatest cold-tolerance could be achieved by acclimating insects at slower temperature declines i.e. acclimation over a longer duration using gradually declining temperatures. Creating acclimation regimes in the laboratory close to those observed in field conditions (storage) would be optimum for studies related to cold-hardiness. However, the constraint is that temperature declines are slow in non-aerated bulk grain and vary with climate and storage facilities which are difficult to reproduce under laboratory conditions. Acclimation at cooler temperatures avoids underestimation of cold-hardiness of insects and gives a better understanding of their survival at low temperatures.

3.4 Population Regulation and Competition in Stored-grain Ecosystems

Population regulation of insect species in stored grain is a complex process involving many factors and their combinations acting in a regulatory role. There are two basic concepts in population regulation (Price 1984): 1) the factors external to the population called the exogenous (extrinsic) population processes ; and 2) the factors that change within the population affecting the numbers and producing regulation called the endogenous (intrinsic) population processes. Price (1984) has compiled the various extrinsic and intrinsic processes that regulate the population and these are combinations of various biotic and abiotic processes. Lloyd (1967) has explained the mechanism of regulation of adult populations by cannibalism and predation in laboratory strains of *T. castaneum*. Investigations by various researchers (Lloyd 1967, Park 1954, Niven 1967) have proved that predators and parasitoids act as population regulating factors.

Various definitions and interpretations of the term competition have evolved over the years. Clements and Shelford (1939) defined competition as 'the process defined inclusively as a more or less active demand in excess of the immediate supply of material or condition on the part of two or more organisms'. According to Park (1954), competition includes predator-prey and parasitoid-host interactions, in addition to the struggle for a common object or resource (e.g. food). Andrewartha and Birch (1974) have defined competition as an occurrence whenever a valuable or necessary resource is sought together by a number of animals (of the same kind or different kinds) when the resource is in short supply. Further they indicated that if the food or the resource is not in short supply, competition still exists when one species seeking the resources harms or victimizes themselves or other species. In a mixed-species combination of adults of *C. ferrugineus* and *T. castaneum* in a stored-grain ecosystem, the interactions within and among the species, called intraspecific and interspecific (or intraspecies and interspecies), respectively influence the population of either of the species and may lead to extinction, or increased rates of emigration and dispersal of one of the species.

Experimental studies of interspecies competition, predation and cannibalistic behavior of insect species have been comprehensive, tedious and complex. Park (1948) observed the interspecific competition between two flour beetles considering factors such as fecundity, metamorphosis, and adult longevity and the experiments involved sifting and counting of larvae, pupae, and imagoes over a total period of 1380 d (3.75 years). The nutritive medium was replenished every 30 d and the medium was also tested for any invading mites or infection by other species and consisted of 20 replicates at two relative humidities. Similarly, Park et al. (1941) experimented with granary beetles' interspecific competition for a period of 720 d with two insect densities, 13 treatments with 20 replicates and counts of larvae, pupae and imagoes was taken every 30 d along with sexing and sex-ratio analysis. Park et al. (1965) experimented with cannibalistic predation of flour bettles comprehensively where various developmental stages and their interactions in cannibalism were studied and the eggs were marked and checked every 48 h to verify cannibalism. Lloyd (1967) counted eggs, small larvae, medium larvae, large larvae, pupae and adults in his experiments in cannibalistic behavior involving two strains of *T. castaneum*. Park et al. (1965) described cannibalism in a *Tribolium* population as 'a cannibalistic orgy - an orgy characterized by gluttony.'

3.4.1 Intraspecies competition

The competition within the same species is called intraspecies competition and is of two types: contest competition and scramble competition (Nicholson 1954). The term interference competition is now used in place of contest competition as contest competition is applied to both interspecific and intraspecific competition. The interference competition has been defined as 'any activity which either directly or indirectly limits a competitor's access to necessary resources or requirements (Nicholson 1954). Here, the winner obtains the resource as much as is needed for survival and reproduction whereas the loser relinquishes the resource to its successful competitor. The result of interference competition is that the population increases until the carrying capacity is reached and then reaches a plateau to maintain it indefinitely since each individual has enough food to live on (assuming the food is self-generating). The second type of intraspecies competition is scramble or exploitation competition where all members have equal access to the limited resource and a free-for-all results. With limited food supply, the interactions over time result in series of population peaks unlike the interference competition (Nicholson 1954). In the laboratory, single or multi-species experiments have limited food supply and thus a scramble or exploitation competition effect is expected with a series of population peaks and troughs.

The various stages of development of species interact and compete with each other for survival (Park 1948). Population density, sex ratio, mating status, and crowding affect developmental stages, the development rate, fecundity, and mortality of insect species (Park et al. 1965, Smith 1966, and White and Bell 1993, and White et al. 1995).

Park et al. (1965) have discussed the cannibalistic behavior of *Tribolium* species and the combinations of predations that can occur within a species. In *T. castaneum* populations, various life stages (except eggs and pupae) exhibit cannibalistic behavior. The cannibalistic combinations have been summarized by Park et al. (1965) as:

1. adults feeding on eggs, larvae, pupae, and non-sclerotized adults or 'callows'; and
2. larvae feeding on eggs, pupae, and non-sclerotized adults or 'callows'.

The three combinations wherein cannibalistic behavior has not been observed are: mature adults feeding on mature adults, larvae feeding on larvae, and larvae feeding on mature adults. The rate of cannibalistic predation can vary by gender as demonstrated by Sonleitner (1961) who showed that females were 19 times more voracious than the males. The cannibalistic behavior in *T. castaneum* is extensive and acts as a self-regulatory mechanism that reduces the probability of extinction when a population is small and alternatively reduces the probability of disastrous crowding when the population is large (Park et al. 1965).

The cannibalism is not as widespread in *C. ferrugineus* populations as it is in *T. castaneum*. There are few references (Rilett 1949, Kawamoto et al. 1990) about the cannibalistic behavior in *C. ferrugineus* and it has been inferred that if cannibalism exists at all, it does not affect the population dynamics significantly (Kawamoto et al. 1990). Rilett (1949) in his experiments with *C. ferrugineus*, concluded that cannibalism may be one of the reasons why development is more rapid on whole kernels than broken ones and suggested that prepupae and pupae may be cannibalized by larvae in broken kernels.

3.4.2 Interspecies competition

In a study involving interspecies population of two species, Park et al. (1941) set forth four important considerations:

1) it must be feasible to culture all species in the same medium in a confined space,

2) the culture or rearing medium should be reproducible both in terms of quality and quantity,

3) the husbandry of each species should be relatively simple, and

4) a method of taking census must exist.

The interspecies competition can only be studied when it is known how an individual species survives by itself in the absence of the competition. Hence, for all the environmental conditions single-species controls along with mixed-species are necessary.

The interspecies competition is exploitation and interference of two species for a common food source with a predator-prey relationship between the two species (Park 1954). The results of interspecies competition can be migration, extinction or dispersal. Extinction of one of the species can be due to the population-depressing effect of one species on another. The presence of a third party like an endemic pathogen or a parasite can significantly affect the population balance and survival or extinction of a species in interspecies competition as demonstrated in a classical experiment by Park (1948). Park (1948) experimented with two species of *Tribolium*, *T. castaneum* and *T. confusum* and observed that *T. castaneum* became extinct (or lost) 89% of the times in the presence of the pathogenic coccidia, a protozoan parasite *Adelina tribolii* Bhatia whereas it dropped to 33% when the cultures were completely free of *Adelina tribolii*.

The existence of competition between *C. ferrugineus* and *T. castaneum* is demonstrated by their somewhat similar feeding habits such as both species thriving on germs of grain, broken or cracked kernels, grain dust, and both species occur together in the Canadian prairies in stored grain (Madrid et al. 1990, White and Loschiavo 1995).

3.5 Models for Simulating the Population Dynamics of Stored-Product Insects

The approaches for selection of models for simulating population dynamics of insects vary depending on the purpose and objective of the project. For example, a model to simulate the population dynamics using a stored-product insect as the test organism may be useful for establishing the theory of population dynamics but may not be of practical use in pest control since many other factors (like food type, temperature, moisture content) can affect simulation output in an ecosystem approach. Therefore, the models for simulating the population dynamics in stored grain are classified into two groups: theoretical ecological models and practical pest-management models (Throne 1995).

3.5.1 Ecological models

Ecological models were developed to mathematically describe and investigate an ecological principle or a particular aspect of a stored-grain ecosystem such as the effect of insect density on the rate of oviposition, or inter-species competition on a particular food substrate (Throne 1995). These models generally simulate population growth under restricted temperature and relative humidity conditions. Ecological models generally try to simulate population development in a small quantity of grain and must therefore include factors such as the effects of density and cannibalism on the basic biological components of the model.

Niven (1967) developed the first computer-based single-species stochastic model to simulate population development of *T. castaneum* at 29 °C and 70% RH and included stage-specific rates of development and survival of immature stages of four genetic strains of the insect. The model included age-specific mortality, density-dependent fecundity of adults, and rates of cannibalism by adults and larvae. Simulation results were similar to those observed in laboratory experiments and the model was used to predict long-term population growth of the species. Hardman (1976) compared the results of simulations using deterministic, pseudostochastic, and stochastic models to determine which model best simulated the population growth of *T. confusum*. Simulation results from both the deterministic and pseudostochastic models compared favorably with observed results, although simulated and observed results were not statistically compared. Campbell and Sinha (1990) developed a model for simulating energy transfer from wheat stored at 30 °C and 13.5% m.c. through the various stages of *C. ferrugineus*. The model included rates of insect development and survival, fecundity, respiration, egestion, and biomass changes. Simulation results closely agreed with observed population growth, respiration, and food consumption during the population growth phase. Simulated results differed in some cases, such as the simulated insect population died after food was exhausted, whereas in experiments the population continued at a low level even after the food was badly deteriorated.

3.5.2 Pest management models

Pest management models are used as decision-making tools (or to optimize management strategy) by the managers of stored-grain off or on farms. The models attempt to simulate the stored-grain ecosystem and are intended to simulate pest population dynamics over the entire range of environmental conditions that might be encountered in grain storages and are generally developed to optimize management strategies. Pest management models generally assume Malthusian conditions and try to determine the effects of major abiotic factors on insect population dynamics (Throne 1995). One of the most important variables affecting the insect population development is temperature and it is included in all the pest management models. The second most important variable is grain moisture content or relative humidity. Single-species models are developed and preferred because they are the simplest and are easier to validate compared to a mixed-species model. Other species can be added to the models depending on occurrence of several species in a granary which would involve competition for food, crowding effects, dispersal, predator-prey relationships. Not many pest-management models are available because of the non-availability of detailed basic biological data for insect pest species. The biological data for a species would involve complete life table studies (table look-up function) at the full range of temperatures and humidities at which the pest occurs in grain. Extensive biological data collection by experiments is an arduous, time consuming job not many scientists are willing to undertake (Throne 1995).

Pest management models as decision-making tools in stored grain ecosystems were first used in Australia on wheat infested with *Sitophilus oryzae*. Hardman (1978) developed the model to simulate population growth of the weevil and the effects of the weevil on its environment. The model included effects of temperature (from 16 to 32°C) and grain moisture content (10.5 to 14.5%) on immature development rate; mortality; oviposition; feeding; oxygen consumption; and production of frass, water, and carbon dioxide. This was the first attempt to develop a model for a stored-grain pest that could be used to run simulations over a range of environmental conditions actually encountered in grain storages. The model was validated by conducting experiments with weevils placed in vials under monitored temperature conditions and adult censuses were conducted every 7 to 14 d for 112 d. Simulation results agreed well with the observed data based on statistical analysis except that the model simulated increased adult numbers towards the end of the study since it assumed an unlimited source of food, whereas actually the adult population decreased as the food deteriorated towards the end of the experiment. This validated model was used to investigate the benefits of cooling and drying grain by running simulations for 80 d at constant temperatures from 16 to 28°C and constant moisture contents from 10.5 to 14.5%. The populations did not increase at temperatures below 20°C and population growth increased at temperatures above 20°C with increased moisture content. Airtight storage resulted in the death of all insects within 37 d and the population growth was reduced in bins with 10% leakage proving that simulations were fairly reliable. Hardman's (1978) model was further restructured by Cuff and Hardman (1980) by transformation to a Leslie-type matrix, allowing simulation for heterogeneous environments and inclusion of effects of the insect on its environment. The simulations showed that as gas-tightness increased, insect damage decreased. Progressively, the model was modified and restructured by several researchers (Thorpe et al. 1982, Longstaff and Cuff 1984, and Sinclair and Alder 1985) to include various submodels for protectant insecticides, aeration effects, and modifications such as a change of time step to improve speed of simulations. In North America, Hagstrum and Throne (1989) developed pest management models for stored wheat using the general modelling approach used in Australia. They modified the model developed by

Throne (1983) to simulate effects of temperature and moisture content on population growth of *T. castaneum*, *C. ferrugineus*, and *R. dominica* in wheat. This was a mixed-species model and the simulated results were compared with observed results. Simulated results for all the three species compared favorably with observed insect numbers in the laboratory and in small grain bins. Simulated results showed that daily egg production for *R. dominica*, was dependent on temperature and moisture content but not on age of females; egg production for the other two species was age-specific. Flinn and Hagstrum (1990) expanded the above model by including subroutines for aeration, fumigation, and protectant insecticides. Similar population dynamics models were developed for different species by other researchers (Gordon et al. 1988, Nuttall 1989, Kawamoto et al. 1991).

4. MATERIALS AND METHODS

4.1 Insect Species, Sex Determination, and Sex Ratio

Cryptolestes ferrugineus were reared in laboratory cultures on cracked wheat plus wheat germ (19:1, wt:wt) and *T. castaneum* were reared on wheat flour plus Brewer's yeast (19:1, wt:wt), all maintained at 30 ± 1 °C and 70 ± 5% RH (White and Demianyk 1995). The cultures of *C. ferrugineus* and *T. castaneum* had been reared in the laboratory for 9 years.

Sex determination of adults of *C. ferrugineus* was done on the basis of the shape of mandibles. The male mandible of *C. ferrugineus* has a tooth-like projection on the lateral ventral side near the base whereas the female lacks this projection (Rilett 1949). Sex determination of *T. castaneum* was done by microscopically identifying the sex of pupae based on the form of the pupal genital papillae in Tenebrionidae (Halstead 1963).

Researchers (White and Jayas 1989) have cited the sex ratio of *T. castaneum* as one. Rilett (1949) and Smith (1966) experimentally arrived at sex ratios (males : females) of 0.66 and 0.76, respectively for *C. ferrugineus* (on wheat) and Kawamoto et al. (1989b) assumed the weighted mean (0.75) for his population dynamics model. The sex ratio for both species was determined in the laboratory by sexing 100 adults and pupae in triplicate for *C. ferrugineus* and *T. castaneum*, respectively. The mean sex ratios were observed to be 0.69 and 1.03 for *C. ferrugineus* and *T. castaneum*, respectively. The sex ratios determined in the laboratory agreed well with previous researchers' findings.

4.2 Food Substrate and Dockage Preparation

The resource or food for all the experiments for both the species was hard red spring wheat (grade No. 1, cv. 'AC Barrie' certified) with 5% dockage (19:1 by wt) added to it. The dockage was prepared by grinding the grain using a laboratory grinder (Model M-2, Serial 253, Fred Stein Laboratories, Inc., Atchison, KS) and sifting the ground grain on 0.84 mm aperture (Sieve No. 20) screen to remove fine flour and grain on the top of the screen was further sifted on a 2.36 mm (Sieve No. 8) screen. The coarse grain particles sifted through the 2.36 mm screen were used as dockage.

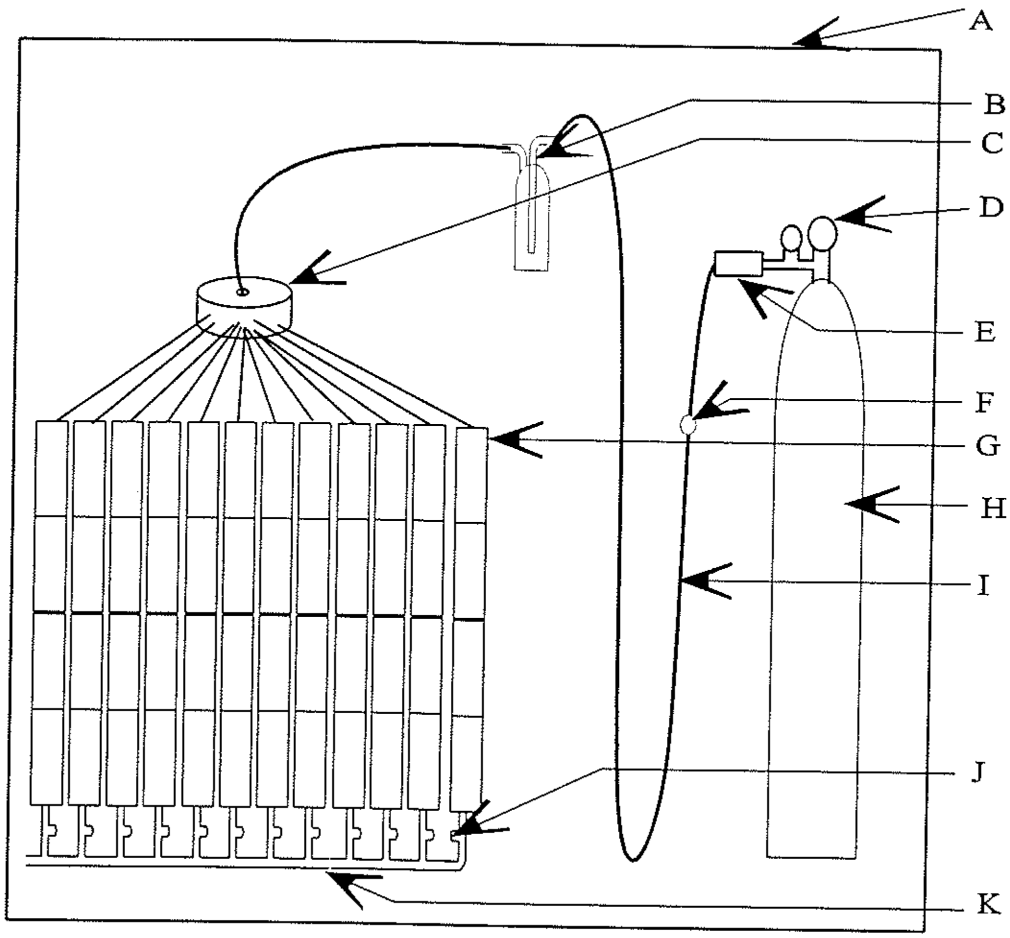
4.3 Insect Density

The initial insect density for all the experiments was 1,000 adults per kg of each species for single species and mixed-species experiments. The insect density selected was arbitrary. The density of 1,000 adults per kg was selected so that high adult populations would be observed over the period of sampling of 8 wk for given temperatures and CO_2 concentrations. Selecting this insect density also facilitated observing greater intra- and interspecific interactions. Kawamoto et al. (1989b) used an initial insect density of 1,000 insects per kg for his model to predict populations of various stages of *C. ferrugineus*.

4.4 Experimental Unit

4.4.1 Components

A schematic diagram of the experimental unit and its components are shown in Fig. 4.1. The controlled environment chamber maintained temperature with a precision of ±0.5 °C. The temperature was set in the chamber a day prior to commencement of a test for



A - temperature controlled chamber
B - relative humidity unit
C - gas distributor
D - gas pressure regulator
E - flow controller
F - gas sampling port
G - grain-insect units (GIUs)
H - CO_2 or air cylinder
I - flexible polyethylene tubing
J - gas sampling ports
K - exhaust assembly

Fig. 4.1 Schematic diagram of experimental unit and its components in temperature controlled chamber.

stabilization. The tests for both dry and damp grain were carried out in the same chamber for a test temperature and CO_2 level. The various components of the experimental unit were: compressed CO_2 cylinders with pressure regulators, flow controllers, gas sampling ports, RH units, distributors, grain-insect exposure units, and exhaust assembly. The compressed CO_2 from cylinders passed sequentially through from a gas pressure regulator, flow controller, RH unit, distributor, grain-insect exposure unit (GIU) and exited through the exhaust assembly. Flexible polyethylene tubing and nylon connectors were extensively used in the entire set up and therefore teflon tape was used to tighten all the joints for effective sealing.

4.4.2 Compressed CO_2 and air

The investigation into single and mixed-species interactions at various temperatures was carried out at four CO_2 levels of 0.03 (compressed ambient air controls), 2, 5, and 10%. The compressed CO_2 and air cylinders (for ambient CO_2) of desired composition were obtained from a gas speciality company (Praxair Inc., Mississagua, ON) in K type cylinders (SG-109009K, Praxair Inc., Mississagua, ON). The cylinders contained the specified CO_2 concentrations with the balance of ambient air.

Levels of CO_2 and O_2 were measured using a gas chromatograph (Model Sigma 3B, Perkin-Elmer Corp., Norwalk, CT) with a thermal conductivity detector. The carrier gas was helium. The inlet pressure was 207 kPa, the detector temperature was 150°C, and the oven was set at 60°C. The gas chromatograph was regularly calibrated with a series of commercially prepared high purity mixtures of CO_2 or O_2 in He of specified concentrations (Altech Associates, Arlington Heights, IL). The variation of CO_2 concentrations in CO_2 cylinders was less than ±1% of the value. The compressed CO_2 of specified composition in cylinders provided consistent CO_2 environments for all the experimental tests. The CO_2 was supplied to the experimental units at a pressure of 350 kPa and a flow rate of 150 mL/min for all the experimental tests. The O_2 levels for CO_2 levels of 0.03, 2.0, 5.0, and 10.0% were measured to be 21.9, 21.5, 20.9, and 19.8%, respectively using the Sigma 3B gas chromatograph.

The establishment of a uniform CO_2 environment in all the GIUs was confirmed by sampling gas at gas sampling ports J (Fig. 4.1) and analyzing it using the gas chromatograph. The samples were taken 12 hours after the gas flow was initiated and it was observed that all the GIUs achieved the same levels as the inlet CO_2 levels (port F; Fig. 4.1) in this time period.

4.4.3 Gas pressure regulators and flow controllers

The K type, high pressure cylinders stored the compressed CO_2 and air at 15.0 MPa. The cylinders were placed on an equilateral triangular bottom stand with sides of 500 mm and attached to a central pole (40 mm diameter) by chains for safe storage. A pressure regulator with two pressure gauges was fitted to the cylinder. The input pressure gauge had a range of 0 to 24 MPa and indicated the pressure of gas in the cylinder and the output gauge with a range of 0 to 700 kPa indicated the pressure at which gas entered into the flow controller. The output pressure could be adjusted and was set at 345 kPa for all experiments.

The flow controller (Model SA202-3(5)2, Chromatographic Specialties Inc., Brockville, ON) had an adjustable flow rate range from 1 mL/min to 1000 mL/min and could withstand a maximum pressure of 1380 kPa. For all the experimental tests, the flow was maintained at 150 mL/min. The flow controllers delivered the gas at a constant flow rate to the RH unit.

4.4.4 Relative humidity unit

An RH unit consisted of a glass gas washing bottle, 300 mm tall, 60 mm diameter with 45 mm diameter opening, a capacity of 500 mL and a hexagonal base (Model 28220-500 KIMAX, VWR Canlabs, Ottawa, ON). The bottle was provided with standard tapered (50 to 45 mm) stopper at the top. The stopper had an inlet tube 8 mm in diameter reaching 45 mm above the bottom of the bottle and was provided with a fine porous ceramic screen at the bottom through which the gas (compressed CO_2 or air) bubbled into the RH solution. The gas picked up moisture from RH solutions (sulphuric acid solutions) and delivered it through the outlet of the bottle (8 mm dia) to the distributor for distribution to the various GIUs. The density of sulphuric acid solutions was maintained to obtain constant RH by checking the RH of air on a weekly basis. An RH of 50 and 70% was targetted for dry (12% wb) and wet (15% wb) grain, respectively. The RH was checked at the outlet of the washing bottle using a humidity sensor (Model Hygro-M1, General Eastern Instruments Inc., Watertown, MA) and also by marking the initial height of RH solution on the washing bottle at the start of the experimental test and observing the level of solution. In case of depletion of level below the mark on the washing bottle, the RH solution was replenished with distilled water to obtain the density corresponding to the desired RH (Solomon 1951).

4.4.5 Distributor

The purpose of the distributor was to uniformly distribute the CO_2 gas mixtures received from the RH unit to all the 12 grain-insect exposure units. The distributor was fabricated from ultra high molecular weight plastic (UHMW) in the Department of Biosystems Engineering workshop (Fig. 4.2). A solid block of UHMW plastic with a diameter of 90 mm and thickness of 37 mm was procured locally. A threaded, tapered hole (taper diameter from 12.7 mm to 9.5 mm) was drilled at the center of the block. A brass hose bard fitting (12.7 mm diameter) with a 9.5 mm pipe thread was fitted on the top surface and

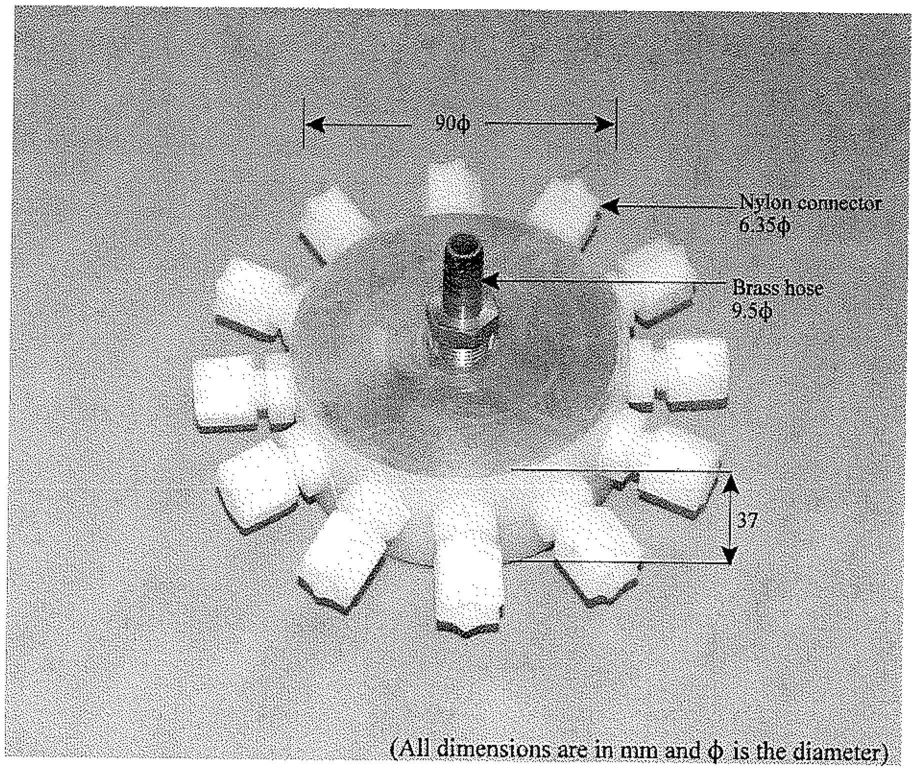


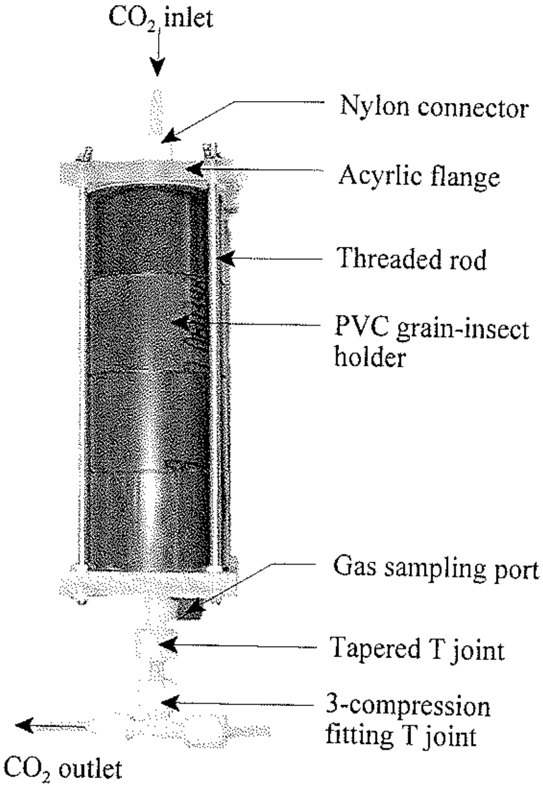
Fig. 4.2 Image of distributor with central brass hose bard and twelve outlets for uniform distribution to twelve GIUs of the experimental unit.

the 9.5 mm opening on the bottom was plugged with 9.5 mm brass plug. A flexible polyethylene pipe of 9.5 mm diameter was fitted on the 9.5 mm threaded brass hose with the other end fitted to outlet of the RH unit. Twelve threaded, equally spaced tapered holes (taper diameter of 6.35 mm to 3.2mm) were drilled along the circumference of the distributor and connectors were fitted to each of the holes with a polyethylene flexible tubing of 915 mm length and 6.5 mm diameter (Fig. 4.2). The other ends of the flexible tubings were attached to the 12 inlet connectors of the GIUs.

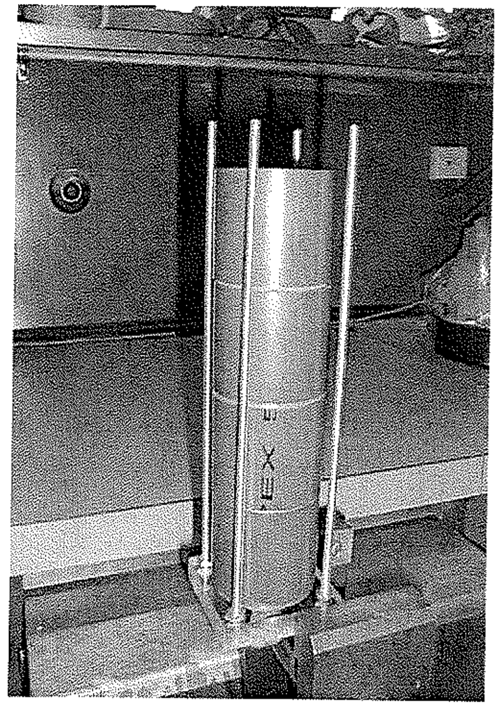
4.4.6 Grain-insect exposure units

A grain-insect exposure unit (GIU) consisted of an assembly of four PVC (poly vinyl chloride) holders (or cups), covered by acrylic flanges at top and bottom and was clamped by wing nuts on threaded rods passing through the clearance holes of two flanges (Fig. 4.3(a)). At any test temperature and CO_2 concentration, there were three species combinations (two single-species and one mixed-species) and four sampling intervals of 2 wk each over an exposure time of 8 wk. Hence in all there were (3 X 4) 12 GIUs each for dry and wet grains at the start of the experiment. The 12 GIUs were clamped to a 3 ply, wooden board 910 mm in length and 380 mm tall. The wooden board was placed perpendicular with its ends at midpoint of two wooden planks, each 255x10x20 mm and screwed together to form an experimental unit (Fig. 4.3(c)). Each experimental unit was provided with individual peripheral components such as CO_2 cylinder with pressure gauges, flow controller, RH unit, distributor, and exhaust assembly. Experimental tests for both the dry and damp grains were carried out at the same time for a constant temperature and CO_2 conditions, by placing two experimental units in the temperature controlled chamber.

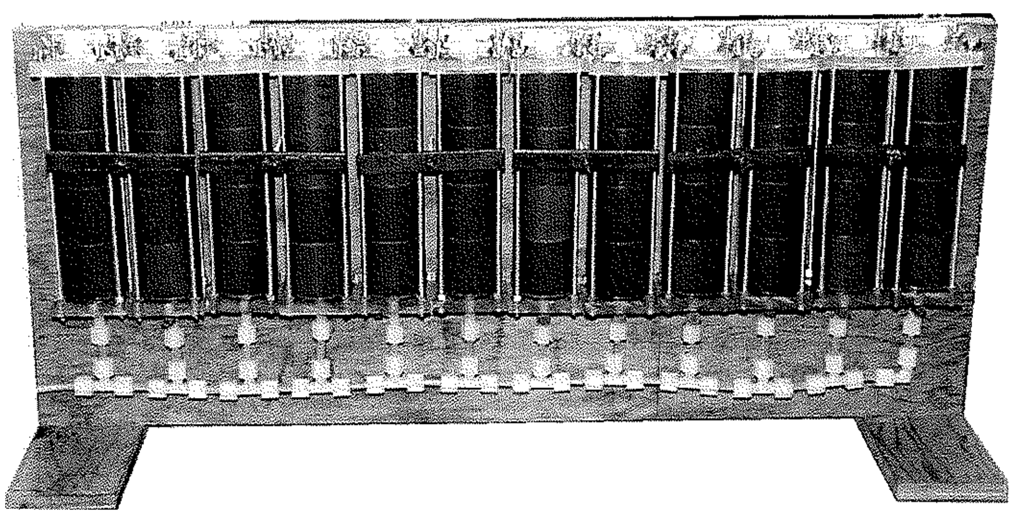
Each PVC grain-insect holder was 50 mm high with outside and inside diameters of



(a)



(b)

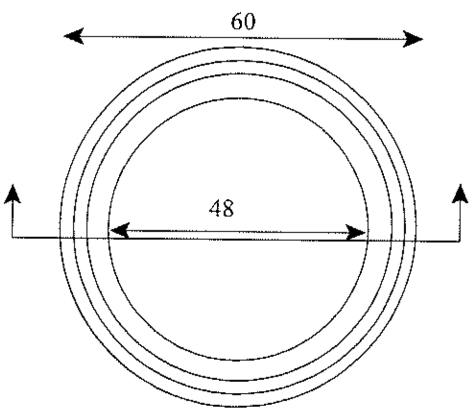


(c)

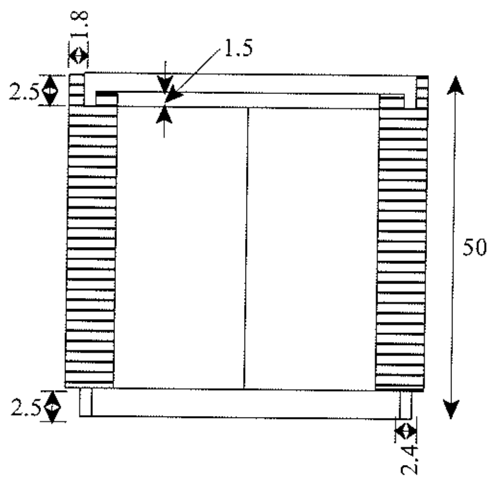
Fig. 4.3 An assembled GIU (a); 4 PVC holders placed on bottom flange between the threaded rods (b); and an experimental unit of 12 GIUs with exhaust assembly (c).

60 and 48 mm, respectively and a volume of 82 mL (enough to hold 70 g of grain with 5% dockage added to it). The top, bottom, and cross sectional views of PVC holders are shown in Figs. 4.4(a),(b) and (c), respectively. The images of the top view and view of an inverted PVC holder are shown in Fig. 4.4(d) and (e), respectively. A nylon screen of 80 mesh (110 μm opening) was attached at the bottom of each PVC holder (Fig. 4.4(e)) by heating edges of nylon screen and edge of PVC cup and heat-pressing them together. The screen allowed the gas to pass but constrained adult insects and their developmental stages from crossing into the next holder. The top of the PVC holder (female-end, Fig. 4.4(d)) was provided with a groove (2.4 mm wide) and the bottom with a corresponding projecting circular ring (male-end, Fig. 4.4(e)) for a proper fit and effective seal between the holders. A compressible 'O' ring of rubber (nitrile) fitted into the top groove before other cup was fitted over it. The 'O' ring wedged in the groove between the two holders served to provide a leakproof joint between the PVC holders.

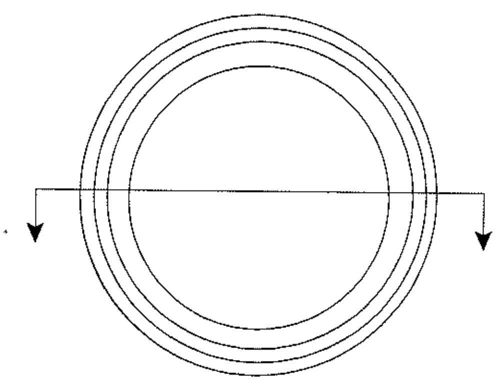
The four PVC grain-insect holders represented the four replicates for both single and mixed-species combinations. The assembly of four cups was covered at top and bottom with acrylic flanges. The flanges were 70 x 70 x 12.5 mm, with a central tapered opening of 6.0 mm and had four clearance holes of 5 mm diameter. A nylon connector (6.35 mm diameter) was fitted to the top flange of the GIU (Fig. 4.3(a)) for entry of CO_2 gas coming from the distributor. A circular piece of nylon screen, 12 mm diameter, 80 mesh (110 μm opening) was glued to the central opening of the top flange on the inside to restrict the insects from moving into the inlet but allowing the gas to come into the holders. A tapered T joint (3.2/6.35 mm), with tapered end (3.2 mm diameter) was fitted into a center opening of the bottom flange and the the other end (6.35 mm diameter) went into one of the joints of



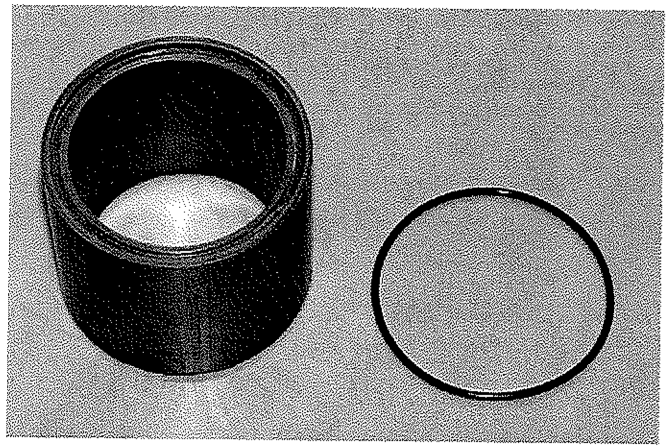
(a) Top view of PVC holder



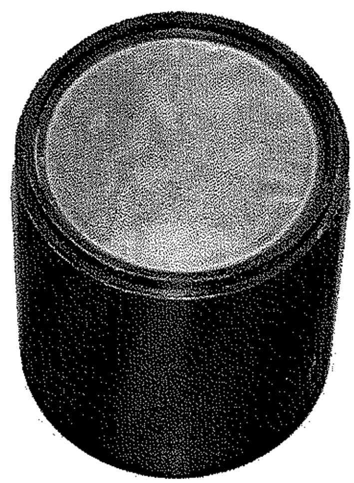
(b) Cross sectional view of PVC holder



(c) View from bottom of PVC holder



(d) Image of PVC holder from top with 'O' ring on the side



(e) Image of inverted PVC holder

Fig. 4.4 Various views of a PVC grain-insect holder.

another T joint (6.35 mm diameter with 3 compression fittings) and the remaining end of the T joint was used as a gas sampling port (Fig. 4.3(a)). The T joint with three compression fittings had the central end attached to compression fitting of the T joint fitted to the lower flange and the other two ends were connected with polyethylene tube (6.35 mm diameter) with those of the adjacent GIU to form the exhaust assembly (Fig. 4.3(c)).

Four threaded rods (type 10-24) passed through clearance holes of the bottom flange were held in place by the hexagonal nuts welded at the bottom of the clearance holes, the rods also passed through the clearance holes of top flange. A set of four PVC holders containing grain and insects with O-rings in place was placed between the four threaded rods on top of the bottom flange (Fig. 4.3(b)). The four clearance holes of the top flange were aligned with the threaded rods and the flange was slid to fit on top of the upper PVC holder and tightened with the wing nuts.

The compressed CO_2 entered the GIU through the inlet at the top and exited after passing through the four grain-insect holders into the exhaust assembly. The continuous flushing maintained a consistent CO_2 environment in all the four grain-insect holders and also prevented change in the environment due to respiration by grain and metabolic activity of the insects.

4.4.7 Exhaust assembly

The gases from the outlets of 12 GIUs (a unit each for dry and wet grain, Fig. 4.3(c)) were exhausted to the atmosphere through the exhaust assembly. The assembly consisted of a continuous pipe formed by connectors, T joints, and polyethylene tubing of a GIU with the adjacent GIU. An extension of polyethylene tubing was attached at the end to exhaust gases out of the temperature controlled chamber. One GIU on the extreme end of an experimental unit had an elbow joint (6.35 mm with 2 compression fittings) instead of a T joint so that gases could be exhausted in one direction only. The entire set up in a temperature controlled chamber with the CO_2 cylinders is shown in Fig. 4.5.

4.5 Experimental Design

A balanced, factorial design was used to study the interspecies and intraspecies interactions between *C. ferrugineus* and *T. castaneum* and other environmental factors. The following factors with their treatments formed the factorial design:

Insect species	:	*C. ferrugineus*, *T. castaneum* (single species controls), and mixed-species
Temperature	:	15, 20, and 25 °C
Moisture content	:	12 and 15% (wb)
CO_2 concentration	:	0.03 (ambient or control), 2, 5, and 10%
Total Exposure time for a treatment	:	8 wk
Sampling interval	:	2 wk for a total of 8 wk per treatment

The experimental tests were done at constant temperature and CO_2 conditions, for dry and wet grains in the temperature controlled chamber. A total of twelve experiments, each with an observation period of 8 wk, were conducted at three temperatures and four CO_2 levels in the temperature controlled chamber. There were four replicates for each combination of treatment.

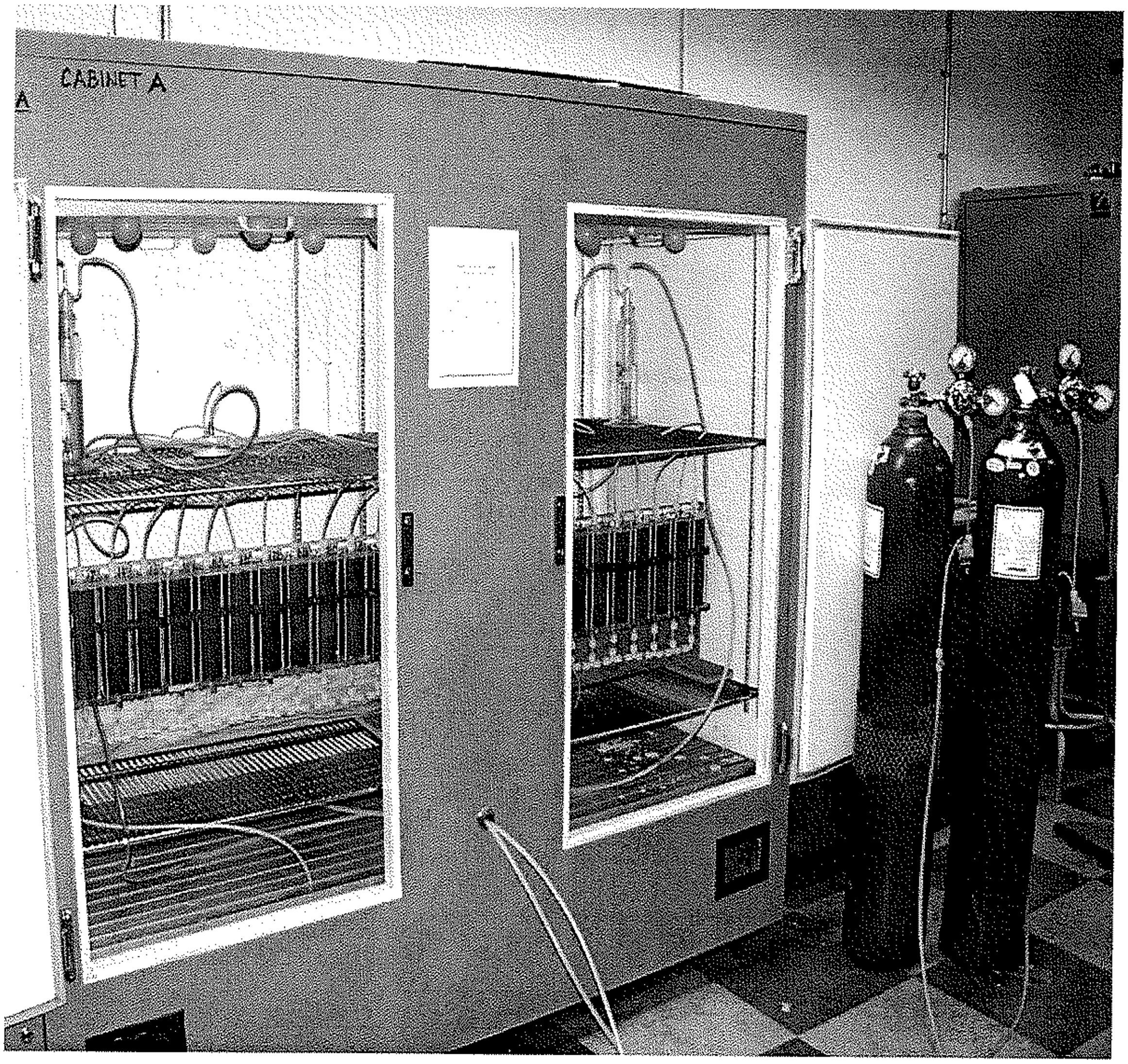


Fig. 4.5 Temperature controlled chamber with two experimental units and components.

4.6 Test Procedures and Methodology

4.6.1 Grain conditioning

The hard red spring No. 1 certified wheat, cv. 'AC Barrie' was used as food for all the experiments was stored at 10°C in bags of 12.5 kg. The initial moisture content of grain ranged from 10 to 11% wb. The grain was conditioned by adding and mixing a calculated quantity of distilled water to obtain moisture contents of 12 and 15% wb for dry and damp samples, respectively. The rewetted samples were kept in a sealed container and tumbled gently and constantly for 1 h after adding distilled water, to ensure uniform and complete mixing. The samples were kept for 24 h in sealed plastic bags at ambient temperature with occasional tumbling to ensure uniform distribution of moisture, prior to use in tests. The initial moisture content and the conditioned moisture content were determined according to the procedure outlined for whole wheat seeds, in the ASAE standard D352.2 (ASAE 1998b) by drying triplicate sub-samples in a convection air oven at 130°C for 19 h.

4.6.2 Determination of equilibrium relative humidity (ERH)

All the experimental tests for single and mixed-species combinations at various temperatures and CO_2 concentrations required dry and damp grains to be at constant moisture content. To maintain the constant moisture content during experiments, gas was conditioned to a RH in equilibrium with moisture content. Equilibrium relative humidity was calculated using a modified Henderson equation (ASAE 1998a). These values of ERH were used to prepare RH solutions through which CO_2 or air was passed into the grain so that the grain neither gained or lost any moisture during the experiments. The ERH values for dry (12% wb) and damp (15% wb) wheat are given in Table 4.1.

Table 4.1 Equilibrium relative humidities at selected temperatures for dry and wet wheat calculated using modified Henderson equation (ASAE 1998a).

Test temperature (°C)	ERH (%)	
	Dry grain (12% wb)	Wet grain (15% wb)
15	47	68
20	50	71
25	52	73

4.6.3 Preparation of RH solution

The RH solutions were prepared using the ERH values from Table 4.1. Solomon (1951) has explained the procedure and precautions to prepare the RH solution using sulphuric acid and has tabulated the values of densities of final solutions to attain a range of relative humidities. The RH solution for each test temperature (Table 4.1) was prepared by a volumetric method of adding concentrated sulphuric acid (H_2SO_4) to distilled water and checking the density of the solution with a hydrometer (Model 11-520, Eimer and Amend, New York, NY). The relative humidities produced were measured using a Vaisala, humicap, HM 1698 probe equipped with a thin layer polymer capacitance sensor and HMI digital meter (Helsinki, Finland). The measured RH values were within ± 3 percentage points. The probe was calibrated with standard solutions of LiCl, NaCl, and K_2SO_4 using standard procedure and a Vaisala HM 11 calibrator.

4.6.4 Determination of germination

The initial germination of dry and damp (or wet) wheat seeds was determined. Also, the germination of seeds after the exposure intervals of 2, 4, 6, and 8 wk was determined to observe the effect of infestation by insects in single and mixed-species combinations. Twenty-five seeds were taken randomly from each replicate and placed on a filter paper in a petri dish, saturated with 4.5 mL of distilled water (White et al. 1986). The petri dishes with filter paper were covered, sealed in plastic bags and kept at 22 ± 1 °C for a period of 7 days after which the germination count was taken. The mean percent of germination counts for the four replicates of 25 seeds each was recorded.

4.6.5 Single and mixed-species setup

Adults of *C. ferrugineus* and *T. castaneum* were obtained from 6 to 8 week old laboratory cultures. The culture medium with adults and immatures was sifted and adults of both species were separated from immature stages. The adults were collected by vacuum aspiration and introduced into the grain-insect holders. Each holder had a capacity to hold 70 g of grain and therefore, 70 adults of each species were introduced into each of the four holders to make a GIU. Similarly, the mixed-species controls comprised of 70 adults of each species i.e. a total of 140 adults with 70 g of grain into each of four holders (replicates).

An experiment for single and mixed-species at a constant temperature and CO_2 condition was 8 wk (exposure time) with sampling intervals of 2 wk. Therefore, 12 GIUs comprising 8 singles-species controls (four each for *C. ferrugineus* and *T. castaneum*) and 4 mixed-species formed an experimental unit (Fig. 4.3(C). Every 2 wk, 3 GIUs (two single species and one mixed-species) were taken out and replaced with dummy GIUs with grain to keep the flow rate consistent in all the GIUs. The GIUs were sampled for adult count, germination, and moisture content.

4.6.6 Grain sampling, adult, and incubation counts of insects

An exposure time of 8 wk was selected so that second generation could also emerge at 25°C and the sublethal effect of CO_2 on the subsequent generation in terms of adult numbers could be observed.

At each sampling interval of 2 wk, the insect-grain holder from each of the 3 GIUs were carefully taken out after loosening the wing nuts on the top flange and easing out the holders from threaded rods. Each holder (a replicate) was emptied into a 2 mm aperture (Sieve No.10) screen placed in a tray. The screen was gently shaken until adults and immatures along with some dockage were deposited in the tray and then the grain at the top of the screen was transferred to a glass bottle (one for each replicate). Using a vacuum aspirator, live and dead adults were aspirated from the tray, counted and discarded. The immatures with dockage and broken grain were added to the remaining grain in the glass bottle. The grain was sampled for moisture content and germination. The bottles with grain were transferred for incubation to the incubation chamber maintained at 30°C and 70% RH for 4 wk. At the end of the incubation period, a count of live and dead adults was recorded. The same procedure was repeated for all time intervals for dry and wet grains for various combinations of temperature and CO_2 levels. Survival at sampling intervals was defined as the sum of live adults on the first count (at 2, 4, 6, and 8 wk) and the live adults from the incubation count after 4 wk from the corresponding sampling interval.

4.7 Statistical Analyses

4.7.1 Data transformation and statistical procedures

For the tests of significance to be valid in the analysis of variance, it is necessary that the experimental errors are independently and normally distributed with a common variance. Whether variances are equal for untransformed data is determined by analyzing the untransformed data using GLM and a regression procedure. The residuals are plotted against the fitted or predicted values and the plot is visually assessed for randomness or lack of a pattern. A random pattern of residuals indicates that the data are randomly distributed. Another important test is the significance of the value of slope at α=0.05 in the output of the regression procedure. If the slope is significant at α=0.05, then the data need to be transformed.

Steel and Torrie (1980) have explained the common transformations and the necessity to transform the raw data. Common transformations are the square root, logarithm, and angular or arcsin transformation. The square root ($\sqrt{\ }$) transformation by taking the square root of an observation, is usually applied when data consists of small whole numbers such as the number of individuals within a sample (e.g. the number of plants or insects of a species or a bacterial colony). The logarithmic transformation (log x)is used when data consist of positive integers covering a wide range. It cannot be directly used for zero values but can be used in the form log (x+1). The data are transformed first and then the analysis of variance is done. In mean comparisons, it is essential to use means of transformed values or the back transformed means instead of raw means for true presentation of transformed data.

Data for four replicates at various treatment combinations were obtained and means of the four replicates for all species combinations were analyzed using SAS (2000) for tests of statistical significance at a significance level of α= 0.05 (5%). Procedure REG (regression) was used to assess the necessity for data transformation. The procedure REG was also used for fitting the data of live adults from first and incubation counts for a suitable model consisting of main effects of time, temperature, RH, and CO_2 levels and their interactions. An ANOVA, procedure GLM (General Linear Model) was performed with five variables (time, temperature, RH, CO_2, and species effect) and their interactions and the means were compared. The effect of three temperatures on the survival at various CO_2 levels and species combination over exposure time was analyzed using the procedure MIXED and the SLICE effect (F test) on variables.

4.7.2 Square root and arcsin transformation of experimental data

The data were obtained at various exposure times for adult count, adults from incubation, and germination. The raw data were separately analyzed (adults from first and incubation counts and germination percentage) using the GLM (General Linear Model) and regression procedures. Regression of variance of residuals and mean of predicted (or fitted values) values was assessed by studying the significance of slope at α=0.05. Plots of residuals versus the predicted values were visually assessed for lack of pattern (Montgomery 1984). The slopes were significant at α=0.05 for incubation and germination data indicating that variances were not equal and data needed to be transformed. However, the data from the first count of adults did not require transformation.

The data for the incubation count were transformed using the square root transformation before running GLM procedures and the means were back transformed for presentation in the tables. Similarly, the data of germination were transformed using the arcsin square root transformation (arcsin $\sqrt{x/100}$) and the means were back transformed for presentation in tabular form.

5. RESULTS AND DISCUSSION

5.1 Context

Various researchers (Park 1948, Smith 1962, Spratt 1984, Kawamoto et al. 1989a) have reported the effects of abiotic and biotic factors on the developmental stages (egg, larvae, pupae, and adults) of insect species. The present study observed adult insect numbers at exposure intervals of 2 wk for a total observation period of 8 wk (first count)and adults emerging out from immatures after incubation for 4 wk (incubation count). The incubation count accounted for adults emerging from the immatures and eliminated the error in counting and damaging the developmental stages during sampling at the ends of exposure intervals. Single species controls at all combinations of temperature, CO_2, and moisture content were maintained for the corresponding mixed-species combinations to quantify the 'species effect' in terms of interspecies and intraspecies interactions such as competition, cannibalism and predation.

At low temperatures and sublethal CO_2 levels there is no insect mortality (lethal effect) in the short term; however exposure at these CO_2 levels can cause inhibition, or delayed egg hatch or laying (AliNiazee et al. 1971), impede mating (Nicolas and Sillans 1989), and females to abort (Lum and Flaherty 1972). Due to this indirect effect on populations instead of direct mortality of adults, the first count and incubation count were separately analyzed for tests of statistical significance. The probability of adult survival being more at low CO_2 and temperature levels compared with lethal levels ($CO_2 > 40\%$), the adult survival instead of mortality has been graphically represented for various treatments. The term 'adult survival', unless specifically mentioned in the context of first or incubation counts, connotes the sum of adults from the first count at an exposure interval (2, 4, 6, or 8 wk) and the corresponding number of adults from immatures i.e. incubation count (first generation offspring).

5.2 ANOVA tables and procedure MIXED of SAS

The entire data for all the treatments was combined to perform a combined analysis of variance with necessary data transformation. An ANOVA was performed with 5-way classfication for adults from first and incubation counts, and total adult survival. The combined ANOVA for the three adult counts (first, incubation, and total) for *C. ferrugineus* and *T. castaneum* are given in Appendix D (Tables D1 to D6). From these tables (Appendix D, Tables D1 to D6), it is observed that apart from significant main effects ($P < 0.0001$), there were complex interactions among variables. Therefore, separate ANOVAs were performed on the subsets by grouping them on the basis of species, moisture content, and species combination. Also procedure MIXED (SAS 2000) was used to analyze significant effects of variables across temperatures and this was necessary since variances were different at different temperatures. The tables of type 3 tests of fixed effects from mixed model analysis are given in Appendix D (Tables D7 to D12) for both species in dry (12% wb) and wet (15% wb) grain for single and mixed-species experiments.

5.3 Effect of Temperature

5.3.1 Single species controls

Temperature had a significant ($P < 0.05$) effect on mean adult survival in single-species controls of both species in dry (12% wb) and wet (15% wb) grain. At the end of the observation period of 8 wk, temperature had a positive correlation with mean adult survival i.e. mean adult survival of both species increased with increasing temperature (15 to 25 °C) in both dry and wet grain at all levels of CO_2 with the exception of *C. ferrugineus* in wet grain at 2 and 5% levels of CO_2 in which mean adult survival was higher at 15 °C compared to 20 and 25 °C (Tables 5.1 and 5.2). However, the positive correlation of temperature with mean adult survival is at a constant CO_2 levels at the end of the observation period and not with reference to the initial adult population. At 2, 5, and 10% levels of CO_2, the mean adult survival fluctuated with exposure time interval and has been discussed under effect of CO_2 in the subsequent section. In dry grain after an exposure of 2 wk, mean adult survival of *C. ferrugineus* at three temperatures was significantly different only at the 10% level of CO_2 (Table 5.1, Fig. A1 (Appendix A)) whereas in wet grain at 2 wk there were no significant differences at 2, 5, and 10% CO_2 levels [Table 5.2, Fig. A2 (Appendix A)]. Overall, the significant differences in mean adult survival of *C. ferrugineus* started with an exposure of 4 wk. For *T. castaneum* in dry grain, mean adult survival increased with temperature from 2 wk onwards with the exception of mean adult survival at 15 and 20°C were not significantly different (at 2 wk) but were significantly different from 25 °C whereas, in wet grain mean adult survival was significantly different at all temperatures from an exposure interval of 2 wk. The mean adult survival of each species was plotted over an exposure period of 8 wk at three temperatures and four constant CO_2 levels to observe the effect of three temperatures (Appendix A, Figs. A1 to A4). At constant temperatures, the mean adult survival as well as the adults from first and incubation counts declined with increasing CO_2 levels and decreasing moisture content and has been discussed under the effect of CO_2, relative humidity, and exposure time in the subsequent sections.

The adult survival data from the first and incubation counts for exposure intervals of

Table 5.1 Mean adult survival (first and incubation counts) and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	60 ± 1*	59 ± 1	55 ± 2	26 ± 2	67 ± 1	67 ± 1	66 ± 1	64 ± 3
	20	72 ± 2	58 ± 1	57 ± 2	46 ± 2	70 ± 5	67 ± 2	65 ± 0	64 ± 1
	25	87 ± 2	60 ± 5	51 ± 8	40 ± 3	136 ± 1	135 ± 1	90 ± 1	84 ± 6
4	15	58 ± 1	44 ± 3	39 ± 1	10 ± 2	66 ± 0	65 ± 1	53 ± 3	51 ± 3
	20	69 ± 3	55 ± 1	47 ± 2	37 ± 2	74 ± 1	66 ± 1	66 ± 1	64 ± 1
	25	124 ± 7	58 ± 6	43 ± 6	34 ± 5	138 ± 6	136 ± 19	78 ± 13	70 ± 1
6	15	45 ± 3	35 ± 3	31 ± 2	5 ± 2	64 ± 1	58 ± 1	56 ± 0	51 ± 4
	20	68 ± 2	47 ± 3	42 ± 2	22 ± 8	68 ± 2	67 ± 2	63 ± 1	60 ± 1
	25	107 ± 6	51 ± 4	46 ± 7	36 ± 3	136 ± 5	137 ± 17	101 ± 21	79 ± 17
8	15	42 ± 3	31 ± 2	33 ± 2	2 ± 1	65 ± 0	52 ± 2	51 ± 1	1 ± 1
	20	59 ± 3	42 ± 6	38 ± 4	18 ± 3	61 ± 5	71 ± 2	63 ± 1	42 ± 4
	25	115 ± 12	48 ± 2	41 ± 10	28 ± 2	193 ± 15	137 ± 20	68 ± 1	55 ± 2

* Standard error based on n=4.

Table 5.2 Mean adult survival (first and incubation counts) and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	63 ± 3*	70 ± 0	65 ± 0	53 ± 2	60 ± 1	69 ± 1	69 ± 0	66 ± 3
	20	80 ± 1	78 ± 1	69 ± 1	63 ± 3	92 ± 5	75 ± 2	67 ± 0	74 ± 3
	25	125 ± 2	90 ± 14	73 ± 3	64 ± 3	151 ± 3	109 ± 14	96 ± 2	86 ± 2
4	15	62 ± 3	69 ± 0	58 ± 3	58 ± 1	66 ± 1	69 ± 0	71 ± 1	63 ± 1
	20	109 ± 2	98 ± 4	64 ± 3	51 ± 1	74 ± 2	66 ± 1	64 ± 1	61 ± 0
	25	258 ± 9	96 ± 6	82 ± 3	63 ± 2	289 ± 15	142 ± 13	112 ± 4	97 ± 2
6	15	54 ± 4	68 ± 2	60 ± 2	33 ± 2	65 ± 1	67 ± 1	70 ± 1	62 ± 2
	20	104 ± 10	77 ± 3	62 ± 4	48 ± 2	72 ± 2	69 ± 2	65 ± 1	62 ± 5
	25	268 ± 8	73 ± 4	59 ± 4	46 ± 3	392 ± 14	169 ± 22	117 ± 22	83 ± 2
8	15	55 ± 2	72 ± 2	64 ± 1	31 ± 2	62 ± 2	67 ± 1	67 ± 1	61 ± 2
	20	79 ± 2	53 ± 3	48 ± 1	39 ± 1	69 ± 1	74 ± 5	66 ± 0	63 ± 4
	25	232 ± 10	55 ± 5	47 ± 2	42 ± 1	389 ± 10	163 ± 33	107 ± 2	74 ± 4

* Standard error based on n=4.

2, 4, 6, and 8 wk at all temperatures were compared using procedure MIXED (SAS 2000) and the tests of effects slices and the F values were analyzed at the 5% level of significance. The data of mean adult incubation counts were transformed using the square root transformation prior to the statistical analysis . Over the observation period of 8 wk, the temperature had a significant effect ($P < 0.05$) on adult survival from both first and incubation counts of both the species.

The adults in the first count were directly exposed to different CO_2 environments at 15, 20, and 25 °C for an exposure period of 8 wk. The mean survivals of adults of both species from first count at all test temperatures and CO_2 levels in dry (12% wb) and wet (15% wb) grain are shown in Tables 5.3 and 5.4, respectively. In dry grain at ambient CO_2 level, mean adult survival from first count of *C. ferrugineus* at 25 °C was significantly higher than 20 °C at the 8th wk whereas mean adult survival from first count at both these temperatures was significantly higher compared to 15 °C over all the exposure intervals and a similar trend was observed in wet grain with the first generation of adults emerging at 25 °C from 6 wk onwards (Table 5.4, adult count > 70). In dry grain at ambient CO_2 conditions, the mean adult survival from first count decreased with time at all three temperatures compared to the initial population of 70 adults. At 2, 5, and 10% levels of CO_2, mean adult survival of *C. ferrugineus* from the first count at 20 °C was higher than 15 and 25 °C at almost all exposure intervals in dry (10 out 12 tests) and wet (12 out of 12 tests) grain indicating that temperature had a significant effect on efficacy of CO_2 at 25 °C whereas at 15 °C the cool temperature reduced the adult survival. For *T. castaneum* in dry and wet grain at the ambient CO_2 level, mean adult survival from the first count was higher compared to *C. ferrugineus* at all temperatures with the first generation of adults appearing at 25 °C after

Table 5.3 Mean adult survival from first count and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	60 ± 1*	59 ± 1	55 ± 2	26 ± 2	67 ± 1	67 ± 1	66 ± 1	63 ± 3
	20	68 ± 1	57 ± 1	56 ± 2	46 ± 2	62 ± 3	64 ± 1	64 ± 0	62 ± 1
	25	67 ± 0	46 ± 2	42 ± 7	38 ± 3	69 ± 0	67 ± 2	68 ± 0	69 ± 0
4	15	58 ± 1	44 ± 3	39 ± 1	10 ± 2	66 ± 0	65 ± 1	53 ± 3	50 ± 4
	20	62 ± 3	54 ± 1	46 ± 2	37 ± 2	62 ± 3	64 ± 2	65 ± 1	64 ± 1
	25	65 ± 1	39 ± 2	31 ± 7	26 ± 2	68 ± 1	64 ± 1	58 ± 5	58 ± 2
6	15	45 ± 3	35 ± 3	30 ± 2	5 ± 2	64 ± 1	58 ± 1	56 ± 0	51 ± 4
	20	62 ± 1	43 ± 3	41 ± 2	22 ± 8	66 ± 1	65 ± 2	63 ± 1	60 ± 1
	25	63 ± 4	41 ± 2	39 ± 8	32 ± 2	76 ± 2	74 ± 5	59 ± 7	57 ± 9
8	15	42 ± 3	31 ± 2	33 ± 2	2 ± 1	65 ± 0	52 ± 2	51 ± 1	1 ± 1
	20	54 ± 3	39 ± 6	36 ± 3	18 ± 3	60 ± 5	64 ± 0	63 ± 1	42 ± 4
	25	66 ± 2	44 ± 2	30 ± 10	24 ± 1	131 ± 5	119 ± 13	51 ± 1	41 ± 1

* Standard error based on n=4.

Table 5.4 Mean adult survival from first count and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	63 ± 3*	70 ± 0	65 ± 0	53 ± 2	60 ± 1	69 ± 1	69 ± 0	64 ± 3
	20	71 ± 0	66 ± 1	64 ± 1	61 ± 2	68 ± 1	68 ± 1	64 ± 1	68 ± 2
	25	69 ± 0	56 ± 3	54 ± 3	51 ± 2	69 ± 1	66 ± 1	64 ± 1	63 ± 2
4	15	62 ± 3	69 ± 0	57 ± 3	58 ± 1	66 ± 1	69 ± 0	71 ± 1	63 ± 1
	20	71 ± 1	56 ± 1	54 ± 1	50 ± 1	67 ± 1	65 ± 1	63 ± 1	61 ± 0
	25	70 ± 0	38 ± 2	41 ± 1	36 ± 3	68 ± 0	63 ± 1	61 ± 1	60 ± 0
6	15	54 ± 4	68 ± 2	59 ± 3	33 ± 2	65 ± 1	67 ± 1	70 ± 1	62 ± 2
	20	71 ± 1	54 ± 3	51 ± 2	47 ± 2	68 ± 1	65 ± 2	65 ± 1	62 ± 5
	25	72 ± 1	35 ± 5	32 ± 1	29 ± 2	81 ± 2	76 ± 2	67 ± 1	64 ± 2
8	15	55 ± 2	68 ± 1	62 ± 1	31 ± 2	62 ± 2	66 ± 1	67 ± 1	61 ± 2
	20	70 ± 1	46 ± 2	42 ± 2	39 ± 1	68 ± 1	64 ± 1	66 ± 0	63 ± 4
	25	83 ± 1	42 ± 4	36 ± 1	32 ± 1	157 ± 7	139 ± 23	86 ± 1	59 ± 3

* Standard error based on n=4.

an exposure period of 6 wk indicating that *T. castaneum* survived better in dry grain compared to *C. ferrugineus* (Table 5.3). For *T. castaneum* at 2, 5, and 10% levels of CO_2, mean adult survival from the first count at 20°C was higher than (or equal to) 15 and 25°C at majority of exposure intervals in dry (8 out 12 tests) grain, whereas in wet grain the mean adult survival from first count at 25°C was higher. In both the species, the first generation of adults in the first count emerged only at 25°C from an exposure period of 6 wk onwards at ambient, and 2% levels of CO_2 in dry and wet grain (Tables 5.3 and 5.4). At 25°C, the first generation of adults of *C. ferrugineus* were recruited only at the ambient CO_2 level in wet grain whereas, for *T. castaneum* they were observed in both dry and wet grain at ambient and 2% levels of CO_2. Adult of *T. castaneum* survives well in dry conditions compared to *C. ferrugineus* and therefore the first generation of adults was observed in dry grain unlike *C. ferrugineus* at 25°C. At 15 and 20°C, no adults of the first generation were produced by either species. Kawamoto et al. (1990) reported low survival rates for eggs of *C. ferrugineus* at 15 and 19°C compared to 25°C and observed no egg-hatch at 15°C. Smith (1963) observed the effect of temperature (20 to 40°C) on the oviposition rates of *C. ferrugineus* and reported that the second generation of adults did not emerge until the seventh week at 20°C. The adult survival from first count of the two single-species was plotted over an exposure period of 8 wk at three temperatures and four constant CO_2 levels to observe the effect of three temperatures (Appendix A, Figs. A5 to A8). The temperature range of 15 to 25°C is below the optimum required for survival, growth and reproduction of these two species (Fields and White 1997). A grain temperature of 18°C is sufficient to stop adult insects from laying eggs (Fields and White 1997).

Temperature had a significant ($P < 0.05$) and positive correlation with the incubation count with an increasing incubation count of adults at higher temperatures. For both species at 15°C, there was no adult emergence in the incubation count over the entire observation period in dry (12% wb) grain except a lone adult of *T. castaneum* which could be an experimental error (Tables 5.5 and 5.6). However, in wet grain at 15°C, there was adult emergence in the incubation count at 2 wk and 10% CO_2 level in *T. castaneum* (but not observed at intervals of 4, 6, and 8 wk) whereas it was observed in *C. ferrugineus* from 4 wk onwards at 2 and 5% levels of CO_2. The emergence of adults in the incubation count at higher levels of CO_2 and an their absence at ambient CO_2 levels at 15°C can probably be attributed to an increased rate of oviposition at higher levels of CO_2 (up to 10%) as reported by Spratt (1984). Few adults emerged at 20°C, an observation also confirmed by Kawamoto et al. (1990) and there was a significant ($P < 0.05$) incubation count at 25°C with higher incubation count at ambient CO_2 levels and significantly lower incubation count at other CO_2 levels of 2, 5, and 10%. The efficacy of CO_2 in impeding the growth and multiplication and causing mortality increases with increasing temperature and decreasing relative humidity (Nicolas and Sillans 1989) and hence at 25°C the incubation count was higher in wet (15% wb) grain compared to dry (12% wb) grain. At 25°C, generally the adults from incubation decreased with increasing CO_2 levels (Tables 5.5 and 5.6).

5.3.2 Mixed-species combination

The effect of temperature was significant ($P < 0.05$) on mean adult survival of both species in mixed-species combination in both dry (12% wb) and wet (15% wb) grain. For both species in dry grain at ambient level of CO_2, mean adult survival decreased at 15 and 20°C with time whereas at 25°C mean adult survival increased and peaked at 6 wk before declining at the end of 8 wk (Table 5.7) indicating that at lower temperatures of 15 and 20°C

Table 5.5 Mean adult incubation count and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	0 ± 0*	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	1 ± 1
	20	4 ± 1	1 ± 0	0 ± 0	0 ± 0	8 ± 3	3 ± 1	1 ± 1	2 ± 0
	25	20 ± 1	15 ± 4	9 ± 2	2 ± 1	67 ± 1	69 ± 3	22 ± 1	15 ± 6
4	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	6 ± 1	1 ± 0	1 ± 1	0 ± 0	12 ± 3	2 ± 0	1 ± 1	0 ± 0
	25	59 ± 8	19 ± 6	12 ± 2	9 ± 4	70 ± 6	72 ± 18	20 ± 9	12 ± 2
6	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	6 ± 1	4 ± 1	1 ± 0	0 ± 0	2 ± 1	2 ± 0	0 ± 0	0 ± 0
	25	44 ± 9	10 ± 3	7 ± 2	5 ± 3	60 ± 5	63 ± 14	42 ± 14	22 ± 8
8	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	5 ± 1	3 ± 1	2 ± 0	0 ± 0	1 ± 0	6 ± 1	0 ± 0	0 ± 0
	25	49 ± 10	4 ± 1	11 ± 1	4 ± 2	62 ± 17	18 ± 8	17 ± 1	14 ± 1

* Standard error based on n=4.

Table 5.6 Mean adult incubation count and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*				*T. castaneum*			
		CO_2 levels (%)				CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	0 ± 0*	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	2 ± 1
	20	9 ± 1	12 ± 1	5 ± 1	2 ± 1	24 ± 4	8 ± 2	3 ± 0	7 ± 2
	25	56 ± 2	34 ± 12	19 ± 2	13 ± 1	82 ± 4	44 ± 14	32 ± 1	23 ± 1
4	15	0 ± 0	1 ± 1	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	38 ± 2	42 ± 4	10 ± 1	1 ± 0	7 ± 2	1 ± 0	1 ± 1	0 ± 0
	25	188 ± 9	58 ± 6	41 ± 2	27 ± 1	221 ± 15	80 ± 13	51 ± 4	37 ± 2
6	15	0 ± 0	1 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	32 ± 10	23 ± 2	11 ± 2	0 ± 0	4 ± 2	4 ± 2	0 ± 0	0 ± 0
	25	196 ± 7	39 ± 1	27 ± 3	16 ± 2	311 ± 12	93 ± 21	50 ± 22	19 ± 1
8	15	0 ± 0	5 ± 1	2 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	9 ± 1	7 ± 1	6 ± 1	0 ± 0	1 ± 1	10 ± 5	0 ± 0	0 ± 0
	25	149 ± 9	13 ± 1	11 ± 1	10 ± 1	231 ± 7	24 ± 13	21 ± 2	15 ± 1

* Standard error based on n=4.

Table 5.7 Mean adult survival (first and incubation counts) and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*				*T. castaneum*			
		CO_2 levels (%)				CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	62 ± 2*	61 ± 2	56 ± 2	26 ± 7	64 ± 1	66 ± 0	65 ± 1	51 ± 9
	20	65 ± 4	56 ± 2	57 ± 3	43 ± 7	70 ± 2	64 ± 1	66 ± 2	66 ± 1
	25	80 ± 2	75 ± 13	53 ± 3	38 ± 2	90 ± 4	64 ± 3	62 ± 6	63 ± 2
4	15	56 ± 2	44 ± 6	37 ± 3	5 ± 1	62 ± 1	61 ± 1	63 ± 2	47 ± 2
	20	53 ± 2	65 ± 3	52 ± 2	32 ± 4	61 ± 3	64 ± 2	65 ± 1	60 ± 1
	25	110 ± 6	63 ± 6	37 ± 4	24 ± 2	81 ± 1	61 ± 1	61 ± 12	54 ± 2
6	15	48 ± 3	23 ± 3	19 ± 7	2 ± 0	62 ± 2	48 ± 3	58 ± 5	31 ± 7
	20	34 ± 1	54 ± 1	42 ± 2	33 ± 5	64 ± 1	65 ± 2	62 ± 2	53 ± 2
	25	146 ± 9	60 ± 5	39 ± 3	35 ± 3	104 ± 8	62 ± 1	51 ± 3	50 ± 3
8	15	42 ± 2	11 ± 4	18 ± 6	1 ± 1	61 ± 1	26 ± 8	46 ± 11	3 ± 3
	20	40 ± 2	45 ± 4	37 ± 3	26 ± 2	66 ± 2	60 ± 1	58 ± 4	9 ± 4
	25	91 ± 10	34 ± 2	43 ± 14	27 ± 3	84 ± 10	56 ± 0	50 ± 7	36 ± 10

* Standard error based on n=4.

survival was lower and increased at the near optimum temperature of 25 °C (Table 3.2). In wet grain at the ambient CO_2 level, mean adult survival of *C. ferrugineus* declined (adult < 70) at 15 °C with time whereas it increased at 20 and 25 °C peaking at 6 wk before declining at 8 wk (Table 5.8). Temperature also had a significant ($P < 0.05$) and positive effect on mean adult survival of *Tribolium castaneum* in wet grain at ambient level of CO_2 at 25 °C whereas mean adult survival declined at 15 and 20 °C over the exposure period of 8 wk. At 2, 5, and 10% CO_2 levels in dry grain, mean adult survival of *C. ferrugineus* at 15 °C was significantly ($P < 0.05$) less compared to 20 and 25 °C and decreased with exposure time and variation of mean adult survival at 20 and 25 °C was similar to single-species controls with adult numbers significantly less compared to respective single-species controls. In experiments with *T. castaneum* in at these conditions (dry grain at 2, 5, and 10% CO_2 levels), temperature did not have a significant effect after up to 4 wk of exposure time except at the 10% CO_2 level and the mean adult survival was significantly lower at 15 °C compared to 20 and 25 °C with mean adult survival generally decreasing at the end of exposure period of 8 wk. In wet grain at the end of the observation period, mean adult survival of *C. ferrugineus* at 15 °C was higher than 20 and 25 °C for 2 and 5% levels of CO_2, whereas fluctuation was observed in the mean adult survival at 20 and 25 °C at various exposure intervals and CO_2 levels. This aspect has been discussed in subsequent sections under the effect of CO_2, relative humidity, and species effect. Temperature had a significant ($P < 0.05$) effect on mean adult survival of *T. castaneum* in wet grain at 2, 5, and 10% CO_2 levels with adult numbers generally decreasing with time at all test temperatures (except at the 2% level of CO_2 at an exposure interval of 6 wk where adult numbers increased) and the mean adult survival at 15 °C was higher than at 20 and 25 °C (Table 5.8). The mean adult survival of the two

Table 5.8 Mean adult survival (first and incubation counts) and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*				*T. castaneum*			
		CO_2 levels (%)				CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	55 ± 1*	69 ± 0	66 ± 1	58 ± 2	59 ± 1	69 ± 0	69 ± 0	67 ± 2
	20	77 ± 2	78 ± 2	73 ± 0	64 ± 1	70 ± 0	65 ± 1	63 ± 1	63 ± 0
	25	100 ± 2	82 ± 7	69 ± 4	60 ± 3	90 ± 2	72 ± 4	69 ± 1	64 ± 2
4	15	63 ± 1	70 ± 0	58 ± 1	43 ± 2	56 ± 1	69 ± 0	67 ± 1	61 ± 1
	20	85 ± 3	89 ± 4	56 ± 1	46 ± 3	63 ± 2	61 ± 1	58 ± 1	56 ± 0
	25	156 ± 5	79 ± 2	71 ± 5	55 ± 2	83 ± 2	63 ± 7	66 ± 2	59 ± 2
6	15	61 ± 2	70 ± 1	58 ± 2	32 ± 4	65 ± 1	69 ± 1	69 ± 1	57 ± 3
	20	88 ± 3	96 ± 15	69 ± 2	52 ± 1	59 ± 1	65 ± 1	58 ± 0	53 ± 2
	25	165 ± 5	51 ± 4	45 ± 1	43 ± 2	84 ± 2	81 ± 6	65 ± 2	57 ± 5
8	15	49 ± 2	69 ± 1	59 ± 3	34 ± 4	58 ± 2	65 ± 1	67 ± 1	56 ± 4
	20	77 ± 7	55 ± 2	46 ± 2	42 ± 1	63 ± 1	53 ± 2	53 ± 0	49 ± 2
	25	155 ± 2	64 ± 2	52 ± 3	32 ± 3	92 ± 3	63 ± 1	53 ± 2	49 ± 3

* Standard error based on n=4.

species in mixed-species experiments was plotted over the observation period of 8 wk and is presented in Appendix A (Figs. A9 to A12).

The temperature had a significant ($P < 0.05$) effect on mean adult survival from the first count of both species in mixed-species combination. The first generation of adults in the first count of both species emerged only at 25 °C in wet (15% wb) grain after an exposure period of 8 wk at ambient level of CO_2 (Tables 5.9 and 5.10, Appendix A (Figs. A13 to A16)). However, at the same conditions the first generation of adults was also observed at 6 wk in *T. castaneum* to some extent (Table 5.10). For both species in dry grain at all CO_2 levels and exposure intervals, mean adult survival from first count at 15 °C was significantly lower compared to 20 an 25 °C whereas the mean adult survival from the first count at 20 °C was higher than that of 25 °C (except at ambient CO_2 level) suggesting that in dry grain CO_2 reduced survival at 25 °C. In wet (15% wb) grain, except at the ambient CO_2 level, the mean adult survival from the first count of both species at 15 °C was higher compared to that at 20 and 25°C suggesting that survival at 15°C was higher due to higher moisture content compared to dry grain. The mean adult survival from the first count in wet grain at 20°C was significantly higher compared to 25 °C at all CO_2 levels except ambient suggesting lower survival due to the effect of CO_2 at higher temperature but to a lesser extent than compared to dry grain (Tables 5.9 and 5.10). The CO_2 effect and interaction with temperature and moisture content is discussed in the subsequent sections.

Temperature had a significant ($P < 0.05$) and positive correlation with adult count from incubation i.e. incubation count generally increased with temperature. At 15 °C, no adults emerged from the incubation count in dry grain for both the species whereas in wet grain only a few adults (one or two adults at 2 and 5% CO_2 level) emerged from *C.*

Table 5.9 Mean adult survival from first count and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	62 ± 2*	61 ± 2	56 ± 2	26 ± 7	64 ± 1	66 ± 0	65 ± 1	51 ± 9
	20	64 ± 3	55 ± 2	56 ± 3	41 ± 6	68 ± 1	64 ± 1	66 ± 2	66 ± 1
	25	66 ± 1	48 ± 5	52 ± 2	37 ± 2	68 ± 1	63 ± 2	61 ± 6	60 ± 1
4	15	56 ± 2	44 ± 6	37 ± 3	5 ± 1	62 ± 1	61 ± 1	63 ± 2	47 ± 2
	20	53 ± 2	55 ± 1	48 ± 3	32 ± 4	61 ± 3	64 ± 2	65 ± 1	60 ± 1
	25	65 ± 1	41 ± 2	29 ± 2	24 ± 1	68 ± 1	61 ± 1	54 ± 7	52 ± 2
6	15	48 ± 3	23 ± 3	19 ± 7	2 ± 0	62 ± 2	48 ± 3	58 ± 5	31 ± 7
	20	34 ± 1	49 ± 1	42 ± 2	33 ± 5	64 ± 1	65 ± 2	62 ± 2	53 ± 2
	25	66 ± 2	43 ± 2	35 ± 2	31 ± 1	68 ± 1	62 ± 1	51 ± 3	48 ± 4
8	15	42 ± 2	11 ± 4	18 ± 6	1 ± 1	61 ± 1	26 ± 8	46 ± 11	3 ± 3
	20	40 ± 2	41 ± 3	36 ± 2	26 ± 2	66 ± 2	60 ± 1	58 ± 4	9 ± 4
	25	59 ± 1	32 ± 1	31 ± 9	23 ± 2	64 ± 2	56 ± 0	46 ± 5	36 ± 10

* Standard error based on n=4.

Table 5.10 Mean adult survival from first count and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	55 ± 1*	69 ± 0	66 ± 1	58 ± 2	59 ± 1	69 ± 0	69 ± 0	67 ± 2
	20	68 ± 1	68 ± 2	67 ± 1	61 ± 3	62 ± 1	64 ± 1	63 ± 1	62 ± 0
	25	68 ± 0	53 ± 2	52 ± 1	49 ± 3	71 ± 0	62 ± 0	62 ± 1	58 ± 1
4	15	63 ± 1	69 ± 0	58 ± 1	43 ± 2	56 ± 1	69 ± 0	67 ± 1	61 ± 1
	20	69 ± 0	56 ± 3	51 ± 1	46 ± 3	61 ± 0	61 ± 1	58 ± 1	56 ± 0
	25	69 ± 0	42 ± 3	40 ± 2	32 ± 1	69 ± 1	51 ± 2	55 ± 1	53 ± 2
6	15	61 ± 2	69 ± 0	58 ± 2	32 ± 4	65 ± 1	69 ± 1	69 ± 1	57 ± 3
	20	67 ± 2	56 ± 2	57 ± 1	51 ± 1	59 ± 1	64 ± 0	58 ± 0	53 ± 2
	25	69 ± 0	32 ± 4	34 ± 1	31 ± 2	73 ± 0	62 ± 4	52 ± 1	50 ± 3
8	15	49 ± 2	67 ± 1	58 ± 3	34 ± 4	58 ± 2	65 ± 1	67 ± 1	56 ± 4
	20	65 ± 3	50 ± 2	43 ± 1	42 ± 1	63 ± 1	53 ± 2	53 ± 0	49 ± 2
	25	76 ± 1	43 ± 2	39 ± 2	26 ± 2	87 ± 2	57 ± 2	49 ± 2	44 ± 2

* Standard error based on n=4.

ferrugineus with no emergence of adults from *T. castaneum* (Tables 5.11 and 5.12). At 20 and 25 °C, the adult count from incubation in both dry and wet grain for *C. ferrugineus* generally increased with temperature i.e. adult numbers were higher at 25 °C compared to 20 °C at constant CO_2 levels and the variation of adult numbers between CO_2 levels has been discussed under sections on the effect of CO_2 and species combination. At 20 °C, there was no adult emergence of *T. castaneum* in dry grain at all CO_2 levels except at the ambient CO_2 level (2 adults at 2 wk exposure interval) and this exception could be an experimental variation since no adults numbers were observed at other exposure intervals at the same CO_2 level. At 25 °C, the incubation count in both the species was significantly ($P < 0.05$) higher compared to other temperatures. In general, total adult survival, for first and incubation counts of both species in mixed-species experiments were significantly lower ($P < 0.05$) compared to their respective single-species controls. The main effect of temperature for both the dry and wet grains at constant CO_2 levels is separately illustrated for single and mixed-species combinations in Figs. 5.1 to 5.4.

5.3.3 Interaction effect of temperature with other variables

The adult survival for single and mixed-species combination was significantly ($P < 0.05$) affected by the interaction of temperature with other variables. For all the treatments, generally there was significant ($P < 0.05$) two way interaction of temperature with RH, CO_2, and exposure time. The mean adult survival over all time intervals increased with temperature and RH, i.e. the adult population at high moisture content was higher than at low moisture content with an increase of temperature from 15 to 25 °C. However, the exception was the mixed-species combination of *T. castaneum* in dry grain (50% RH) where population decreased at 20 °C for all the CO_2 levels except at the ambient level before increasing again

Table 5.11 Mean adult incubation count and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	0 ± 0*	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	1 ± 1	1 ± 0	1 ± 1	1 ± 0	2 ± 1	0 ± 0	0 ± 0	0 ± 0
	25	14 ± 3	27 ± 8	1 ± 0	0 ± 0	22 ± 3	1 ± 1	1 ± 1	3 ± 1
4	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	1 ± 0	10 ± 4	5 ± 2	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	25	45 ± 6	22 ± 5	8 ± 5	1 ± 1	13 ± 1	0 ± 0	7 ± 7	2 ± 1
6	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	0 ± 0	5 ± 2	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	25	80 ± 9	17 ± 4	4 ± 3	4 ± 3	36 ± 9	0 ± 0	0 ± 0	2 ± 2
8	15	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	0 ± 0	4 ± 1	2 ± 1	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	25	32 ± 11	3 ± 1	12 ± 6	4 ± 3	20 ± 8	0 ± 0	4 ± 3	0 ± 0

* Standard error based on n=4.

Table 5.12 Mean adult incubation count and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	0 ± 0*	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	9 ± 2	11 ± 2	6 ± 0	3 ± 2	8 ± 1	1 ± 0	0 ± 0	1 ± 0
	25	32 ± 1	29 ± 5	16 ± 3	11 ± 1	19 ± 2	10 ± 4	7 ± 1	6 ± 0
4	15	0 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	16 ± 4	33 ± 3	4 ± 1	0 ± 0	3 ± 2	0 ± 0	0 ± 0	0 ± 0
	25	87 ± 4	37 ± 3	31 ± 5	23 ± 2	14 ± 1	12 ± 8	11 ± 1	6 ± 2
6	15	0 ± 0	1 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	21 ± 3	40 ± 14	12 ± 2	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	25	96 ± 6	20 ± 1	11 ± 1	12 ± 1	11 ± 2	19 ± 2	13 ± 2	8 ± 3
8	15	0 ± 0	2 ± 1	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	20	11 ± 5	5 ± 1	3 ± 1	0 ± 0	0 ± 0	1 ± 1	0 ± 0	0 ± 0
	25	79 ± 4	21 ± 2	13 ± 1	6 ± 1	5 ± 1	6 ± 1	4 ± 1	5 ± 1

* Standard error based on n=4.

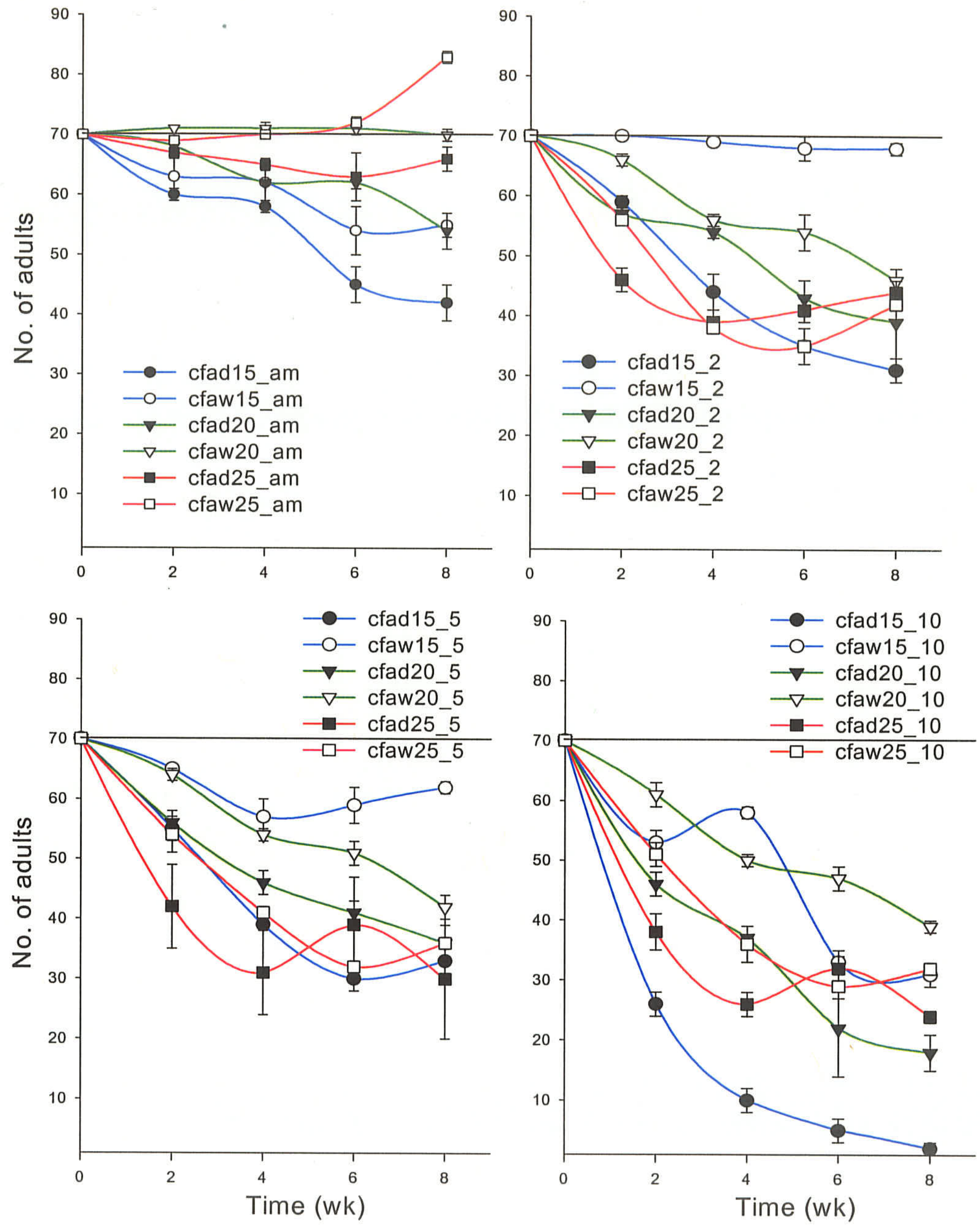


Fig. 5.1 Effect of temperature on mean adult survival (n=4) in single-species controls of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2 at selected time intervals. The characters in the legend represent (from left to right): cf and tc refer to *C. ferrugineus* and *T. castaneum*, respectively; 'a' or 'c' refer to single-species and mixed species combination of preceding species, respectively; 'd' or 'w' refer to dry (12% wb) and wet (15% wb) grain, respectively; next two digits refer to temperature in °C; last two digits following underscore represent level of CO_2 for the test.

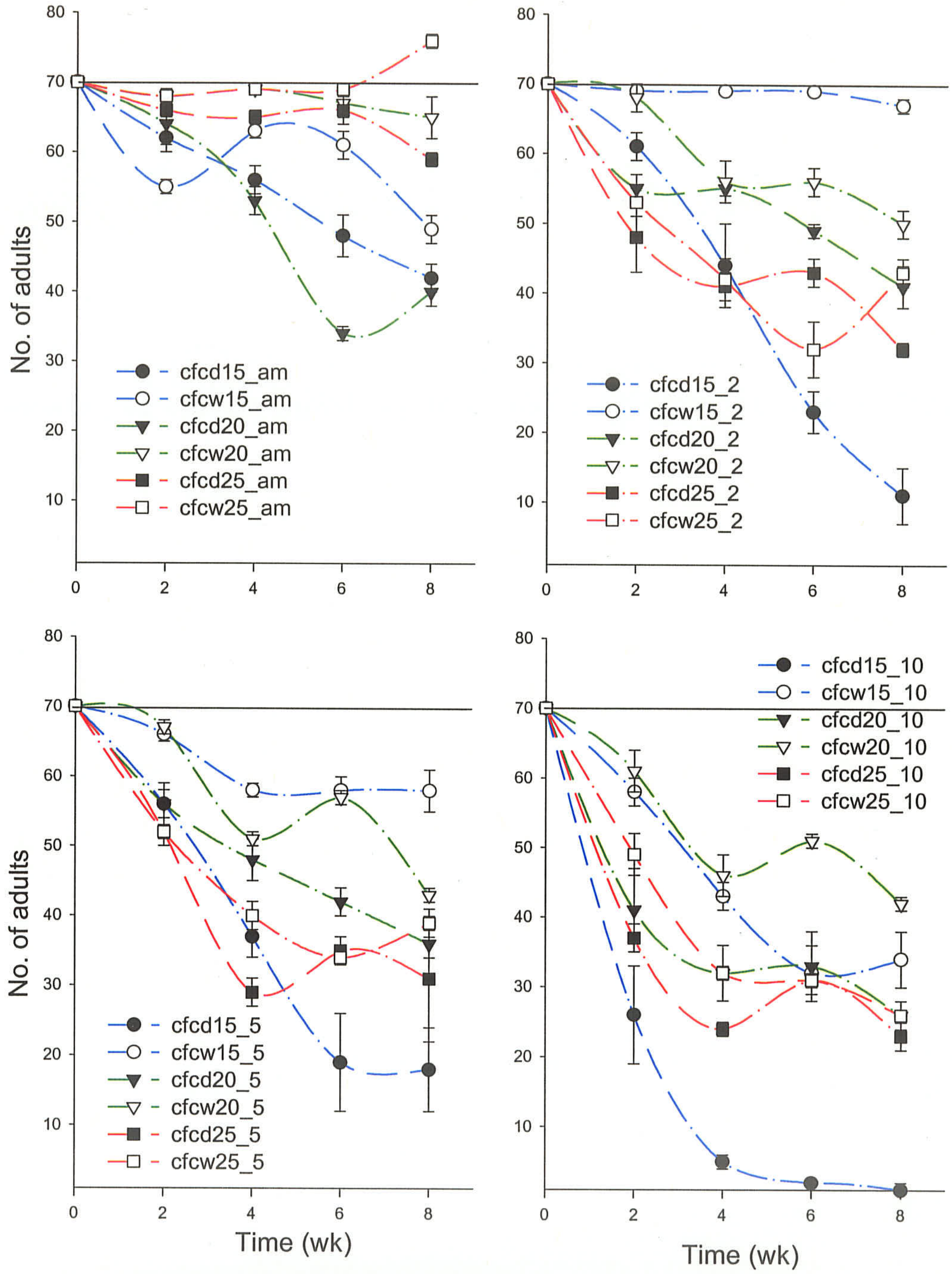


Fig. 5.2 Effect of temperature on mean adult survival (n=4) in mixed-species combination *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain at ambient (am),2, 5, and 10% levels of CO_2 at selected time intervals. Refer to Fig. 5.1 for explanation of characters in the legend.

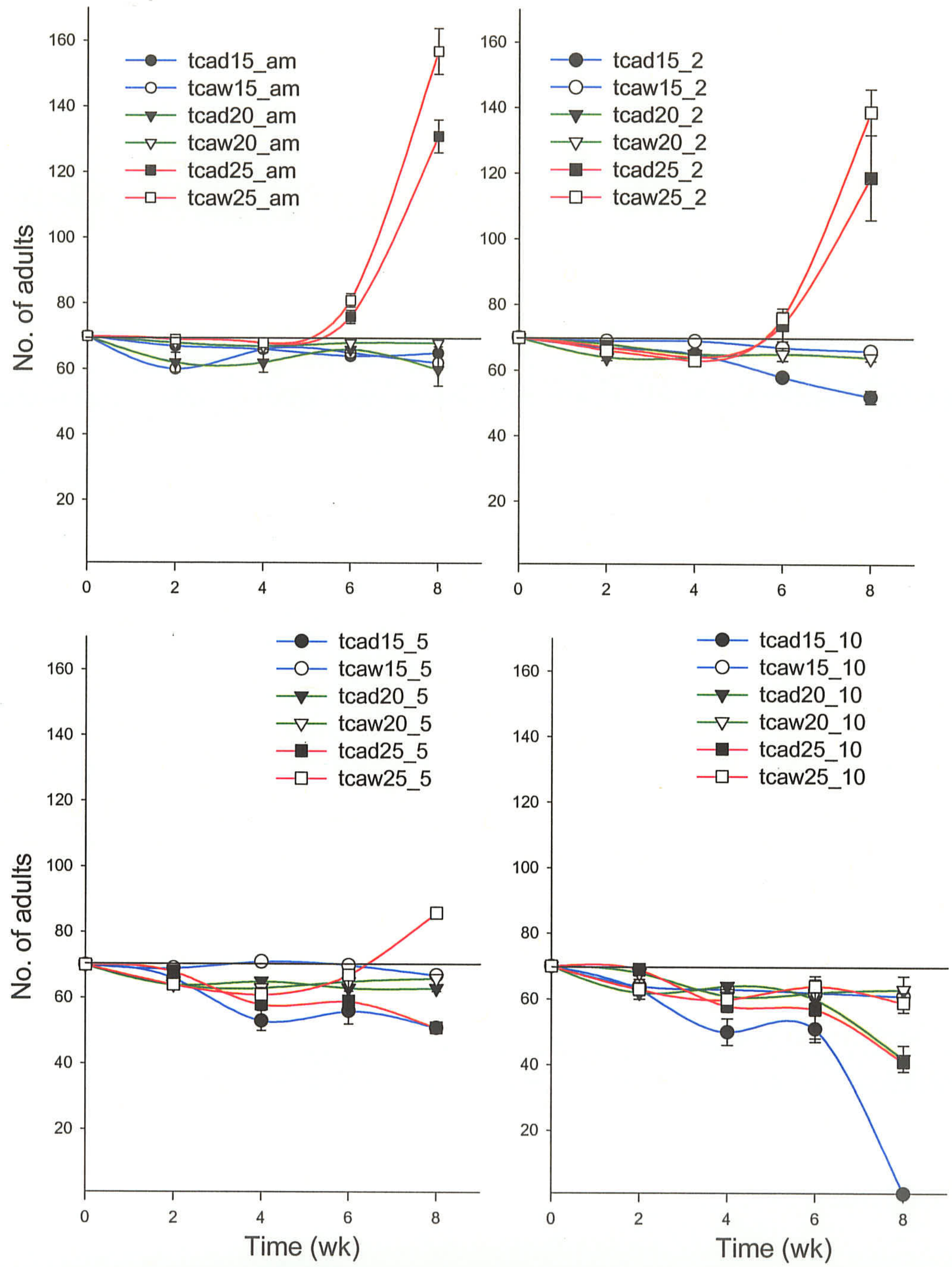


Fig. 5.3 Effect of temperature on mean adult survival (n=4) in single-species controls of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2 at selected time intervals. Refer to Fig. 5.1 for explanation of characters in the legend.

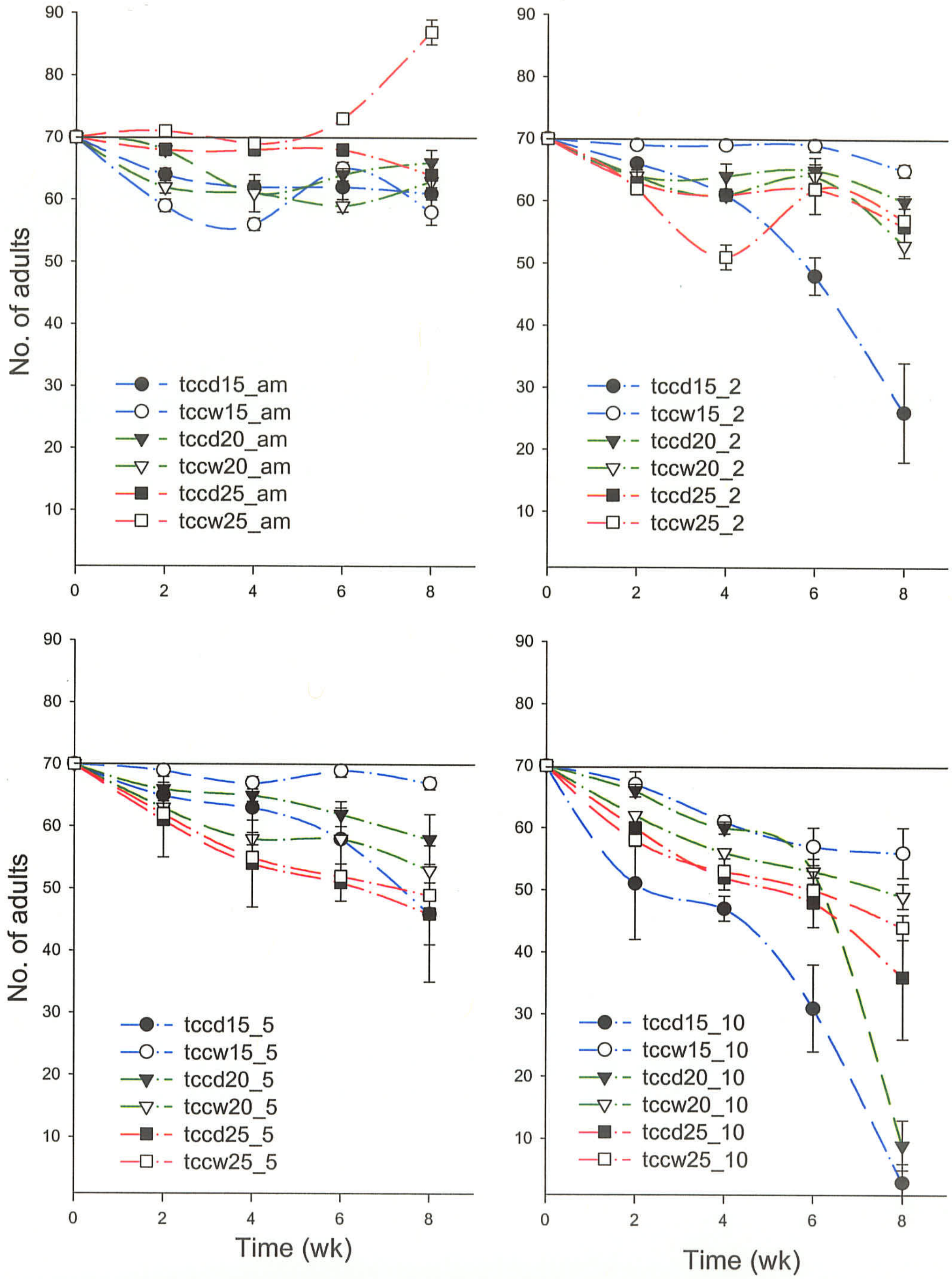


Fig. 5.4 Effect of temperature on mean adult survival (n=4) in mixed-species combination of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2 at selected time intervals. Refer to Fig. 5.1 for explanation of characters in the legend.

at 25°C. A significant ($P < 0.05$) two-way interaction between temperature and CO_2 indicated adult survival increasing with temperature but decreasing with increasing CO_2 levels for both the single and mixed-species combinations (Figs. 5.5 to 5.8). A significant ($P < 0.05$) two way interaction between temperature and species combination also was observed. The adult survival increased with temperature and was higher for single species controls compared to the mixed-species combination (Figs. 5.9 to 5.12). A three way interaction between temperature, CO_2 and exposure time was significant ($P < 0.05$) indicating survival increased with temperature and time but decreasing with increasing CO_2 levels. Similarly, a four way interaction of temperature with CO_2, moisture content, and time was also significant ($P < 0.05$), indicating adult survival increasing with temperature and time but decreasing with increasing CO_2 levels with higher adult survival in wet grains (15% wb) compared to dry (12% wb) grains for both the single and mixed-species experiments.

5.4 Effect of Exposure Time on Adult Survival

Procedure MIXED of SAS (SAS 2000) was used to test the effect of exposure intervals of 2, 4, 6, and 8 weeks on adult survival of two species compared to the initial adult population of 70 adults for all the treatments. The upper and lower confidence limits (at 95%) of LSMEANS of adult survival at time intervals of 2, 4, 6, and 8 wk were compared with the initial population to analyze the effect of exposure time intervals on the adult survival. The test of effect SLICES (F test) using the procedure MIXED was used to compare mean adult survival at four exposure intervals for all CO_2 levels and temperatures and is shown in Tables 5.13 to 5.16, for single and mixed-species combinations for both the species in dry and wet grain. The analysis showed that exposure time had significant ($P < 0.05$) effect

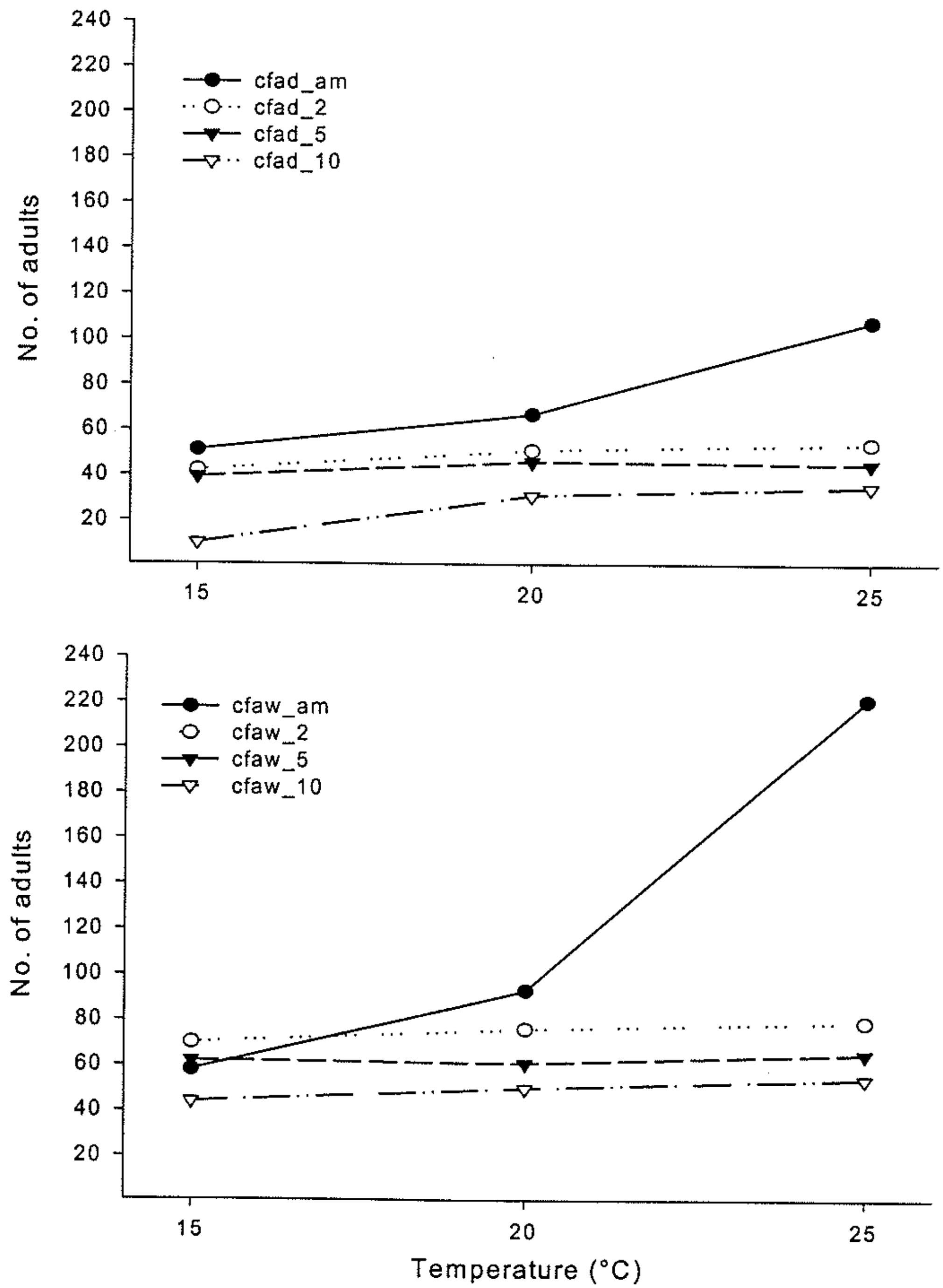


Fig. 5.5 The effect of 2-way interaction between temperature and CO_2 levels on mean adult survival (n=4) in single-species controls of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain at various temperatures. Refer to Fig. 5.1 for explanation of characters in the legend.

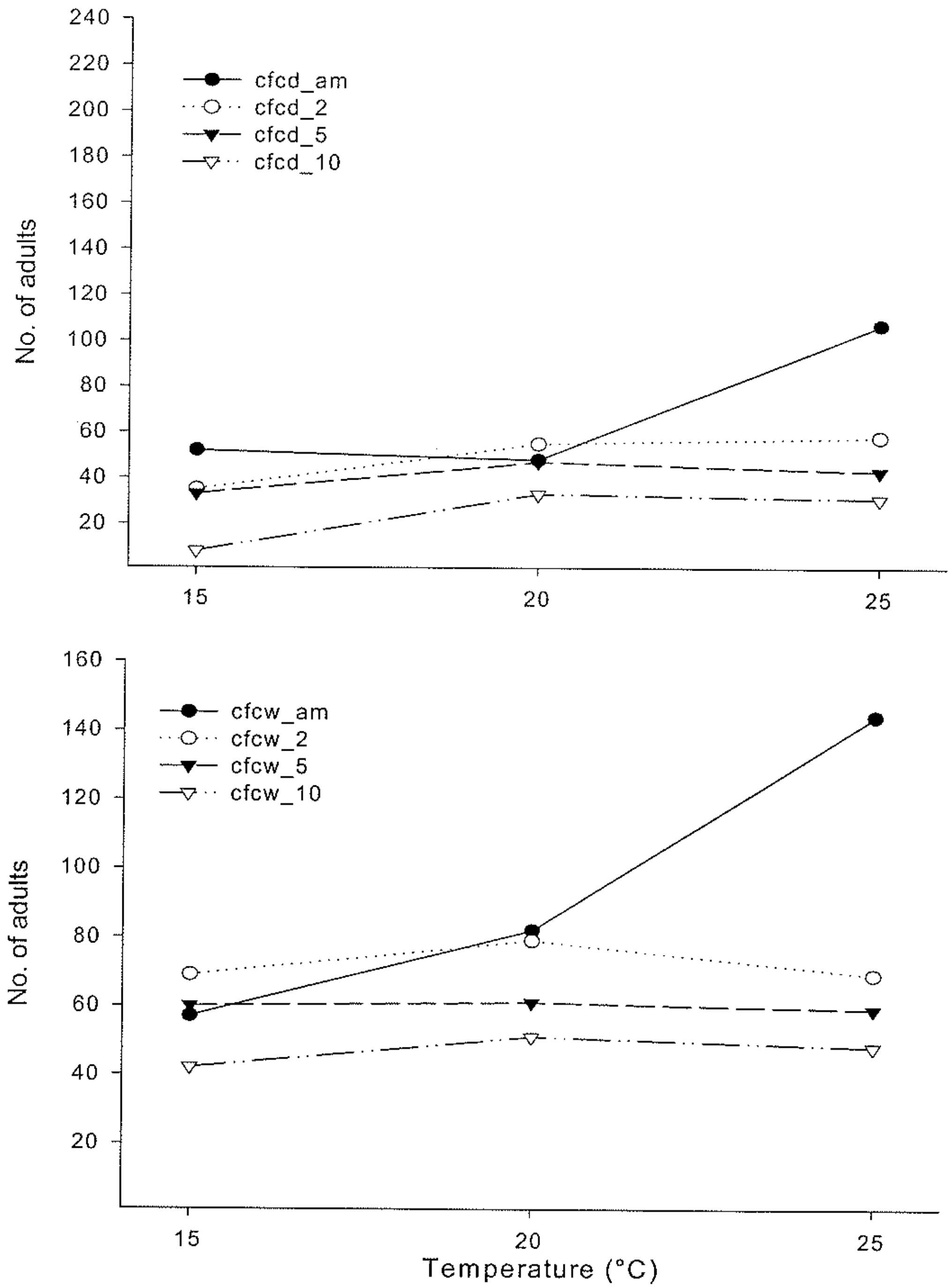


Fig. 5.6 The effect of 2-way interaction between temperature and CO_2 levels on mean adult survival (n=4) in mixed-species combination of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain at various temperatures. Refer to Fig. 5.1 for explanation of characters in the legend.

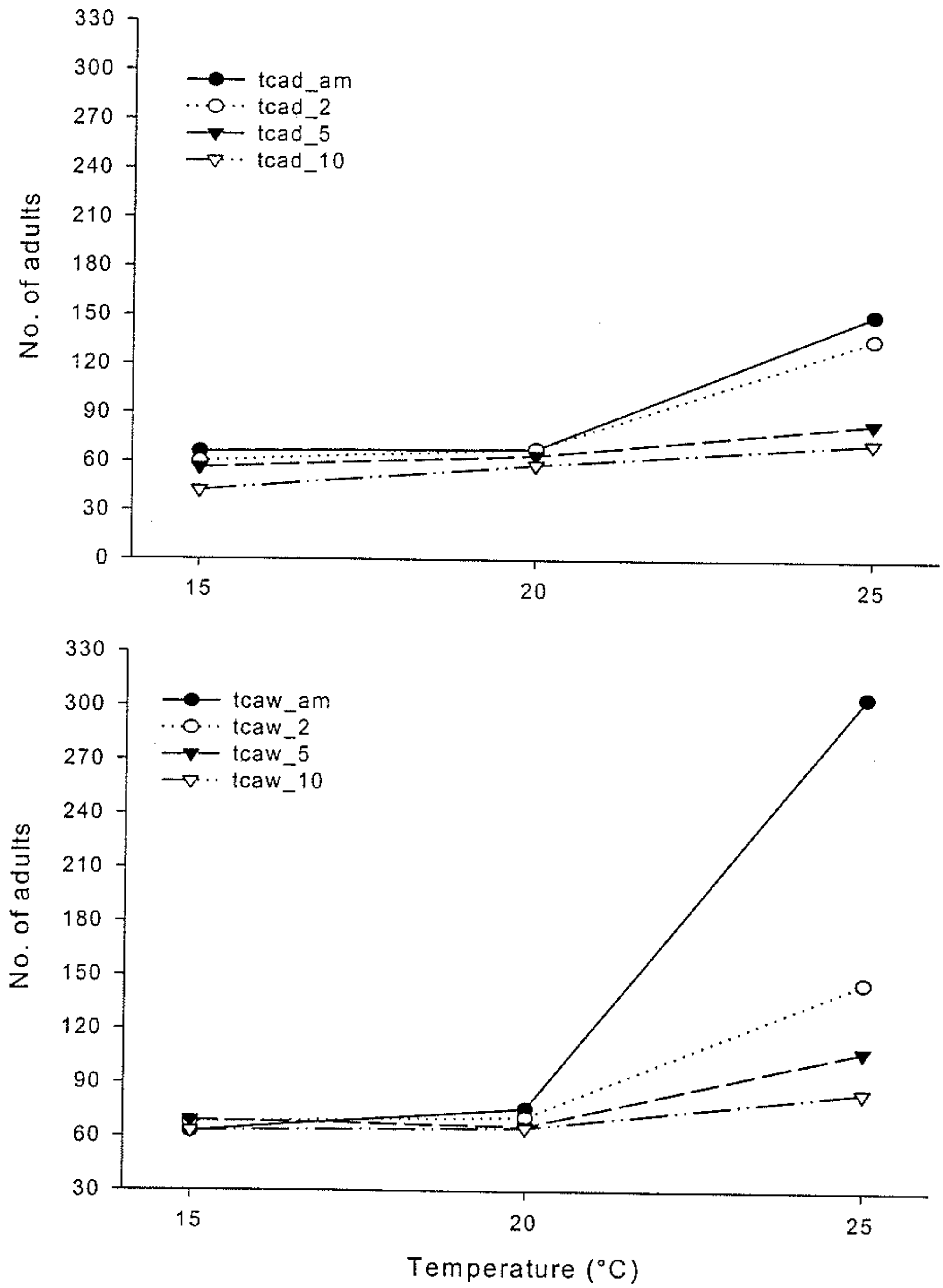


Fig. 5.7 The effect of 2-way interaction between temperature and CO_2 levels on mean adult survival (n=4) in single-species controls of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at various temperatures. Refer to Fig. 5.1 for explanation of characters in the legend.

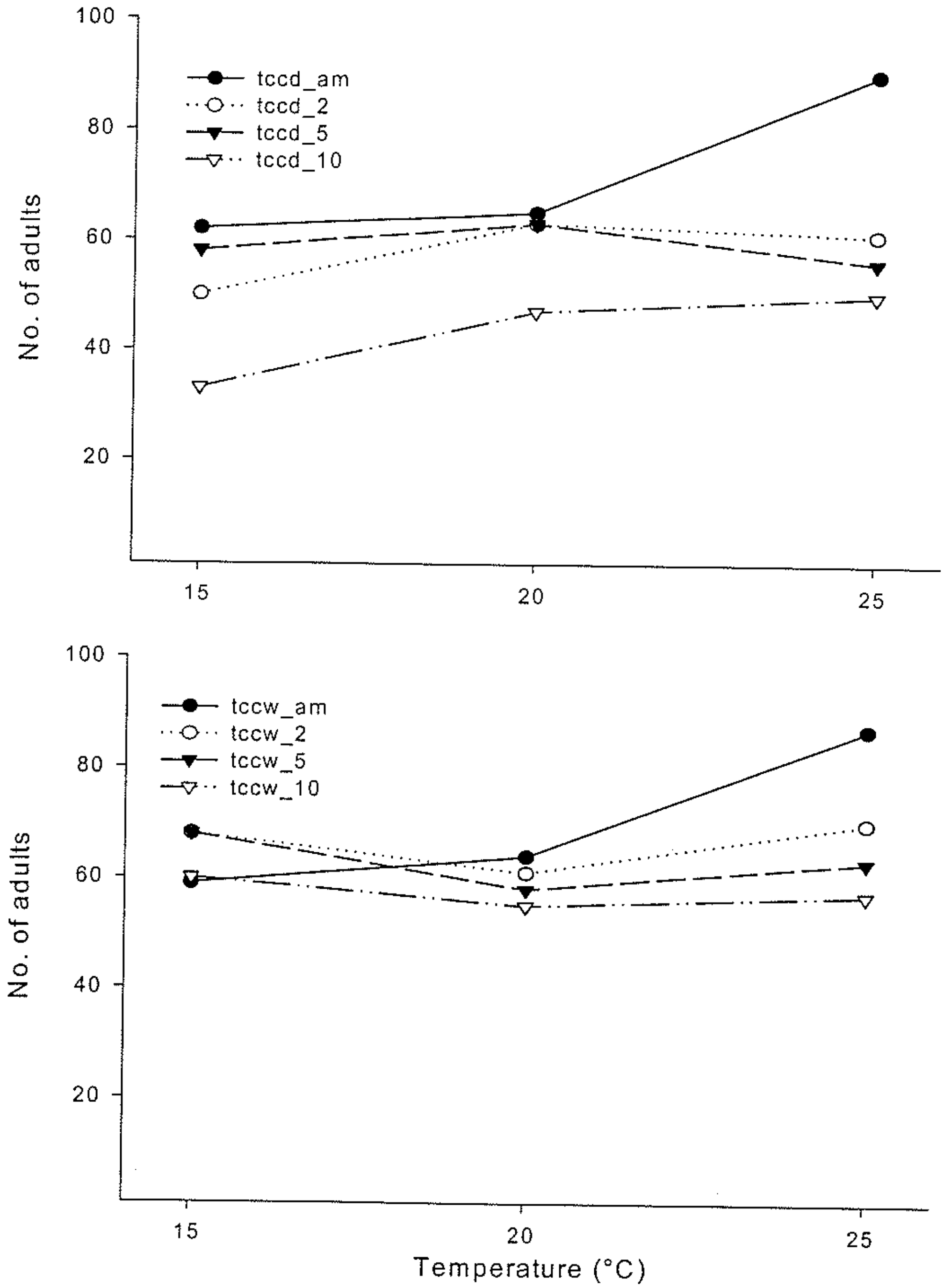


Fig. 5.8 The effect of 2-way interaction between temperature and CO_2 levels on mean adult survival (n=4) in mixed-species combination of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at various temperatures. Refer to Fig. 5.1 for explanation of characters in the legend.

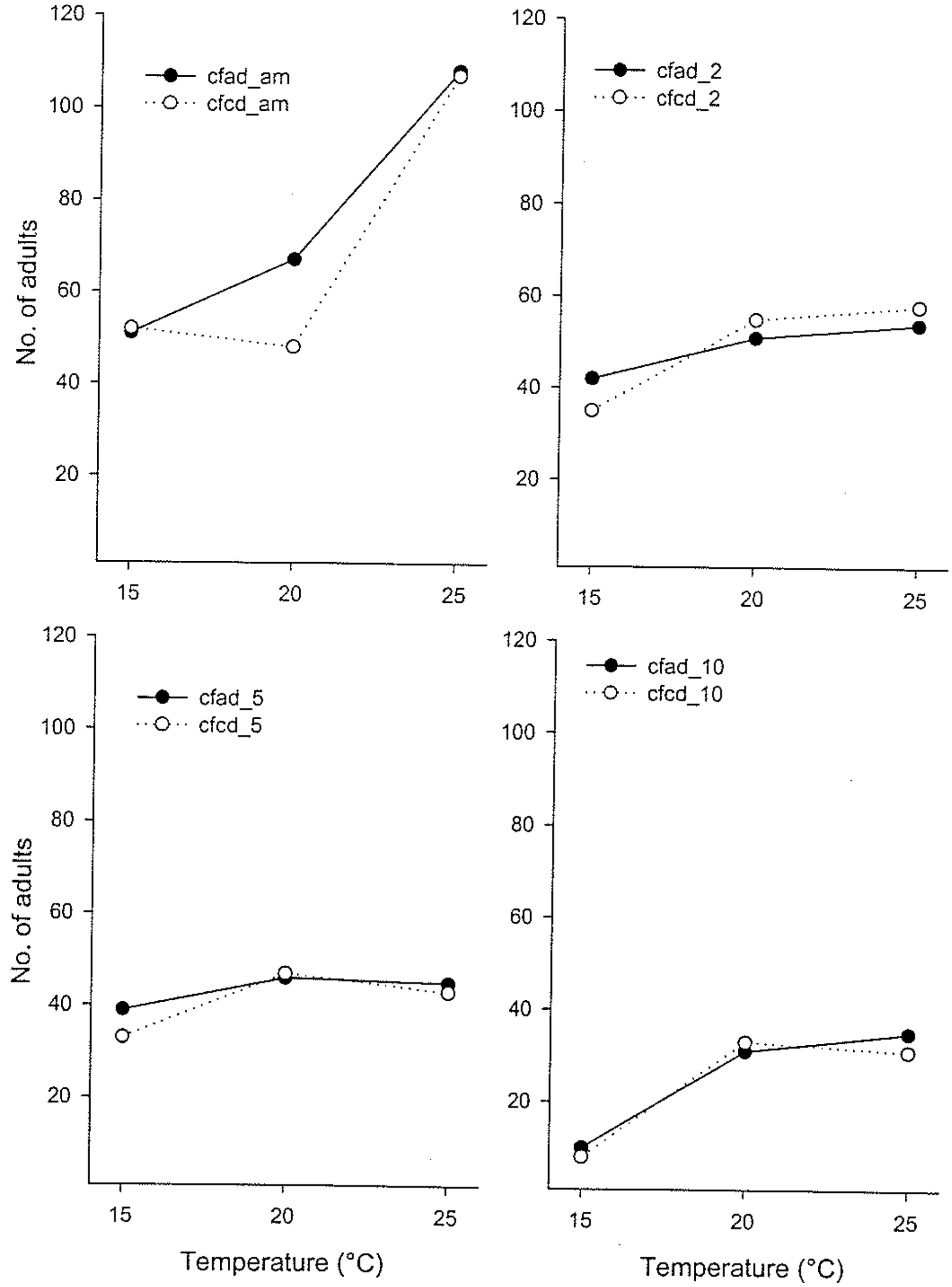


Fig. 5.9 The effect of 2-way interaction between temperature and species combination on the mean adult survival (n=4) in single and mixed-species experiments of *Cryptolestes ferrugineus* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

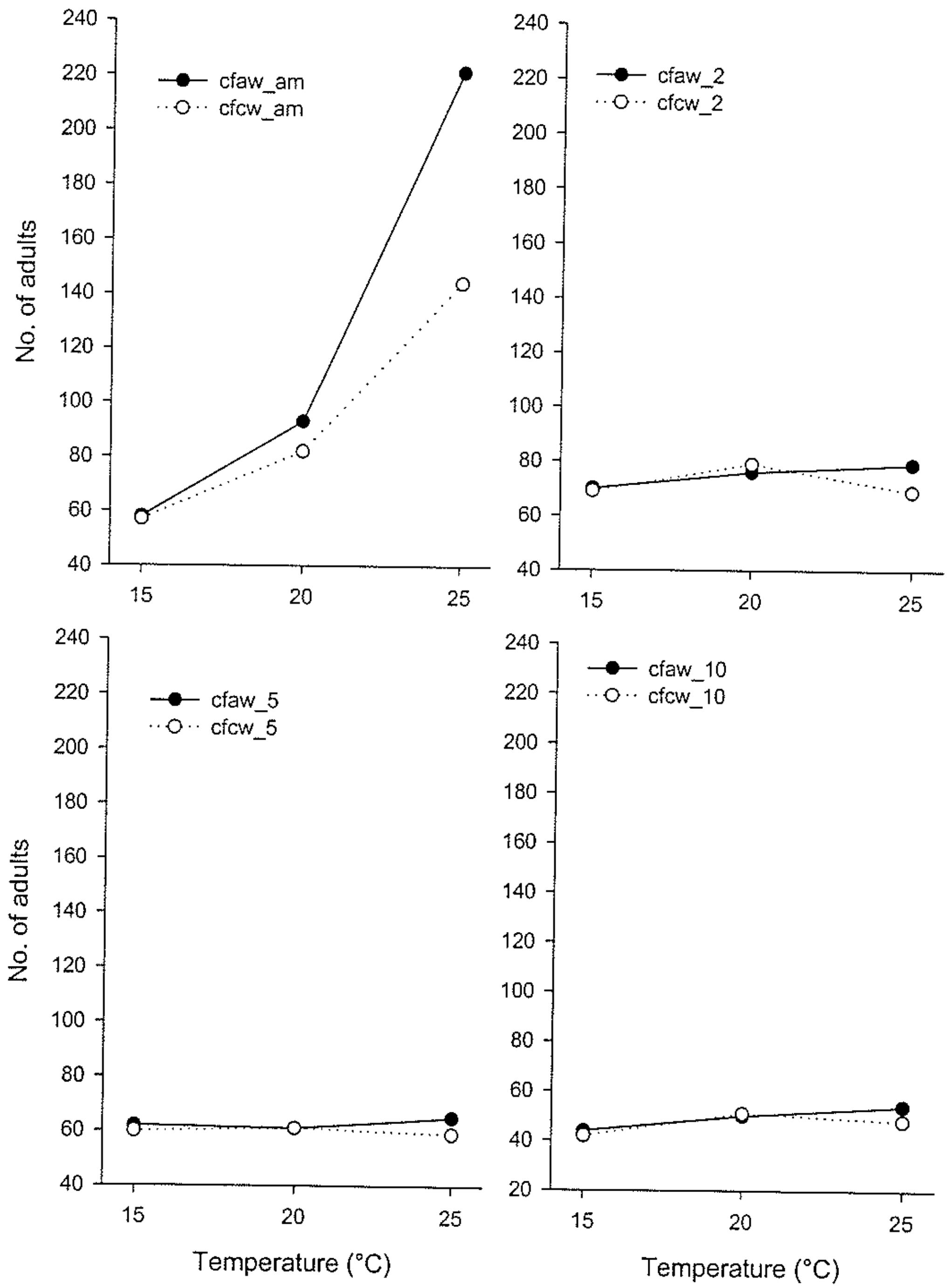


Fig. 5.10 The effect of 2-way interaction between temperature and species combination on the mean adult survival (n=4) in single and mixed-species experiments of *Cryptolestes ferrugineus* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

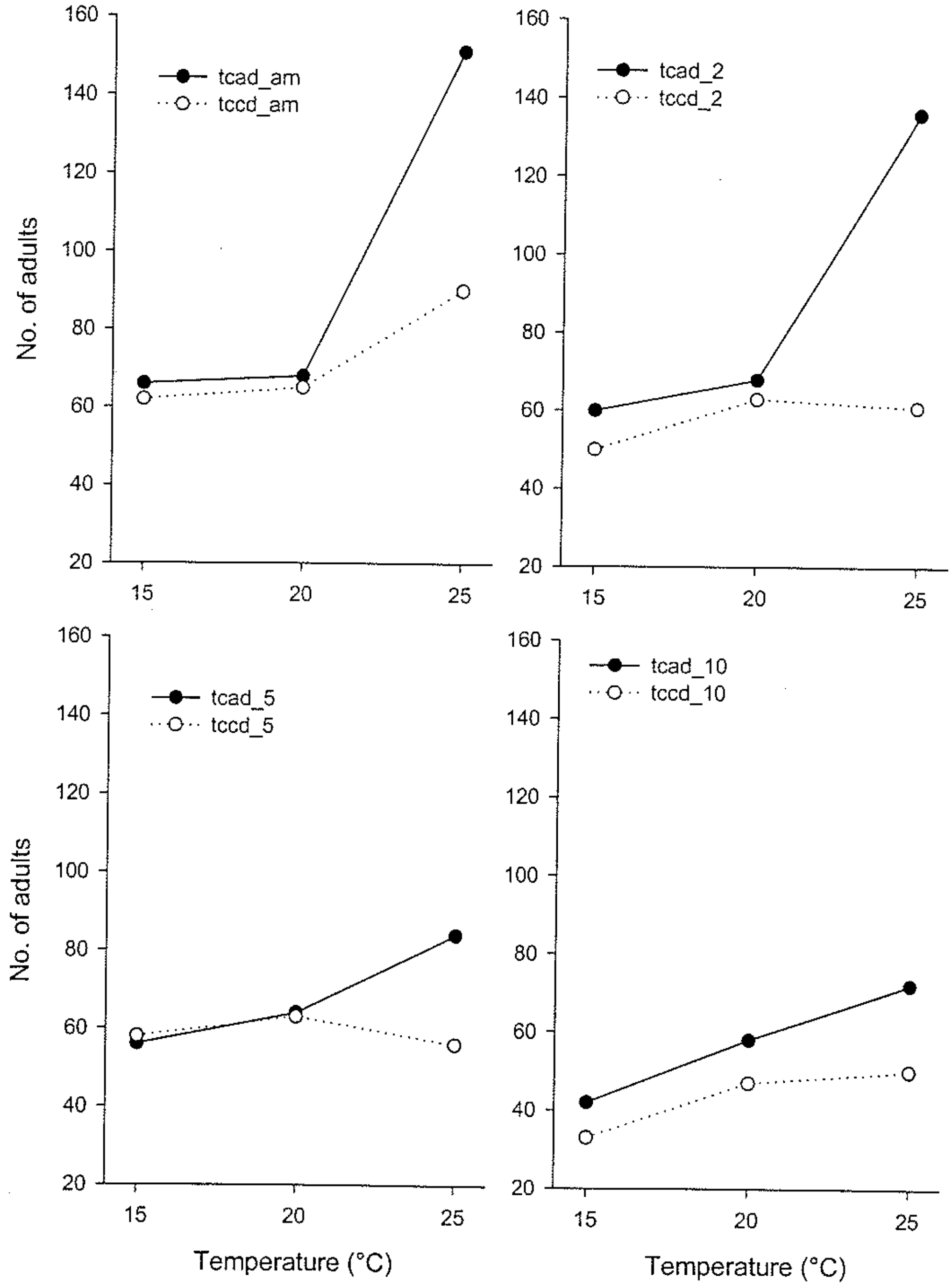


Fig. 5.11 The effect of 2-way interaction between temperature and species combination on the mean adult survival (n=4) in single and mixed-species experiments of *Tribolium castaneum* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

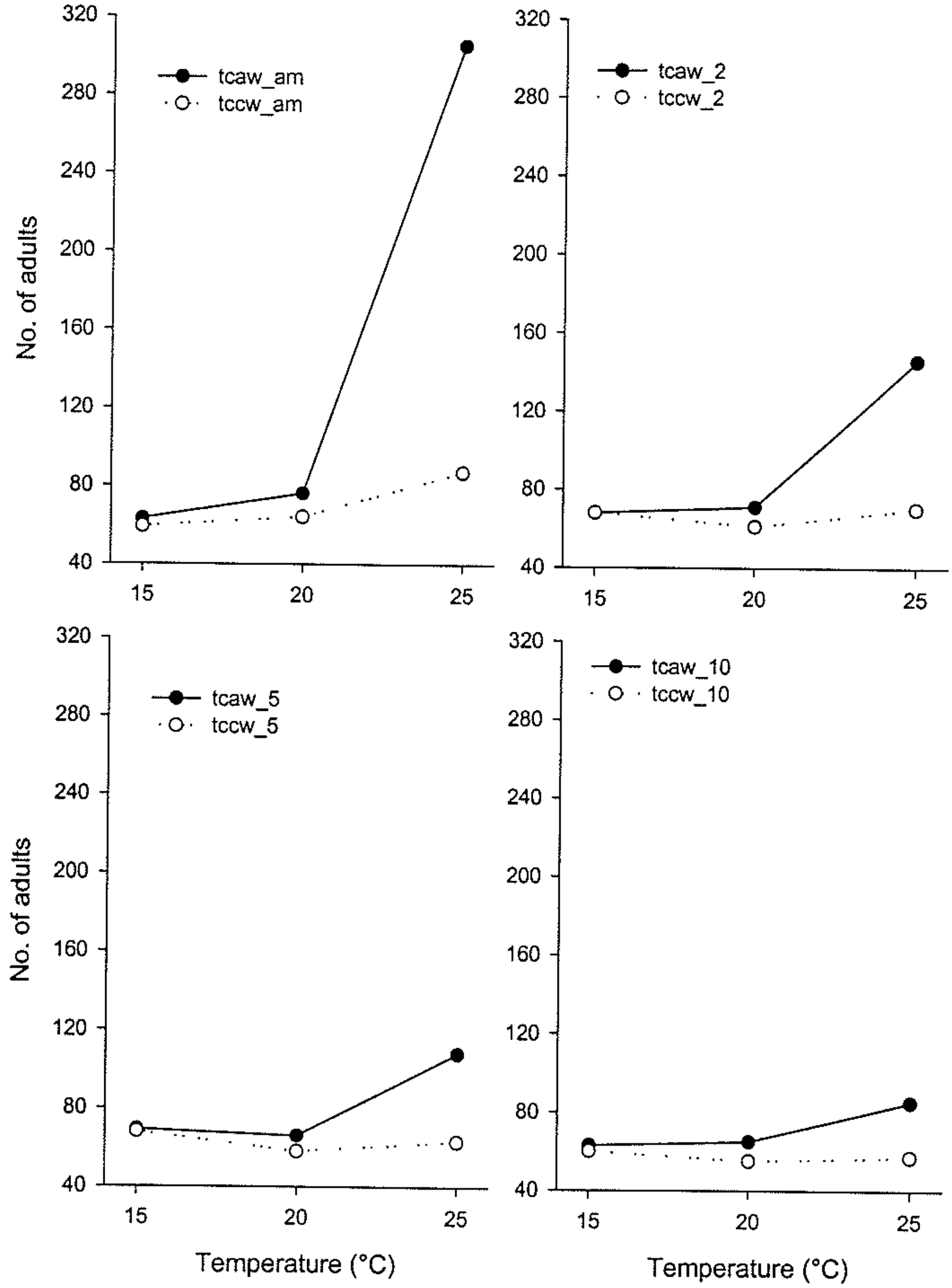


Fig. 5.12 The effect of 2-way interaction between temperature and species combination on the mean adult survival (n=4) in single and mixed-species experiments of *Tribolium castaneum* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

Table 5.13 Effect of exposure time on the mean adult survival (first and incubation counts) in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2.

Temp (°C)	Exposure time (wk)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
15	0	70	70	70	70	70 a	70 c	70 e	70 h
	2	60	59	55	26	67 a	67 c	66 e	64 h
	4	58	44	39	10	66 a	65	53	51
	6	45	35	31	5	64	58	56	51
	8	42	31	33	2	65	52	51	1
20	0	70 a	70	70	70	70 b	70 d	70 f	70
	2	72 a	58	57	46	70 b	67 d	65 f	64
	4	69 a	55	47	37	74 b	66 d	66 f	64
	6	68 a	47	42	22	68 b	67 d	63	60
	8	59	42	38	18	61	71 d	63	42
25	0	70	70	70	70	70	70	70 g	70 i
	2	87	60	51	40	136	135	90	84
	4	124	58	43	34	138	136	78 g	70 i
	6	107	51	46	36	136	137	101	79
	8	115	48	41	28	193	137	68 g	55

The means of adult survival represented by the same letter in the same column are not significantly different (Student's t-test, α=0.05).

Table 5.14 Effect of exposure time on the mean adult survival (first and incubation counts) in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2.

Temp (°C)	Exposure time (wk)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
15	0	70	70 a	70	70	70 a	70 c	70 e	70 g
	2	63	70 a	65	53	60	69 c	69 e	66 g
	4	62	69 a	58	58	66 a	69 c	71 e	63
	6	54	68 a	60	33	65	67 c	70 e	62
	8	55	72	64	31	62	67 c	67 e	61
20	0	70	70 b	70 d	70 f	70 b	70 d	70 f	70 h
	2	80	78 b	69 d	63 f	92	75 d	67 f	74 h
	4	109	98	64 d	51	74 b	66 d	64 f	61
	6	104	77 b	62 d	48	72 b	69 d	65 f	62
	8	79	53	48	39	69 b	74 d	66 f	63
25	0	70	70 c	70 e	70 g	70	70	70	70 i
	2	125	90	73 e	64 g	151	109	96	86
	4	258	96	82	63 g	289	142	112	97
	6	268	73 c	59	46	392	169	117	83
	8	232	55	47	42	389	163	107	74 i

The means of adult survival represented by the same letter in the same column are not significantly different (Student's t-test, α=0.05).

Table 5.15 Effect of exposure time on the mean adult survival (first and incubation counts) in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2.

Temp (°C)	Exposure time (wk)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
15	0	70 a	70 d	70	70	70 a	70 c	70 e	70
	2	62 a	61 d	56	26	64 a	66 c	65 e	51
	4	56	44	37	5	62 a	61	63 e	47
	6	48	23	19	2	62 a	48	58	31
	8	42	11	18	1	61	26	46	3
20	0	70 b	70 e	70	70	70 b	70 d	70 f	70 h
	2	65 b	56 e	57	43	70	64 d	66 f	66 h
	4	53	65 e	52	32	61	64 d	65 f	60
	6	34	54 e	42	33	64 b	65 d	62	53
	8	40	45	37	26	66	60	58	9
25	0	70 c	70 f	70	70	70	70	70 g	70 i
	2	80 c	75 f	53	38	90	64	62 g	63 i
	4	110	63 f	37	24	81	61	61	54
	6	146	60	39	35	104	62	51	50
	8	91	34	43	27	84	56	50	36

The means of adult survival represented by the same letter in the same column are not significantly different (Student's t-test, α=0.05).

Table 5.16 Effect of exposure time on the mean adult survival (first and incubation counts) in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2.

Temp (°C)	Exposure time (wk)	*C. ferrugineus*				*T. castaneum*			
		CO_2 levels (%)				CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
15	0	70 a	70 c	70 f	70	70 a	70 c	70 f	70 h
	2	55	69 c	66 f	58	59	69 c	69 f	67 h
	4	63 a	70 c	58	43	56	69 c	67 f	61
	6	61	70 c	58	32	65 a	69 c	69 f	57
	8	49	69	59	34	58	65 c	67 f	56
20	0	70 b	70 d	70 g	70 i	70 b	70 d	70	70
	2	77 b	78 d	73 g	64 i	70 b	65 d	63	63
	4	85	89	56	46	63	61	58	56
	6	88	96	69 g	52	59	65 d	58	53
	8	77 b	55	46	42	63	53	53	49
25	0	70	70 e	70 h	70	70	70 e	70 g	70 i
	2	100	82	69 h	60	90	72 e	69 g	64 i
	4	156	79 e	71 h	55	83	63 e	66 g	59
	6	165	51	45	43	84	81	65 g	57
	8	155	64 e	52	32	92	63	53	49

The means of adult survival represented by the same letter in the same column are not significantly different (Student's t-test, α=0.05).

on mean adult survival of both species in single and mixed-species experiments in dry and wet grain in various treatments.

5.5 Effect of Relative Humidity

5.5.1 Single and mixed-species controls

Grain moisture content determines the ERH of the stored-grain environment and the RH affects the water content of the insect body. Insects exposed to low RH can loose water by dessication resulting in reduced survival, or death may occur if the RH is too high (Bursell 1970).

In all the experimental tests with single species controls of both the species, the effect of moisture content was highly significant ($P < 0.05$) at all the levels of CO_2 and temperatures. The t tests showed that the effect of moisture content on the mean adult survival was significant ($P < 0.05$) at all the levels of CO_2. The adult survival at all temperatures was higher at higher moisture content (15% wb) compared to low moisture content (12% wb) and decreased with an increase in CO_2 levels for both the species in single and mixed-species combinations (Tables 5.17 and 5.18). For both the species in single and mixed-species combinations, the mean adult survival was higher at 15% (wb) compared to 12% (wb) for all levels of CO_2 at all temperatures (Appendix A, Figs. A17 to A28).

The mean adult survival of *T. castaneum* was significantly ($P < 0.05$) higher than that of *C. ferrugineus* at low moisture content (12% wb) for both the single and mixed-species combinations at all CO_2 levels indicating higher tolerance of *T. castaneum* to lower humidity except at ambient CO_2 level in mixed-species combination (Tables 5.17 and 5.18). However, the comparison of mean adult survival of *T. castaneum* in single and mixed-species

Table 5.17 Effect of relative humidity on the mean adult survival (first and incubation counts) in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03		2		5		10		*T. castaneum* CO_2 levels (%) 0.03		2		5		10	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
2	15	60	63	59	70	55	65	26	53	67	60	67	69	66	69	64	66
	20	72	80	58	78	57	69	46	63	70	92	67	75	65	67	64	74
	25	87	125	60	90	51	73	40	64	136	151	135	109	90	96	84	86
4	15	58	62	44	69	39	58	10	58	66	66	65	69	53	71	51	63
	20	69	109	55	98	47	64	37	51	74	74	66	66	66	64	64	61
	25	124	258	58	96	43	82	34	63	138	289	136	142	78	112	70	97
6	15	45	54	35	68	31	60	5	33	64	65	58	67	56	70	51	62
	20	68	104	47	77	42	62	22	48	68	72	67	69	63	65	60	62
	25	107	268	51	73	46	59	36	46	136	392	137	169	101	117	79	83
8	15	42	55	31	72	33	64	2	31	65	62	52	67	51	67	1	61
	20	59	79	42	53	38	48	18	39	61	69	71	74	63	66	42	63
	25	115	232	48	55	41	47	28	42	193	389	137	163	68	107	55	74
Mean of all wk	15	51	58	42	70	39	62	10	44	66	63	60	68	56	69	42	63
	20	67	93	51	76	46	61	31	50	68	76	68	71	64	66	58	65
	25	108	221	54	79	45	65	35	54	151	305	136	146	84	108	72	85

Table 5.18 Effect of relative humidity on the mean adult survival (first and incubation counts) in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*								*T. castaneum*							
		CO_2 levels (%)								CO_2 levels (%)							
		0.03		2		5		10		0.03		2		5		10	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
2	15	62	55	61	69	56	66	26	58	64	59	66	69	65	69	51	67
	20	65	77	56	78	57	73	43	64	70	70	64	65	66	63	66	63
	25	80	100	75	82	53	69	38	60	90	90	64	72	62	69	63	64
4	15	56	63	44	70	37	58	5	43	62	56	61	69	63	67	47	61
	20	53	85	65	89	52	56	32	46	61	63	64	61	65	58	60	56
	25	110	156	63	79	37	71	24	55	81	83	61	63	61	66	54	59
6	15	48	61	23	70	19	58	2	32	62	65	48	69	58	69	31	57
	20	34	88	54	96	42	69	33	52	64	59	65	65	62	58	53	53
	25	146	165	60	51	39	45	35	43	104	84	62	81	51	65	50	57
8	15	42	49	11	69	18	59	1	34	61	58	26	65	46	67	3	56
	20	40	77	45	55	37	46	26	42	66	63	60	53	58	53	9	49
	25	91	155	34	64	43	52	27	32	84	92	56	63	50	53	36	49
Mean of all wk	15	52	57	35	69	33	60	8	42	62	59	50	68	58	68	33	60
	20	48	82	55	79	47	61	33	51	65	64	63	61	63	58	47	55
	25	107	144	58	69	43	59	31	48	90	87	61	70	56	63	50	57

combination revealed that adult population was significantly lower when *T. castaneum* was with *C. ferrugineus* compared to being alone. This aspect has been dealt with in the subsequent section.

There was significant ($P < 0.05$) interaction between moisture content and temperature as discussed earlier and also a significant interaction with CO_2 levels. The significant effect of moisture content on adult survival which is also a two way interaction effect between temperature and moisture content is demonstrated graphically in Figs. 5.13 to 5.16. Generally, the adult survival in single and mixed-species combinations was higher in wet grain (15% wb) than in dry grain (12% wb) and increased with temperature.

5.6 Effect of CO_2 Concentration

5.6.1 Single species controls

The effect of CO_2 was highly significant ($P < 0.05$) in all the treatments for the single species control populations of both the species. At all temperature levels and moisture contents (dry and wet grains at 12 and 15% wb, respectively), the effect of CO_2 was highly significant ($P < 0.05$) compared to ambient level of CO_2. The adult survival in dry and wet grains for both the species at constant temperatures and four CO_2 levels is graphically represented in Appendix A (Figs. A29 to A32). In single-species controls of both the species at all temperatures, generally the adult survival decreased with increasing CO_2 levels compared to the ambient CO_2 levels over the observation period as shown in Tables 5.19 and 5.20 for dry and wet grain, respectively. However, an exception was single-species control of *C. ferrugineus* and *T. castaneum* at 15 °C in wet grain (Table 5.20, Appendix A (Figs. A30 and A32)) in which the adult number at the 2% CO_2 level was higher than at the ambient

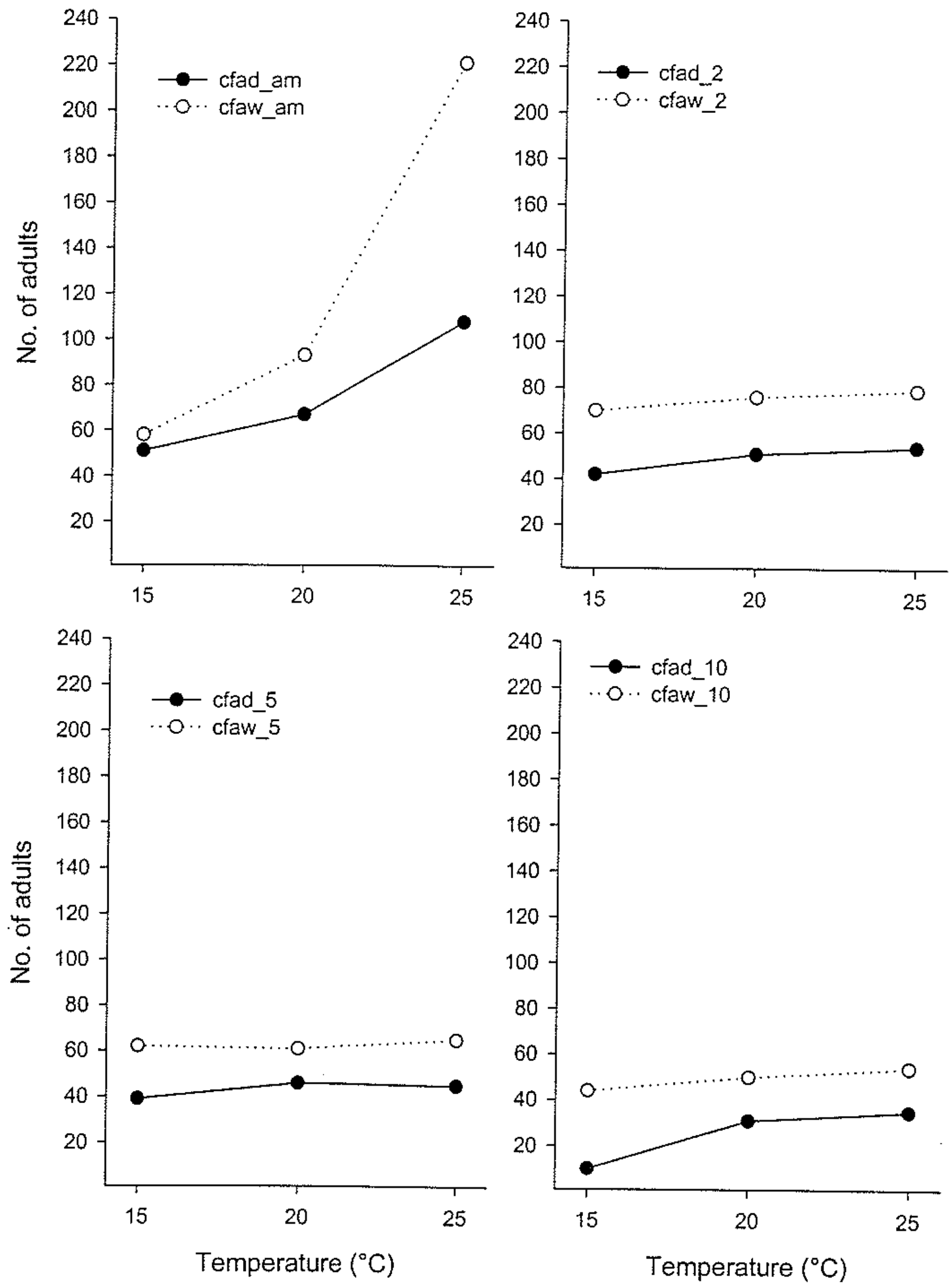


Fig. 5.13 The effect of 2-way interaction between temperature and moisture content on the mean adult survival (n=4) in single species controls of *Cryptolestes ferrugineus* at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

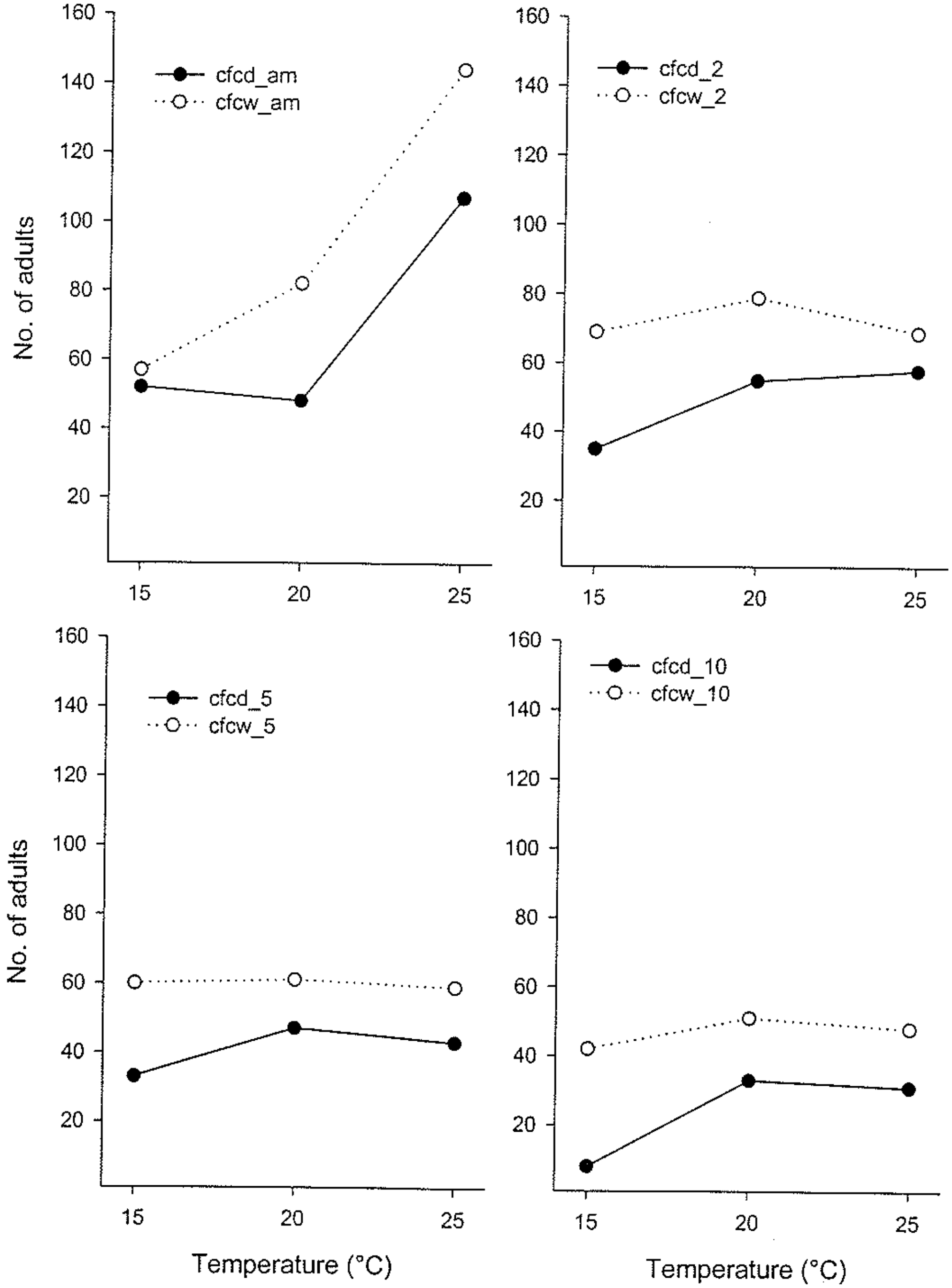


Fig. 5.14 The effect of 2-way interaction between temperature and moisture content on the mean adult survival (n=4) in mixed-species combination of *Cryptolestes ferrugineus* at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

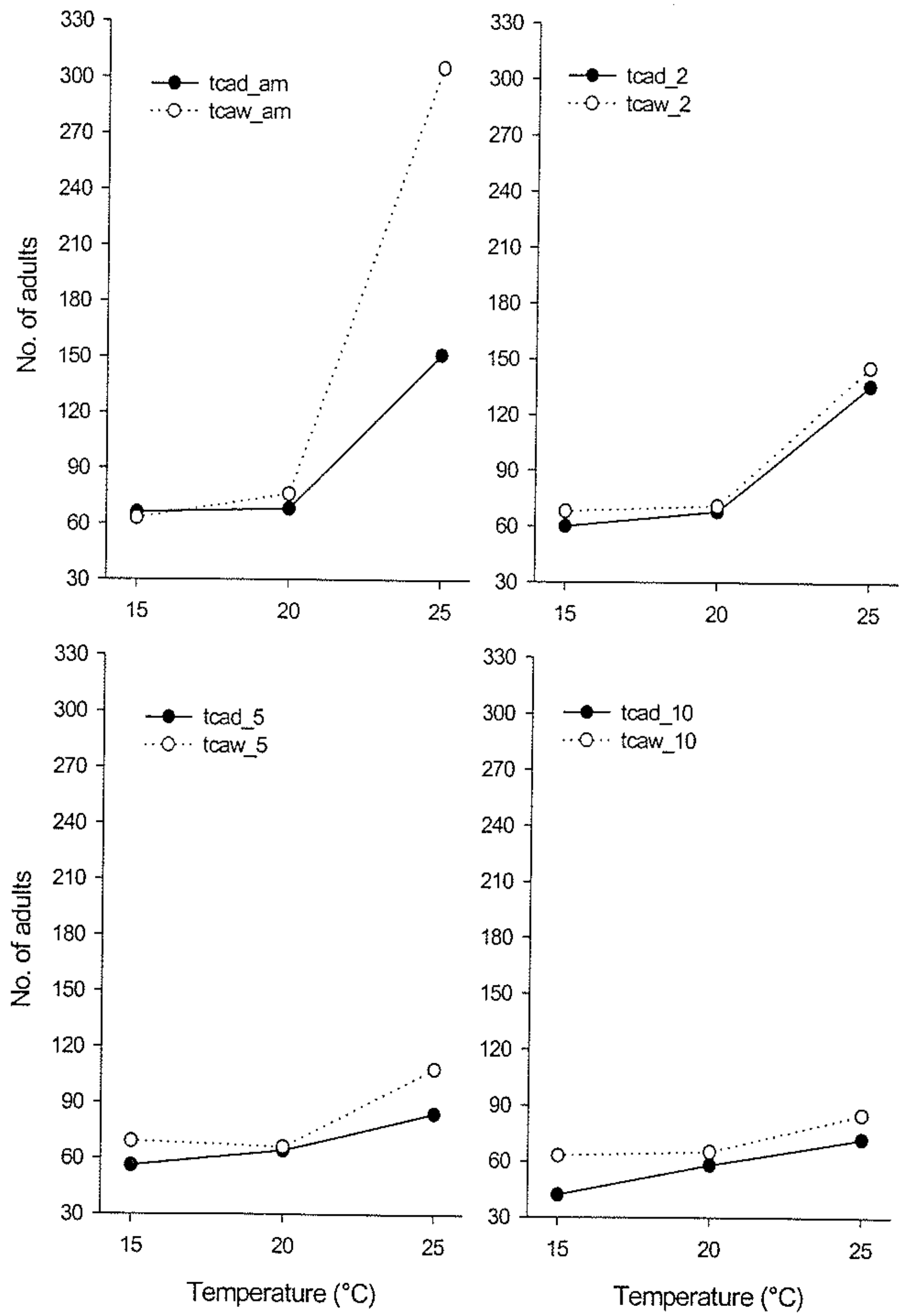


Fig. 5.15 The effect of 2-way interaction between temperature and moisture content on the mean adult survival (n=4) in single species controls of *Tribolium castaneum* at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

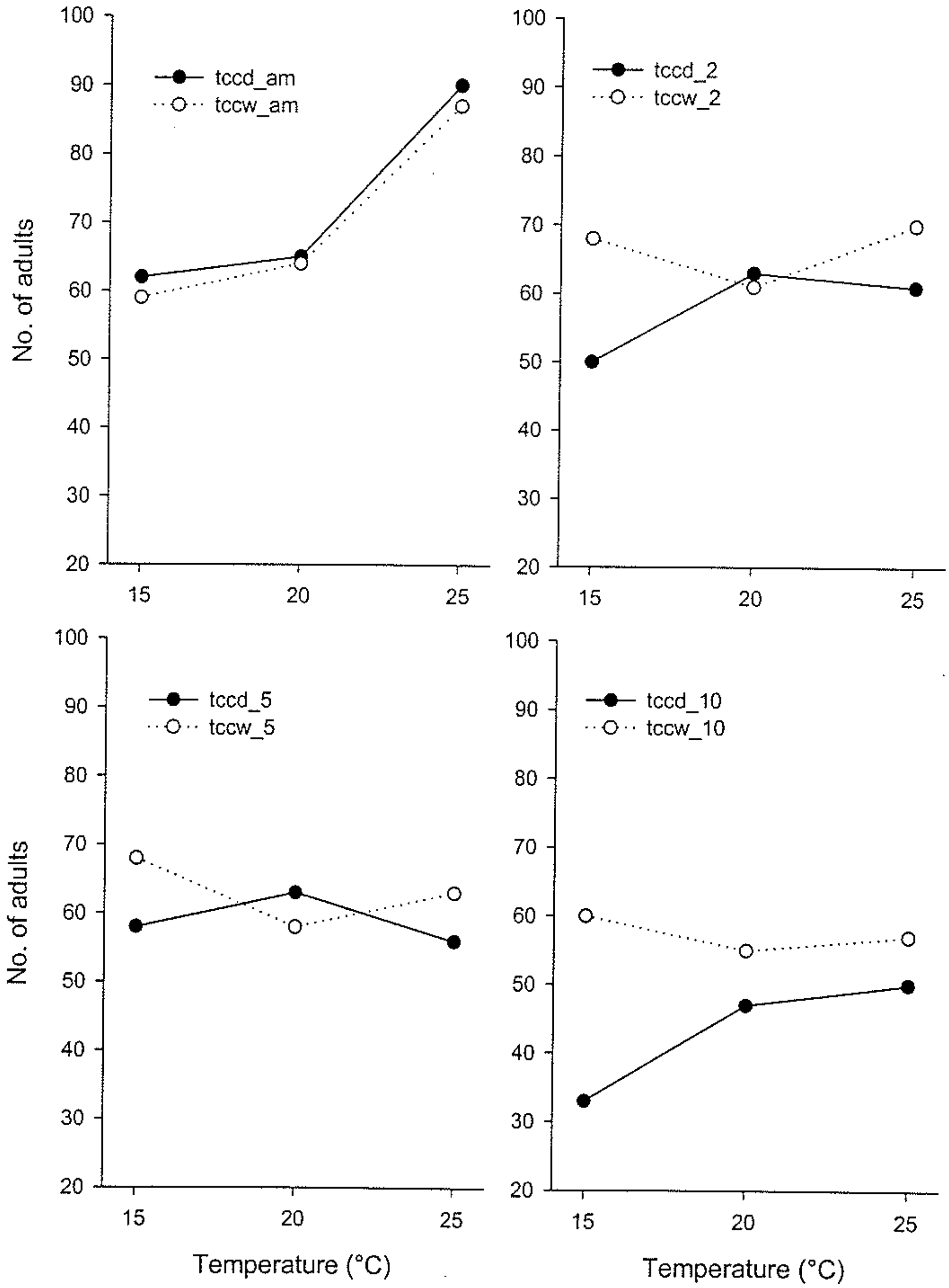


Fig. 5.16 The effect of 2-way interaction between temperature and moisture content on the mean adult survival (n=4) in mixed-species combination of *Tribolium castaneum* at ambient (am), 2, 5, and 10% levels of CO_2. Refer to Fig. 5.1 for explanation of characters in the legend.

Table 5.19 Effect of CO_2 on the mean adult survival (first and incubation counts) in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2, at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15	20	25	*T. castaneum* Temperature (°C) 15	20	25
2	0.03	60 ± 1*	72 ± 2	87 ± 2	67 ± 1	70 ± 5	136 ± 1
	2	59 ± 1	58 ± 1	60 ± 5	67 ± 1	67 ± 2	135 ± 1
	5	55 ± 2	57 ± 2	51 ± 8	66 ± 1	65 ± 0	90 ± 1
	10	26 ± 2	46 ± 2	40 ± 3	64 ± 3	64 ± 1	84 ± 6
4	0.03	58 ± 1	69 ± 3	124 ± 7	66 ± 0	74 ± 1	138 ± 6
	2	44 ± 3	55 ± 1	58 ± 6	65 ± 1	66 ± 1	136 ± 19
	5	39 ± 1	47 ± 2	43 ± 6	53 ± 3	66 ± 1	78 ± 13
	10	10 ± 2	37 ± 2	34 ± 5	51 ± 3	64 ± 1	70 ± 1
6	0.03	45 ± 3	68 ± 2	107 ± 6	64 ± 1	68 ± 2	136 ± 5
	2	35 ± 3	47 ± 3	51 ± 4	58 ± 1	67 ± 2	137 ± 17
	5	31 ± 2	42 ± 2	46 ± 7	56 ± 0	63 ± 1	101 ± 21
	10	5 ± 2	22 ± 8	36 ± 3	51 ± 4	60 ± 1	79 ± 17
8	0.03	42 ± 3	59 ± 3	115 ± 12	65 ± 0	61 ± 5	193 ± 15
	2	31 ± 2	42 ± 6	48 ± 2	52 ± 2	71 ± 2	137 ± 20
	5	33 ± 2	38 ± 4	41 ± 10	51 ± 1	63 ± 1	68 ± 1
	10	2 ± 1	18 ± 3	28 ± 2	1 ± 1	42 ± 4	55 ± 2

* Standard error based on n=4.

Table 5.20 Effect of CO_2 on the mean adult survival (first and incubation counts) in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2, at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15	20	25	*T. castaneum* Temperature (°C) 15	20	25
2	0.03	63 ± 3	80 ± 1	125 ± 2	60 ± 1	92 ± 5	151 ± 3
	2	70 ± 0	78 ± 1	90 ± 14	69 ± 1	75 ± 2	109 ± 14
	5	65 ± 0	69 ± 1	73 ± 3	69 ± 0	67 ± 0	96 ± 2
	10	53 ± 2	63 ± 3	64 ± 3	66 ± 3	74 ± 3	86 ± 2
4	0.03	62 ± 3	109 ± 2	258 ± 9	66 ± 1	74 ± 2	289 ± 15
	2	69 ± 0	98 ± 4	96 ± 6	69 ± 0	66 ± 1	142 ± 13
	5	58 ± 3	64 ± 3	82 ± 3	71 ± 1	64 ± 1	112 ± 4
	10	58 ± 1	51 ± 1	63 ± 2	63 ± 1	61 ± 0	97 ± 2
6	0.03	54 ± 4	104 ± 10	268 ± 8	65 ± 1	72 ± 2	392 ± 14
	2	68 ± 2	77 ± 3	73 ± 4	67 ± 1	69 ± 2	169 ± 22
	5	60 ± 2	62 ± 4	59 ± 4	70 ± 1	65 ± 1	117 ± 22
	10	33 ± 2	48 ± 2	46 ± 3	62 ± 2	62 ± 5	83 ± 2
8	0.03	55 ± 2	79 ± 2	232 ± 10	62 ± 2	69 ± 1	389 ± 10
	2	72 ± 2	53 ± 3	55 ± 5	67 ± 1	74 ± 5	163 ± 33
	5	64 ± 1	48 ± 1	47 ± 2	67 ± 1	66 ± 0	107 ± 2
	10	31 ± 2	39 ± 1	42 ± 1	61 ± 2	63 ± 4	74 ± 4

* Standard error based on n=4.

level of CO_2. The variation could be due to an experimental error or a biological variation due to the age variability of the adults in the replicates.

The adults of both species were directly exposed to a constant CO_2 environment throughout the exposure time of the experiment, therefore the first count was analyzed statistically separately for effect of CO_2 at each temperature at 2 wk time intervals over the observation period of 8 wk after eliminating the main effect of moisture content. At 15°C in both dry and wet grain, mean adult survival from first count of *C. ferrugineus* decreased at all CO_2 levels from 2 wk (except at the 2% CO_2 level in wet grain) whereas for *T. castaneum* in dry grain, the mean adult survival from the first count decreased from 4 wk at the 5 and 10% levels of CO_2 and from 6 wk at the 2% level of CO_2 and in wet grain mean adult survival from the first count was not affected at all levels of CO_2 except 10% over the observation period (Tables 5.21 and 5.22). At 20°C in both dry and wet grain, mean adult survival from first count of *C. ferrugineus* decreased with time at all CO_2 levels from 2 wk (except in wet grain at the ambient CO_2 level)but the survival of *T. castaneum* was unaffected at all CO_2 levels for entire exposure period except at 2 and 4 wk onwards at 10% level of CO_2 in dry and wet grain, respectively. At 25°C, in dry grain, mean adult survival from the first count of *C. ferrugineus* decreased with increasing CO_2 levels from 2 wk (except at the ambient CO_2 level) whereas in *T. castaneum* the mean adult survival from the first count increased at the ambient and 2% level of CO_2 and decreased from 4 wk onwards at 5 and 10% levels of CO_2. At 25°C in wet grain, mean adult survival from first count of *C. ferrugineus* decreased with increasing CO_2 levels from 2 wk (except at ambient CO_2 level) whereas in *T. castaneum* the mean adult survival from first count increased at ambient, 2, and 5% CO_2 levels and decreased at the 10% CO_2 level over the temperature range. The

Table 5.21 Effect of CO_2 on the mean adult survival from first count in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C)			*T. castaneum* Temperature (°C)		
		15	20	25	15	20	25
2	0.03	60 ± 1	68 ± 1	67 ± 0	67 ± 1	62 ± 3	69 ± 0
	2	59 ± 1	57 ± 1	46 ± 2	67 ± 1	64 ± 1	67 ± 2
	5	55 ± 2	56 ± 2	42 ± 7	66 ± 1	64 ± 0	68 ± 0
	10	26 ± 2	46 ± 2	38 ± 3	63 ± 3	62 ± 1	69 ± 0
4	0.03	58 ± 1	62 ± 3	65 ± 1	66 ± 0	62 ± 3	68 ± 1
	2	44 ± 3	54 ± 1	39 ± 2	65 ± 1	64 ± 2	64 ± 1
	5	39 ± 1	46 ± 2	31 ± 7	53 ± 3	65 ± 1	58 ± 5
	10	10 ± 2	37 ± 2	26 ± 2	50 ± 4	64 ± 1	58 ± 2
6	0.03	45 ± 3	62 ± 1	63 ± 4	64 ± 1	66 ± 1	76 ± 2
	2	35 ± 3	43 ± 3	41 ± 2	58 ± 1	65 ± 2	74 ± 5
	5	30 ± 2	41 ± 2	39 ± 8	56 ± 0	63 ± 1	59 ± 7
	10	5 ± 2	22 ± 8	32 ± 2	51 ± 4	60 ± 1	57 ± 9
8	0.03	42 ± 3	54 ± 3	66 ± 2	65 ± 0	60 ± 5	131 ± 5
	2	31 ± 2	39 ± 6	44 ± 2	52 ± 2	64 ± 0	119 ± 13
	5	33 ± 2	36 ± 3	30 ± 10	51 ± 1	63 ± 1	51 ± 1
	10	2 ± 1	18 ± 3	24 ± 1	1 ± 1	42 ± 4	41 ± 1

* Standard error based on n=4.

Table 5.22 Effect of CO_2 on the mean adult survival from first count in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15	20	25	*T. castaneum* Temperature (°C) 15	20	25
2	0.03	63 ± 3	71 ± 0	69 ± 0	60 ± 1	68 ± 1	69 ± 1
	2	70 ± 0	66 ± 1	56 ± 3	69 ± 1	68 ± 1	66 ± 1
	5	65 ± 0	64 ± 1	54 ± 3	69 ± 0	64 ± 1	64 ± 1
	10	53 ± 2	61 ± 2	51 ± 2	64 ± 3	68 ± 2	63 ± 2
4	0.03	62 ± 3	71 ± 1	70 ± 0	66 ± 1	67 ± 1	68 ± 0
	2	69 ± 0	56 ± 1	38 ± 2	69 ± 0	65 ± 1	63 ± 1
	5	57 ± 3	54 ± 1	41 ± 1	71 ± 1	63 ± 1	61 ± 1
	10	58 ± 1	50 ± 1	36 ± 3	63 ± 1	61 ± 0	60 ± 0
6	0.03	54 ± 4	71 ± 1	72 ± 1	65 ± 1	68 ± 1	81 ± 2
	2	68 ± 2	54 ± 3	35 ± 5	67 ± 1	65 ± 2	76 ± 2
	5	59 ± 3	51 ± 2	32 ± 1	70 ± 1	65 ± 1	67 ± 1
	10	33 ± 2	47 ± 2	29 ± 2	62 ± 2	62 ± 5	64 ± 2
8	0.03	55 ± 2	70 ± 1	83 ± 1	62 ± 2	68 ± 1	157 ± 7
	2	68 ± 1	46 ± 2	42 ± 4	66 ± 1	64 ± 1	139 ± 23
	5	62 ± 1	42 ± 2	36 ± 1	67 ± 1	66 ± 0	86 ± 1
	10	31 ± 2	39 ± 1	32 ± 1	61 ± 2	63 ± 4	59 ± 3

* Standard error based on n=4.

differential response of two species at various temperatures and CO_2 levels indicated that in both dry and wet grain, *C. ferrugineus* was more susceptible to CO_2 levels compared to *T. castaneum* and survival of *T. castaneum* was reduced in dry grain after prolonged exposure of more than 4 wk at 5 and 10% levels of CO_2 whereas in wet grain only the 10% level of CO_2 reduced adult survival (at 25 °C). The effect of CO_2 in reducing the adult survival was higher at lower moisture content (dry grain) and higher temperature. The mean adult survival from the first count of *T. castaneum* at 20 °C cannot be satisfactorily explained. In dry and wet grain, the adult survival in the first count of *T. castaneum* was higher than the *C. ferrugineus* at all CO_2 levels and temperatures (Tables 5.21 and 5.22) indicating that *T. castaneum* survives due to its greater range of tolerance to humidity and that *C. ferrugineus* is more susceptible to CO_2 levels. Along with the main effect of CO_2, adult survival in the first count of both the species was significantly ($P < 0.05$) affected by interaction of CO_2 with time of exposure as indicated in Appendix A (Figs. A33 to A36).

The effect of CO_2 levels on the adults from incubation was analyzed by square root transformation of the number of adults from incubation data and using the GLM procedure of SAS (SAS 2000). No adults emerged from the incubation count at 15 °C in dry grain for both the species whereas in wet grain at this temperature few adults emerged in *C. ferrugineus* at 2 and 5% levels of CO_2 from 4 wk onwards and there was no adult emergence in *T. castaneum* in wet grain (Tables 5.23 and 5.24). The incubation count at 20 and 25 °C was significantly ($P < 0.05$) affected by CO_2 levels and generally decreased with increasing CO_2 levels in both dry and wet grain. Between the two species, the adult count from incubation in *T. castaneum* was higher at 25 °C compared to *C. ferrugineus* in dry and wet grain wheras at 20 °C *C. ferrugineus* had higher number of adults than *T. castaneum* .

Table 5.23 Effect of CO_2 on the mean adult survival from incubation count in single-species controls of *C. ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C)			*T. castaneum* Temperature (°C)		
		15	20	25	15	20	25
2	0.03	0 ± 0	4 ± 1	20 ± 1	0 ± 0	8 ± 3	67 ± 1
	2	0 ± 0	1 ± 0	15 ± 4	0 ± 0	3 ± 1	69 ± 3
	5	0 ± 0	0 ± 0	9 ± 2	0 ± 0	1 ± 1	22 ± 1
	10	0 ± 0	0 ± 0	2 ± 1	1 ± 1	2 ± 0	15 ± 6
4	0.03	0 ± 0	6 ± 1	59 ± 8	0 ± 0	12 ± 3	70 ± 6
	2	0 ± 0	1 ± 0	19 ± 6	0 ± 0	2 ± 0	72 ± 18
	5	0 ± 0	1 ± 1	12 ± 2	0 ± 0	1 ± 1	20 ± 9
	10	0 ± 0	0 ± 0	9 ± 4	0 ± 0	0 ± 0	12 ± 2
6	0.03	0 ± 0	6 ± 1	44 ± 9	0 ± 0	2 ± 1	60 ± 5
	2	0 ± 0	4 ± 1	10 ± 3	0 ± 0	2 ± 0	63 ± 14
	5	0 ± 0	1 ± 0	7 ± 2	0 ± 0	0 ± 0	42 ± 14
	10	0 ± 0	0 ± 0	5 ± 3	0 ± 0	0 ± 0	22 ± 8
8	0.03	0 ± 0	5 ± 1	49 ± 10	0 ± 0	1 ± 0	62 ± 17
	2	0 ± 0	3 ± 1	4 ± 1	0 ± 0	6 ± 1	18 ± 8
	5	0 ± 0	2 ± 0	11 ± 1	0 ± 0	0 ± 0	17 ± 1
	10	0 ± 0	0 ± 0	4 ± 2	0 ± 0	0 ± 0	14 ± 1

* Standard error based on n=4.

Table 5.24 Effect of CO_2 on the mean adult survival from incubation count in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus*			*T. castaneum*		
		Temperature (°C)			Temperature (°C)		
		15	20	25	15	20	25
2	0.03	0 ± 0	9 ± 1	56 ± 2	0 ± 0	24 ± 4	82 ± 4
	2	0 ± 0	12 ± 1	34 ± 12	0 ± 0	8 ± 2	44 ± 14
	5	0 ± 0	5 ± 1	19 ± 2	0 ± 0	3 ± 0	32 ± 1
	10	0 ± 0	2 ± 1	13 ± 1	2 ± 1	7 ± 2	23 ± 1
4	0.03	0 ± 0	38 ± 2	188 ± 9	0 ± 0	7 ± 2	221 ± 15
	2	1 ± 1	42 ± 4	58 ± 6	0 ± 0	1 ± 0	80 ± 13
	5	1 ± 0	10 ± 1	41 ± 2	0 ± 0	1 ± 1	51 ± 4
	10	0 ± 0	1 ± 0	27 ± 1	0 ± 0	0 ± 0	37 ± 2
6	0.03	0 ± 0	32 ± 10	196 ± 7	0 ± 0	4 ± 2	311 ± 12
	2	1 ± 0	23 ± 2	39 ± 1	0 ± 0	4 ± 2	93 ± 21
	5	1 ± 0	11 ± 2	27 ± 3	0 ± 0	0 ± 0	50 ± 22
	10	0 ± 0	0 ± 0	16 ± 2	0 ± 0	0 ± 0	19 ± 1
8	0.03	0 ± 0	9 ± 1	149 ± 9	0 ± 0	1 ± 1	231 ± 7
	2	5 ± 1	7 ± 1	13 ± 1	0 ± 0	10 ± 5	24 ± 13
	5	2 ± 0	6 ± 1	11 ± 1	0 ± 0	0 ± 0	21 ± 2
	10	0 ± 0	0 ± 0	10 ± 1	0 ± 0	0 ± 0	15 ± 1

* Standard error based on n=4.

At 20 °C in dry grain, for both species, the adult count from incubation at 2, 5, and 10% levels of CO_2 was significantly lower compared to the ambient level of CO_2 with zero incubation count at the 10% level (except at 2 wk for *T. castaneum*) and a similar trend was observed in wet grain where adult numbers were higher compared to dry grain but at the 10% level of CO_2 there were no adults from 4 wk onwards in both species. At 25 °C also the mean adult survival from incubation decreased with increasing CO_2 levels and was significantly lower than at the ambient level of CO_2 but at this temperature adults emerged at the 10% CO_2 level. It is clear that at 20 and 25 °C, the adult emergence was inhibited or impeded by levels of CO_2 greater than the ambient level. The exact mechanism of reducing the adult numbers could be by delaying or inhibiting egg hatch (AliNiazee et al. 1971), reducing mating frequency (Nicolas and Sillans 1989) or by reducing the oviposition (Lum et al. 1972). Lum et al. (1972) reported that both the egg production and hatchability in *Plodia interpunctella* (Hubner) were reduced by a single exposure to sublethal CO_2 levels for 1 h. The low incubation count compared to ambient CO_2 levels could also be the result of reduced metabolic growth and development of the eggs (Press et al. 1973).

5.6.2 Mixed-species combination

Similar to the single-species controls, the effect of CO_2 was highly significant ($P < 0.05$) on mean adult survival in all the treatments for the mixed-species experiments of both species. At all the temperature levels and moisture contents (dry and wet grains at 12 and 15% wb, respectively), the CO_2 effect was highly significant compared to ambient levels of CO_2. The mean adult survival decreased with increasing CO_2 levels compared to the ambient CO_2 in both the species as indicated in Tables 5.25 and 5.26 for dry and wet grains, respectively and demonstrated graphically in Appendix A (Figs. A37 to A40). However, an

Table 5.25 Effect of CO_2 on the mean adult survival (first and incubation counts) in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus*			*T. castaneum*		
		Temperature (°C)			Temperature (°C)		
		15	20	25	15	20	25
2	0.03	62 ± 2	65 ± 4	80 ± 2	64 ± 1	70 ± 2	90 ± 4
	2	61 ± 2	56 ± 2	75 ± 13	66 ± 0	64 ± 1	64 ± 3
	5	56 ± 2	57 ± 3	53 ± 3	65 ± 1	66 ± 2	62 ± 6
	10	26 ± 7	43 ± 7	38 ± 2	51 ± 9	66 ± 1	63 ± 2
4	0.03	56 ± 2	53 ± 2	110 ± 6	62 ± 1	61 ± 3	81 ± 1
	2	44 ± 6	65 ± 3	63 ± 6	61 ± 1	64 ± 2	61 ± 1
	5	37 ± 3	52 ± 2	37 ± 4	63 ± 2	65 ± 1	61 ± 12
	10	5 ± 1	32 ± 4	24 ± 2	47 ± 2	60 ± 1	54 ± 2
6	0.03	48 ± 3	34 ± 1	146 ± 9	62 ± 2	64 ± 1	104 ± 8
	2	23 ± 3	54 ± 1	60 ± 5	48 ± 3	65 ± 2	62 ± 1
	5	19 ± 7	42 ± 2	39 ± 3	58 ± 5	62 ± 2	51 ± 3
	10	2 ± 0	33 ± 5	35 ± 3	31 ± 7	53 ± 2	50 ± 3
8	0.03	42 ± 2	40 ± 2	91 ± 10	61 ± 1	66 ± 2	84 ± 10
	2	11 ± 4	45 ± 4	34 ± 2	26 ± 8	60 ± 1	56 ± 0
	5	18 ± 6	37 ± 3	43 ± 14	46 ± 11	58 ± 4	50 ± 7
	10	1 ± 1	26 ± 2	27 ± 3	3 ± 3	9 ± 4	36 ± 10

* Standard error based on n=4.

Table 5.26 Effect of CO_2 on the mean adult survival (first and incubation counts) in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C)			*T. castaneum* Temperature (°C)		
		15	20	25	15	20	25
2	0.03	55 ± 1	77 ± 2	100 ± 2	59 ± 1	70 ± 0	90 ± 2
	2	69 ± 0	78 ± 2	82 ± 7	69 ± 0	65 ± 1	72 ± 4
	5	66 ± 1	73 ± 0	69 ± 4	69 ± 0	63 ± 1	69 ± 1
	10	58 ± 2	64 ± 1	60 ± 3	67 ± 2	63 ± 0	64 ± 2
4	0.03	63 ± 1	85 ± 3	156 ± 5	56 ± 1	63 ± 2	83 ± 2
	2	70 ± 0	89 ± 4	79 ± 2	69 ± 0	61 ± 1	63 ± 7
	5	58 ± 1	56 ± 1	71 ± 5	67 ± 1	58 ± 1	66 ± 2
	10	43 ± 2	46 ± 3	55 ± 2	61 ± 1	56 ± 0	59 ± 2
6	0.03	61 ± 2	88 ± 3	165 ± 5	65 ± 1	59 ± 1	84 ± 2
	2	70 ± 1	96 ± 15	51 ± 4	69 ± 1	65 ± 1	81 ± 6
	5	58 ± 2	69 ± 2	45 ± 1	69 ± 1	58 ± 0	65 ± 2
	10	32 ± 4	52 ± 1	43 ± 2	57 ± 3	53 ± 2	57 ± 5
8	0.03	49 ± 2	77 ± 7	155 ± 2	58 ± 2	63 ± 1	92 ± 3
	2	69 ± 1	55 ± 2	64 ± 2	65 ± 1	53 ± 2	63 ± 1
	5	59 ± 3	46 ± 2	52 ± 3	67 ± 1	53 ± 0	53 ± 2
	10	34 ± 4	42 ± 1	32 ± 3	56 ± 4	49 ± 2	49 ± 3

* Standard error based on n=4.

exception was the mixed-species combination of *C. ferrugineus* at 20° C in dry grain and at 15 and 20°C in wet grain and (Appendix A, Fig. A37 and A38, respectively) where the adult number at the 2% CO_2 level was higher than at the ambient level of CO_2.

The adult survival in the first count for both the species at all temperatures was significantly ($P < 0.05$) affected by CO_2 levels and the interaction effect between CO_2 and exposure time. At constant temperatures, the mean adult survival from first count of both species decreased with increasing CO_2 levels over the observation period of 8 wk in both dry (12% wb) and wet (15% wb) grain. At 15°C in both dry and wet grain, mean adult survival from first count of *C. ferrugineus* decreased at all CO_2 levels from 2 wk (except at 2% CO_2 level in wet grain) whereas for *T. castaneum* in dry grain, the mean adult survival from the first count decreased from 4 wk at 10% level of CO_2 and from 6 wk at 2% and 5% levels of CO_2 and in wet grain mean adult survival from first count was not affected at 2 and 5% levels of CO_2 but decreased at ambient and 10% CO_2 levels over the observation period (Tables 5.27 and 5.28). At 20°C in both dry and wet grain, mean adult survival from first count of *C. ferrugineus* decreased with time at all CO_2 levels from 2 wk (except in wet grain at the ambient CO_2 level) but the adult survival of *T. castaneum* was unaffected at all CO_2 levels for the entire exposure period except at 4 wk onwards at the 10% level of CO_2 in dry and wet grain. At 25°C, in dry grain, mean adult survival from the first count of *C. ferrugineus* decreased with increasing CO_2 levels from 2 wk (except at the ambient CO_2 level) whereas for *T. castaneum* the mean adult survival from the first count decreased from 2 wk at 2, 5, and 10% levels of CO_2 and after 8 wk at the ambient level of CO_2. At 25°C in wet grain, mean adult survival from the first count of *C. ferrugineus* decreased with increasing CO_2 levels from 2 wk (except at ambient CO_2 level) and the same trend was observed in *T.*

Table 5.27 Effect of CO_2 on the mean adult survival from first count in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15	20	25	*T. castaneum* Temperature (°C) 15	20	25
2	0.03	62 ± 2	64 ± 3	66 ± 1	64 ± 1	68 ± 1	68 ± 1
	2	61 ± 2	55 ± 2	48 ± 5	66 ± 0	64 ± 1	63 ± 2
	5	56 ± 2	56 ± 3	52 ± 2	65 ± 1	66 ± 2	61 ± 6
	10	26 ± 7	41 ± 6	37 ± 2	51 ± 9	66 ± 1	60 ± 1
4	0.03	56 ± 2	53 ± 2	65 ± 1	62 ± 1	61 ± 3	68 ± 1
	2	44 ± 6	55 ± 1	41 ± 2	61 ± 1	64 ± 2	61 ± 1
	5	37 ± 3	48 ± 3	29 ± 2	63 ± 2	65 ± 1	54 ± 7
	10	5 ± 1	32 ± 4	24 ± 1	47 ± 2	60 ± 1	52 ± 2
6	0.03	48 ± 3	34 ± 1	66 ± 2	62 ± 2	64 ± 1	68 ± 1
	2	23 ± 3	49 ± 1	43 ± 2	48 ± 3	65 ± 2	62 ± 1
	5	19 ± 7	42 ± 2	35 ± 2	58 ± 5	62 ± 2	51 ± 3
	10	2 ± 0	33 ± 5	31 ± 1	31 ± 7	53 ± 2	48 ± 4
8	0.03	42 ± 2	40 ± 2	59 ± 1	61 ± 1	66 ± 2	64 ± 2
	2	11 ± 4	41 ± 3	32 ± 1	26 ± 8	60 ± 1	56 ± 0
	5	18 ± 6	36 ± 2	31 ± 9	46 ± 11	58 ± 4	46 ± 5
	10	1 ± 1	26 ± 2	23 ± 2	3 ± 3	9 ± 4	36 ± 10

* Standard error based on n=4.

Table 5.28 Effect of CO_2 on the mean adult survival from first count in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C)			*T. castaneum* Temperature (°C)		
		15	20	25	15	20	25
2	0.03	55 ± 1	68 ± 1	68 ± 0	59 ± 1	62 ± 1	71 ± 0
	2	69 ± 0	68 ± 2	53 ± 2	69 ± 0	64 ± 1	62 ± 0
	5	66 ± 1	67 ± 1	52 ± 1	69 ± 0	63 ± 1	62 ± 1
	10	58 ± 2	61 ± 3	49 ± 3	67 ± 2	62 ± 0	58 ± 1
4	0.03	63 ± 1	69 ± 0	69 ± 0	56 ± 1	61 ± 0	69 ± 1
	2	69 ± 0	56 ± 3	42 ± 3	69 ± 0	61 ± 1	51 ± 2
	5	58 ± 1	51 ± 1	40 ± 2	67 ± 1	58 ± 1	55 ± 1
	10	43 ± 2	46 ± 3	32 ± 1	61 ± 1	56 ± 0	53 ± 2
6	0.03	61 ± 2	67 ± 2	69 ± 0	65 ± 1	59 ± 1	73 ± 0
	2	69 ± 0	56 ± 2	32 ± 4	69 ± 1	64 ± 0	62 ± 4
	5	58 ± 2	57 ± 1	34 ± 1	69 ± 1	58 ± 0	52 ± 1
	10	32 ± 4	51 ± 1	31 ± 2	57 ± 3	53 ± 2	50 ± 3
8	0.03	49 ± 2	65 ± 3	76 ± 1	58 ± 2	63 ± 1	87 ± 2
	2	67 ± 1	50 ± 2	43 ± 2	65 ± 1	53 ± 2	57 ± 2
	5	58 ± 3	43 ± 1	39 ± 2	67 ± 1	53 ± 0	49 ± 2
	10	34 ± 4	42 ± 1	26 ± 2	56 ± 4	49 ± 2	44 ± 2

* Standard error based on n=4.

castaneum with the exception that mean adult survival from the first count increased at the ambient CO_2 level. The differential response of two species at various temperatures and CO_2 levels indicated that in dry and wet grain, *C. ferrugineus* was more susceptible to CO_2 levels compared to *T. castaneum*. The effect of CO_2 in reducing the adult survival was higher at lower moisture content (dry grain) and higher temperature. Along with the main effect of CO_2, adult survival in the first count of both the species was significantly ($P < 0.05$) affected by the interaction of CO_2 with time of exposure as demonstrated in Appendix A (Figs. A41 to A44).

Carbon dioxide levels significantly ($P < 0.05$) affected the mean adult counts from incubation at 20 and 25 °C and generally decreased with increasing CO_2 levels with time for both species in dry and wet grain except at the 2% level of CO_2 for *C. ferrugineus* where adult count was higher than the ambient level. No adults emerged from the incubation count at 15 °C in dry grain for both the species whereas in wet grain few adults emerged in *C. ferrugineus* at 2 and 5% levels of CO_2 from 4 wk onwards and there was no adult emergence in *T. castaneum* in wet grain (Tables 5.29 and 5.30).

At 20 °C, in both dry and wet grain, for *T. castaneum* the adult emergence was zero at all levels of CO_2 at all exposure intervals except at 2 and 4 wk intervals at the ambient level of CO_2 in dry and wet grain, respectively (Tables 5.29 and 5.30). For *C. ferrugineus* in dry grain at this temperature (20 °C), adults from the incubation count decreased with increasing CO_2 levels with the exception that adult numbers at the 2% level of CO_2 were higher than at the ambient level of CO_2 whereas in wet grain adults from incubation were more compared to dry grain but decreased with increasing CO_2 level with the similar exception at the 2% level of CO_2. At 25 °C in both dry and wet grain, the adult numbers

Table 5.29 Effect of CO_2 on the mean adult survival from incubation count in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15	20	25	*T. castaneum* Temperature (°C) 15	20	25
2	0.03	0 ± 0	1 ± 1	14 ± 3	0 ± 0	2 ± 1	22 ± 3
	2	0 ± 0	1 ± 0	27 ± 8	0 ± 0	0 ± 0	1 ± 1
	5	0 ± 0	1 ± 1	1 ± 0	0 ± 0	0 ± 0	1 ± 1
	10	0 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0	3 ± 1
4	0.03	0 ± 0	1 ± 0	45 ± 6	0 ± 0	0 ± 0	13 ± 1
	2	0 ± 0	10 ± 4	22 ± 5	0 ± 0	0 ± 0	0 ± 0
	5	0 ± 0	5 ± 2	8 ± 5	0 ± 0	0 ± 0	7 ± 7
	10	0 ± 0	0 ± 0	1 ± 1	0 ± 0	0 ± 0	2 ± 1
6	0.03	0 ± 0	0 ± 0	80 ± 9	0 ± 0	0 ± 0	36 ± 9
	2	0 ± 0	5 ± 2	17 ± 4	0 ± 0	0 ± 0	0 ± 0
	5	0 ± 0	1 ± 0	4 ± 3	0 ± 0	0 ± 0	0 ± 0
	10	0 ± 0	0 ± 0	4 ± 3	0 ± 0	0 ± 0	2 ± 2
8	0.03	0 ± 0	0 ± 0	32 ± 11	0 ± 0	0 ± 0	20 ± 8
	2	0 ± 0	4 ± 1	3 ± 1	0 ± 0	0 ± 0	0 ± 0
	5	0 ± 0	2 ± 1	12 ± 6	0 ± 0	0 ± 0	4 ± 3
	10	0 ± 0	0 ± 0	4 ± 3	0 ± 0	0 ± 0	0 ± 0

* Standard error based on n=4.

Table 5.30 Effect of CO_2 on the mean adult survival from incubation count in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	CO_2 level (%)	*C. ferrugineus*			*T. castaneum*		
		Temperature (°C)			Temperature (°C)		
		15	20	25	15	20	25
2	0.03	0 ± 0	9 ± 2	32 ± 1	0 ± 0	8 ± 1	19 ± 2
	2	0 ± 0	11 ± 2	29 ± 5	0 ± 0	1 ± 0	10 ± 4
	5	0 ± 0	6 ± 0	16 ± 3	0 ± 0	0 ± 0	7 ± 1
	10	0 ± 0	3 ± 2	11 ± 1	0 ± 0	1 ± 0	6 ± 0
4	0.03	0 ± 0	16 ± 4	87 ± 4	0 ± 0	3 ± 2	14 ± 1
	2	1 ± 0	33 ± 3	37 ± 3	0 ± 0	0 ± 0	12 ± 8
	5	0 ± 0	4 ± 1	31 ± 5	0 ± 0	0 ± 0	11 ± 1
	10	0 ± 0	0 ± 0	23 ± 2	0 ± 0	0 ± 0	6 ± 2
6	0.03	0 ± 0	21 ± 3	96 ± 5	0 ± 0	0 ± 0	11 ± 2
	2	1 ± 0	40 ± 14	20 ± 1	0 ± 0	0 ± 0	19 ± 2
	5	1 ± 0	12 ± 2	11 ± 1	0 ± 0	0 ± 0	13 ± 2
	10	0 ± 0	1 ± 0	12 ± 1	0 ± 0	0 ± 0	8 ± 3
8	0.03	0 ± 0	11 ± 5	79 ± 4	0 ± 0	0 ± 0	5 ± 1
	2	2 ± 1	5 ± 1	21 ± 2	0 ± 0	1 ± 1	6 ± 1
	5	1 ± 0	3 ± 1	13 ± 1	0 ± 0	0 ± 0	4 ± 1
	10	0 ± 0	0 ± 0	6 ± 1	0 ± 0	0 ± 0	5 ± 1

* Standard error based on n=4.

from incubation of both species decreased with increasing CO_2 levels in both species and the adult count of *T. castaneum* was significantly lower than that of *C. ferrugineus*. It is clear that at 20 and 25 °C, the adult emergence was inhibited or impeded by levels of CO_2 greater than the ambient level and that *T. castaneum* populations are lower than *C. ferrugineus* populations in mixed-species combination. Compared to single-species controls, in mixed-species combination *C. ferrugineus* has an inhibitory and depressing effect on *T. castaneum* numbers and that *C. ferrugineus* emerges as the dominant species.

5.6.3 Interaction effect of CO_2 with other variables

The single and mixed-species populations were significantly ($P < 0.05$) affected by the main effect of CO_2 levels for all the treatments. The adult survival was also significantly affected by significant ($P < 0.05$) multiple interactions of CO_2 levels with other variables. There was significant two way interaction of CO_2 levels with temperature as explained in the interaction effects of temperature. Generally, significant ($P < 0.05$) two way interactions between of CO_2 and moisture content and CO_2 and exposure time were also observed. This means that adult survival decreased with an increase of CO_2 levels and decreasing moisture contents and also decreased with increasing exposure time. A three-way significant interaction ($P < 0.05$) between CO_2, moisture content and time was also observed signifying increased survival at decreasing CO_2 levels and increasing moisture content over exposure time.

5.7 Effect on Germination

The germination data were transformed using the arcsin transformation and the effect of time and CO_2 were analyzed at each temperature for dry and wet grains by using procedure

GLM (SAS 2000). The data were analyzed for single-species and mixed-species combinations of both the species. The germination data for single-species and mixed-species combinations, at all three temperatures and four CO_2 levels for dry and wet grains over the observation period of 8 wk are shown in Tables 5.31 and 5.32.

In dry grain (12% wb), germination was not significantly ($P > 0.05$) affected at 15 and 20°C over the exposure period and CO_2 levels in single and mixed-species combinations (Table 5.31). However, at 25°C, germination was affected significantly ($P < 0.05$) in samples with single species of *T. castaneum* and mixed-species combination of both species. At 25°C, the germination in *T. castaneum* single-species and mixed-species samples was higher at 2, 5, and 10% CO_2 levels compared to the ambient CO_2 levels. In wet grain, the effect of exposure time and CO_2 levels was significant ($P < 0.05$) in all treatments. The germination decreased at ambient CO_2 levels in single-species as well as mixed-species combination at all temperatures whereas the germination was higher at 2, 5, and 10% CO_2 levels compared to the ambient CO_2 levels. The variation in germination is probably due to the small sample size, amount of dockage and biological variation within the species and also probably due to inhibition of molds at elevated CO_2 levels (White and Jayas 1993).

5.8 Comparison between Single and Mixed-species Populations and the Species Factor

5.8.1 Context

The present study relies on the adult numbers to represent the population and does not attempt a comprehensive and incisive analysis into cannibalism or predation of either species as carried out by other researchers (Park et al. 1941, Park et al. 1965, Lloyd 1967) who considered various factors such as fecundity, metamorphosis, and imago longevity and

Table 5.31 Mean percent germination in single and mixed-species experiments in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Temp (°C)	Exposure time (wk)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)				Mixed-species combination CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10	0.03	2	5	10
15	0	97	97	97	96	97	97	97	96	97	97	97	96
	2	96	97	97	96	94	95	95	96	94	96	96	96
	4	94	95	96	96	92	94	94	95	92	95	95	96
	6	94	95	96	96	92	93	95	95	92	94	95	95
	8	94	95	96	96	92	93	94	95	91	94	95	95
20	0	95	96	98	96	95	96	98	96	95	96	98	96
	2	94	94	96	96	93	94	95	95	93	95	95	95
	4	92	93	95	95	92	94	95	95	91	93	96	94
	6	90	92	94	95	89	92	94	93	87	92	94	94
	8	91	92	94	95	88	90	92	94	88	91	93	93
25	0	97	98	98	97	97	98	98	97	97	98	98	97
	2	95	98	96	95	91	94	96	96	92	95	97	96
	4	95	96	94	94	86	91	93	95	89	92	94	94
	6	90	92	93	94	83	87	90	92	87	89	90	91
	8	87	93	92	93	82	85	88	90	84	86	89	90

Table 5.32 Mean percent germination in single and mixed-species experiments in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Temp (°C)	Exposure time (wk)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)				Mixed-species combination CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10	0.03	2	5	10
15	0	97	97	97	96	97	97	97	96	97	97	97	96
	2	94	95	94	94	93	94	94	94	93	93	94	94
	4	89	93	93	93	91	91	92	92	91	91	92	92
	6	90	90	92	92	87	90	91	90	87	90	91	92
	8	77	91	92	92	72	88	89	89	74	88	90	90
20	0	95	96	98	96	95	96	98	96	95	96	98	96
	2	92	94	96	94	93	94	94	91	91	91	92	93
	4	91	93	95	94	86	91	93	89	85	87	90	91
	6	87	89	93	92	82	86	88	88	85	88	88	90
	8	84	88	90	92	81	85	86	87	83	86	87	88
25	0	97	98	98	97	97	98	98	97	97	98	98	97
	2	89	94	93	91	88	91	90	92	88	89	88	92
	4	81	89	87	91	80	89	84	86	79	83	86	87
	6	76	86	86	89	74	79	79	83	76	79	82	85
	8	77	84	85	87	72	76	79	82	74	77	81	84

their experiments involved sifting and counting of larvae, pupae, and imagoes and tests for invading parasitoids and endemic pathogens. Although no direct physical evidence of predation, cannibalism, or competition effects was attempted, the effects were deduced by comparison with the single-species controls in similar environments as the mixed-species combination. In addition to the confirmed interspecific and intraspecific cannibalism and predation (Park 1948, Park et al. 1965, Lloyd 1967, Leftkovitch 1968, White and Sinha 1980), population density, sex ratio, mating status, and crowding affect developmental stages, the development rate, fecundity, and mortality of insect species (Park et al. 1965, Smith 1966, and White and Bell 1993, and White et al. 1995). A laboratory experiment (Suresh et al. 2000, unpublished data) was carried out to observe the interactions between various life stages of *C. ferrugineus* and *T. castaneum* at 70% RH and temperatures of 25 and 30°C. They observed that *T. castaneum* caused higher mortality of the immatures of both species than *C. ferrugineus* and that larvae of both beetles were more effective predators than cannibals causing higher mortality to eggs of each other than their own species. Hence, although the cannibalism and predation is not directly measured it is clear that they play a dominant role in population regulation. Due to various factors affecting the interspecies and intraspecies interactions in adult survival of mixed-species combinations, it would be apt to refer to it simply as a species factor.

5.8.2 *Cryptolestes ferrugineus*

The single-species controls were the reference level to compare populations observed in mixed-species combination for the same environmental conditions in dry (12% wb) and wet (15% wb) grains. The objective was to observe the variation in population when two species are reared together compared to being reared singly.

As discussed in previous sections, the survival of singly reared and mixed populations of both species was significantly affected by temperature, RH, and CO_2 and their interactions. The comparison between mean adult survival of *C. ferrugineus* in single (alone) and mixed-species (both) combinations in dry and wet grains is shown in Table 5.33.

The mean adult survival over all the exposure intervals was considered for comparison between single and mixed-species experiments. Survival ratio or the species factor for each species was calculated separately in dry and wet grains, as the ratio of mean adult survival in mixed-species over single-species control for test temperatures and CO_2 levels and is shown in Table 5.33. A species factor of less than unity indicates that the species survived better in isolation (or reared singly) compared to being reared with the other species (both) and the converse is also true i.e. a factor greater than unity connotes higher survival in mixed-species conditions compared to being reared alone.

In dry grain, at 15°C, at all the CO_2 levels except at ambient CO_2 conditions, the mean adult survival of *C. ferrugineus* in isolation was greater compared to being with *T. castaneum*. At the ambient CO_2 level at this temperature (15°C), the species factor neared unity (1.02) indicating that *C. ferrugineus* survived slightly better in mixed-species combination. At 20°C, *C. ferrugineus* survived better in isolation compared to mixed-species combination at ambient levels of CO_2 whereas at all other CO_2 levels, it survived better in the mixed-species setup. At 25°C, the species factor neared unity indicating almost equal survival in single and mixed-species experiments.

The species factor in wet grains at 15 and 20°C neared unity at all CO_2 levels except at the ambient level of CO_2 at 20°C indicating that mean adult survival of *C. ferrugineus* varied only slightly in single and mixed-species whereas for the ambient level of CO_2 at

Table 5.33 Comparison of mean adult survival (first and incubation counts) of *Cryptolestes ferrugineus* in single and mixed-species experiments at 15, 20, and 25°C in dry (12% wb) and wet (15% wb) grain and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*															
		Dry (12% wb) grain								Wet (15% wb) grain							
		CO_2 levels (%)								CO_2 levels (%)							
		0.03		2		5		10		0.03		2		5		10	
		Single*	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both
2	15	60	62	59	61	55	56	26	26	63	55	70	69	65	66	53	58
	20	72	65	58	56	57	57	46	43	80	77	78	78	69	73	63	64
	25	87	80	60	75	51	53	40	38	125	100	90	82	73	69	64	60
4	15	58	56	44	44	39	37	10	5	62	63	69	70	58	58	58	43
	20	69	53	55	65	47	52	37	32	109	85	98	89	64	56	51	46
	25	124	110	58	63	43	37	34	24	258	156	96	79	82	71	63	55
6	15	45	48	35	23	31	19	5	2	54	61	68	70	60	58	33	32
	20	68	34	47	54	42	42	22	33	104	88	77	96	62	69	48	52
	25	107	146	51	60	46	39	36	35	268	165	73	51	59	45	46	43
8	15	42	42	31	11	33	18	2	1	55	49	72	69	64	59	31	34
	20	59	40	42	45	38	37	18	26	79	77	53	55	48	46	39	42
	25	115	91	48	34	41	43	28	27	232	155	55	64	47	52	42	32
Species factor (ratio of 'both' to 'single')																	
	15	1.02		0.76		0.78		0.60		0.98		1.00		0.98		0.98	
	20	0.71		1.09		1.02		1.19		0.89		1.05		1.00		1.02	
	25	0.99		1.06		0.95		0.90		0.67		0.90		0.92		0.88	

* Single and both indicate the mean adult survival of *Cryptolestes ferrugineus* in single and mixed-species experiments, respectively.

20 °C *C. ferrugineus* survived better in isolation compared to the mixed-species setup. The reason for reduced mean survival of *C. ferrugineus* in the mixed-species setup at 20 °C at the ambient level of CO_2 could be predation by *T. castaneum* on the developmental stages of *C. ferrugineus* since eggs are laid at 18 °C and above (Fields and White 1997) and perhaps the same explanation also applies for lower mean adult survival of *C. ferrugineus* at all levels of CO_2 in mixed-species combination at 25 °C (wet grain). At 25 °C in wet grain, the species factor ranged from 0.67 to 0.92 indicating that the adult population of *C. ferrugineus* was also suppressed in mixed-species combination.

5.8.3 *Tribolium castaneum*

In both the dry and wet grains, at all temperature and CO_2 levels the mean survival of *T. castaneum* in mixed-species combination was significantly ($P < 0.05$) lower compared to the single-species control indicating interspecific interaction between the two species resulting in adult population reduction. This indicates that *C. ferrugineus* has an inhibitory or population supressing effect on *T. castaneum* and confirms the observation of Lefkovitch (1968) in which he reported an inhibitory effect of *C. ferrugineus* at ambient levels CO_2 at 30°C and 60% RH. The mean adult survival of *T. castaneum* in single and mixed-species combination is shown in Table 5.34.

At 15 °C, in both dry and wet grain the species factor neared unity except at 2 and 10% levels of CO_2 in dry grain. The species factor of 1.33 at the 10% level of CO_2 in dry grain suggests that *T. castaneum* survived better in the presence of *C. ferrugineus*; this is largely due to the mean adult survival observed at the 8th wk (1 adult in 'single' species and 3 adults in 'both', Table 5.34). At 20°C, the species factor was less than unity in both dry and wet grains with lower values in wet grains indicating cannibalism and predation within

Table 5.34 Comparison of mean adult survival (first and incubation counts) of *Tribolium castaneum* in single and mixed-species experiments at 15, 20, and 25°C in dry (12% wb) and wet (15% wb) grain and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*T. castaneum*															
		Dry (12% wb) grain								Wet (15% wb) grain							
		CO_2 levels (%)								CO_2 levels (%)							
		0.03		2		5		10		0.03		2		5		10	
		Single*	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both	Single	Both
2	15	67	64	67	66	66	65	64	51	60	59	69	69	69	69	66	67
	20	70	70	67	64	65	66	64	66	92	70	75	65	67	63	74	63
	25	136	90	135	64	90	62	84	63	151	90	109	72	96	69	86	64
4	15	66	62	65	61	53	63	51	47	66	56	69	69	71	67	63	61
	20	74	61	66	64	66	65	64	60	74	63	66	61	64	58	61	56
	25	138	81	136	61	78	61	70	54	289	83	142	63	112	66	97	59
6	15	64	62	58	48	56	58	51	31	65	65	67	69	70	69	62	57
	20	68	64	67	65	63	62	60	53	72	59	69	65	65	58	62	53
	25	136	104	137	62	101	51	79	50	392	84	169	81	117	65	83	57
8	15	65	61	52	26	51	46	1	3	62	58	67	65	67	67	61	56
	20	61	66	71	60	63	58	42	9	69	63	74	53	66	53	63	49
	25	193	84	137	56	68	50	55	36	389	92	163	63	107	53	74	49
Species factor (ratio of 'both' to 'single')																	
	15		0.95		0.81		1.03		1.33		0.94		1.00		0.98		0.96
	20		0.96		0.94		0.98		0.77		0.84		0.86		0.89		0.85
	25		0.61		0.45		0.68		0.70		0.33		0.49		0.59		0.68

* Single and both indicate the mean adult survival of *Tribolium castaneum* in single and mixed-species experiments, respectively.

the species with *C. ferrugineus* emerging as the dominant species. At 25 °C, the mean adult population reduction was more pronounced compared to other temperatures. The species factor ranged from 0.45 to 0.70 in dry grain and from 0.33 to 0.68 in wet grain indicating the dominance of *C. ferrugineus* at all levels of CO_2 in the mixed-species combinations. At constant CO_2 levels, the species factor decreased with increasing temperature indicating higher mean adult survival in single-species or lower adult numbers in mixed species with increasing temperature which translates into higher predation with increasing temperature. The mean adult survival in mixed-species of *T. castaneum* decreased with increasing temperature indicating that as the temperature increased, the cannibalism, predation, and also probably the crowding effect due to insect density increased resulting in greater competition in which *T. castaneum* fed on dockage, cannibalized its own species (and to some extent on *C. ferrugineus*) but could not adequately prey on *C. ferrugineus* since developmental stages of *C. ferrugineus* are usually inside the germ of grain and are not easily accessible. However, a number of other factors such as initial insect density, dockage percent, sex ratio, age of insects and cultivar can also affect the insect population.

From Tables 5.33 and 5.34, it is observed that *C. ferrugineus* adult populations did not show a consistent trend with CO_2 levels in both combinations. However, in case of *T. castaneum*, the species factor at ambient and 2% level of CO_2 at 25 °C was consistently lower in both dry (12% wb) and wet (15% wb) grain suggesting that suppression of *T. castaneum* was higher in mixed-species combination at these levels compared to 5 and 10% levels of CO_2. This indicates that even at lower CO_2 levels (ambient and 2%) the *T. castaneum* adult population is suppressed in presence of *C. ferrugineus*. Lower suppression of adult population of *T. castaneum* at 25 °C at higher CO_2 levels is probably due to increased reproduction of adults due to higher metabolic activity and also inhibition of mold growth.

5.9 Effect on Insect Mortality

The mean adult mortality for single and mixed-species combinations for all the treatments is indicated in Tables 5.35 to 5.38. All the variables significantly affecting mean adult survival of both species in single and mixed-species experiments also affected the mean adult mortality. Generally, at all test temperatures, the mean adult mortality significantly ($P < 0.05$) increased with increasing exposure time and CO_2 levels in both the dry and wet grains. The mean adult mortality in single-species controls in dry grain was significantly higher compared to wet grain in all the treatments. A similar trend was also observed for the mixed-species combination for all the treatments. Higher mortality in dry grains is mainly due to starvation and dessication (Fields 1992). In dry grain, at lower moisture content there is greater cannibalism resulting in smaller numbers of adults since the non feeding stages provide a more ready source of water compared to the grains (Park et al. 1965).

A careful scrutiny of mortality in various treatments (Tables 5.35 to 5.38) reveals that over the observation period of 8 wk, significant mortality occurred at the 5 and 10% levels of CO_2 at lower temperatures. High mortality commencing from 6 wk of exposure indicated that prolonged exposure to sublethal (i.e. not acutely toxic) levels of CO_2 sharply reduced the populations through chronic toxic effects and this could enhance population reduction. Five to 10% CO_2 mixed with air would help in achieving mortality, arresting growth by inhibiting the incubation and also act as a slow fumigant at low temperatures during the storage period (Navarro and Calderon 1973).

Table 5.35 Mean adult mortality (first and incubation counts) and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	10 ± 1	11 ± 1	15 ± 2	46 ± 2	3 ± 1	3 ± 1	5 ± 1	8 ± 3
	20	2 ± 1	13 ± 1	14 ± 2	24 ± 1	9 ± 3	6 ± 1	6 ± 1	9 ± 1
	25	3 ± 1	27 ± 1	28 ± 7	34 ± 3	1 ± 0	4 ± 1	2 ± 0	1 ± 0
4	15	12 ± 1	27 ± 3	28 ± 5	61 ± 1	4 ± 0	6 ± 1	17 ± 3	19 ± 3
	20	8 ± 2	17 ± 1	24 ± 2	34 ± 3	8 ± 3	8 ± 2	6 ± 1	6 ± 1
	25	6 ± 2	31 ± 3	39 ± 7	45 ± 2	4 ± 0	9 ± 1	12 ± 5	12 ± 2
6	15	25 ± 3	35 ± 3	40 ± 2	65 ± 2	6 ± 1	13 ± 1	14 ± 0	18 ± 4
	20	9 ± 1	28 ± 3	29 ± 2	51 ± 9	5 ± 2	6 ± 2	8 ± 1	11 ± 2
	25	16 ± 5	30 ± 2	33 ± 8	39 ± 2	7 ± 1	7 ± 0	12 ± 7	15 ± 9
8	15	29 ± 3	40 ± 2	37 ± 2	67 ± 1	5 ± 0	19 ± 2	20 ± 1	69 ± 1
	20	17 ± 3	33 ± 9	37 ± 1	53 ± 4	11 ± 5	7 ± 0	7 ± 1	29 ± 4
	25	6 ± 1	33 ± 1	42 ± 10	47 ± 1	14 ± 3	14 ± 2	22 ± 1	31 ± 1

* Standard error based on n=4.

Table 5.36 Mean adult mortality (first and incubation counts) and standard errors in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%)				*T. castaneum* CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	6 ± 1	0 ± 0	6 ± 0	14 ± 1	8 ± 1	1 ± 1	1 ± 0	7 ± 3
	20	1 ± 0	5 ± 1	6 ± 1	10 ± 2	2 ± 0	4 ± 1	6 ± 1	4 ± 1
	25	2 ± 0	15 ± 3	16 ± 3	19 ± 2	2 ± 1	5 ± 1	6 ± 1	8 ± 1
4	15	8 ± 2	2 ± 0	14 ± 3	15 ± 2	4 ± 1	1 ± 0	3 ± 1	8 ± 1
	20	1 ± 0	16 ± 1	16 ± 1	20 ± 0	3 ± 1	6 ± 2	7 ± 1	10 ± 1
	25	4 ± 1	34 ± 2	29 ± 1	34 ± 3	4 ± 1	11 ± 2	10 ± 1	11 ± 0
6	15	14 ± 5	3 ± 1	11 ± 2	37 ± 2	4 ± 1	3 ± 1	3 ± 1	8 ± 2
	20	2 ± 1	17 ± 3	21 ± 2	24 ± 2	3 ± 1	7 ± 1	5 ± 1	10 ± 5
	25	1 ± 0	44 ± 4	42 ± 2	42 ± 3	2 ± 0	7 ± 1	17 ± 8	7 ± 2
8	15	15 ± 3	2 ± 1	8 ± 1	40 ± 2	8 ± 2	4 ± 1	4 ± 0	11 ± 2
	20	4 ± 1	25 ± 2	28 ± 2	32 ± 1	3 ± 1	7 ± 1	5 ± 0	8 ± 5
	25	1 ± 0	33 ± 3	35 ± 2	39 ± 1	2 ± 1	7 ± 2	9 ± 1	12 ± 3

* Standard error based on n=4.

Table 5.37 Mean adult mortality (first and incubation counts) and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus* CO_2 levels (%) 0.03	2	5	10	*T. castaneum* CO_2 levels (%) 0.03	2	5	10
2	15	8 ± 1	10 ± 2	15 ± 2	45 ± 5	7 ± 1	4 ± 0	5 ± 1	10 ± 2
	20	7 ± 3	17 ± 2	14 ± 3	31 ± 7	2 ± 1	7 ± 1	4 ± 2	4 ± 1
	25	5 ± 1	24 ± 4	19 ± 3	33 ± 2	2 ± 1	7 ± 2	9 ± 6	13 ± 4
4	15	15 ± 2	27 ± 6	35 ± 3	65 ± 0	8 ± 1	9 ± 0	9 ± 2	24 ± 2
	20	20 ± 2	16 ± 2	23 ± 3	43 ± 4	10 ± 3	6 ± 2	5 ± 1	10 ± 1
	25	5 ± 1	31 ± 2	41 ± 2	46 ± 1	3 ± 1	10 ± 1	16 ± 7	19 ± 2
6	15	22 ± 3	47 ± 3	38 ± 14	67 ± 1	8 ± 2	23 ± 3	13 ± 5	39 ± 6
	20	37 ± 2	22 ± 2	29 ± 2	42 ± 6	7 ± 1	5 ± 2	8 ± 2	18 ± 2
	25	5 ± 2	28 ± 1	35 ± 2	39 ± 1	2 ± 1	9 ± 1	21 ± 3	24 ± 4
8	15	28 ± 1	60 ± 5	53 ± 6	69 ± 1	9 ± 1	44 ± 8	26 ± 10	66 ± 3
	20	32 ± 2	31 ± 4	35 ± 2	45 ± 3	5 ± 2	11 ± 1	12 ± 4	61 ± 4
	25	13 ± 2	40 ± 2	40 ± 8	48 ± 2	18 ± 4	15 ± 1	26 ± 4	35 ± 10

* Standard error based on n=4.

Table 5.38 Mean adult mortality (first and incubation counts) and standard errors in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Exposure time (wk)	Temp (°C)	*C. ferrugineus*				*T. castaneum*			
		CO_2 levels (%)				CO_2 levels (%)			
		0.03	2	5	10	0.03	2	5	10
2	15	16 ± 1	1 ± 0	5 ± 0	16 ± 2	11 ± 1	1 ± 0	1 ± 0	3 ± 1
	20	2 ± 1	3 ± 1	4 ± 1	10 ± 3	10 ± 1	6 ± 1	8 ± 1	8 ± 0
	25	3 ± 0	18 ± 2	18 ± 1	22 ± 3	1 ± 0	8 ± 0	9 ± 1	13 ± 1
4	15	8 ± 1	1 ± 0	13 ± 1	28 ± 1	14 ± 1	1 ± 0	4 ± 1	10 ± 2
	20	1 ± 1	15 ± 3	19 ± 1	26 ± 3	10 ± 0	9 ± 1	13 ± 1	16 ± 1
	25	2 ± 0	29 ± 4	31 ± 2	39 ± 2	2 ± 1	20 ± 2	16 ± 1	18 ± 2
6	15	9 ± 2	1 ± 0	13 ± 2	38 ± 4	5 ± 1	2 ± 1	2 ± 1	13 ± 3
	20	8 ± 3	16 ± 2	16 ± 2	20 ± 1	12 ± 0	6 ± 1	13 ± 1	19 ± 1
	25	2 ± 0	41 ± 4	38 ± 1	41 ± 1	0 ± 0	10 ± 3	18 ± 2	21 ± 2
8	15	21 ± 2	3 ± 1	12 ± 3	37 ± 3	12 ± 2	5 ± 1	3 ± 1	13 ± 5
	20	6 ± 2	21 ± 2	28 ± 1	30 ± 1	7 ± 1	17 ± 2	17 ± 1	20 ± 3
	25	1 ± 0	31 ± 3	33 ± 2	46 ± 2	1 ± 0	21 ± 2	22 ± 2	27 ± 2

* Standard error based on n=4.

5.10 Prediction Equations for Single and Mixed-species Populations

The various interactions between temperatures, CO_2 levels and moisture contents were considered along with the non-linear distribution of adult survival over a range of temperatures with respect to exposure time. The adult survival of both the species at time intervals of 2, 4, 6, and 8 wk did not consistently increase or decrease in all the treatments but showed irregular cyclic fluctuations with time. Nicholson (1954) observed that in the laboratory, single or multi-species experiments have limited food supply and thus a scramble or exploitation competition effect is expected with a series of population peaks and troughs. Chapman and Whang (1934) observed periodic fluctuations in the egg populations of *T. confusum* by observing the number of eggs laid and related their decrease with the rise in number of larvae since the larvae are known to feed on eggs. However, in his laboratory experiments, which he called a 'synthetic population' the number of larvae differed from the normal population which served as a control and therefore, he opined that there seems to be no adequate explanation other than calling it an experimental error.

Based on the mean species factors (survival ratios) mentioned in section 5.7, the adult survival of *T. castaneum* showed greater fluctuation with time in both the single and mixed-species combinations compared to *C. ferrugineus*. Therefore, a quadratic factor for time (W^2) was incorporated in addition to the linear time (W) effect. The species combination was considered by introducing a variable 'SPEFF' (species effect) to derive a single model for each species capable of predicting the adult survival for single and mixed-species combination of each species. Linear and non-linear regression using procedure REG (SAS 2000) with various options was performed to obtain one integrated model for each species covering all the variables in the experimental tests. The adult survival data were transformed using logarithmic transformation before the procedure was run and were back-transformed to predict the adult populations at all the exposure time intervals.

The regression model for *C. ferrugineus* yielded an R^2 value of 0.83 and that for *T. castaneum* a value of 0.72. The models accounted for interactions between temperature, RH, and CO_2 levels in addition to the quadratic time factor (W^2) and the species effect (SPEFF). Both the models were initialized with an initial adult population of 70 adults/ 70 g of wheat. The prediction models for the two species are:

C. ferrugineus :

$$\begin{aligned}\text{LSURVCF} = &- 0.03936 \bullet W + W \bullet (- 0.00972 \bullet T - 0.00796 \bullet M - 0.42208 \bullet C \\ &+ 0.00134 \bullet T \bullet M + 0.01745 \bullet T \bullet C + 0.02885 \bullet M \bullet C - 0.00124 \bullet T \bullet M \bullet C \\ &- 0.0196 \bullet S) \end{aligned} \qquad (1)$$

T. castaneum :

$$\begin{aligned}\text{LSURVTC} = &- 0.48211 \bullet W + 0.13908 \bullet W^2 + W \bullet (0.01385 \bullet T + 0.00538 \bullet M \\ &- 0.46423 \bullet C + 0.00073 \bullet T \bullet M - 0.01812 \bullet T \bullet C - 0.02882 \bullet M \bullet C \\ &+ 0.00107 \bullet T \bullet M \bullet C - 0.0537 \bullet S) + W^2 \bullet (-0.00508 \bullet T - 0.0072 \bullet M \\ &- 0.11757 \bullet C + 0.00022 \bullet T \bullet M + 0.00463 \bullet T \bullet C + 0.00773 \bullet M \bullet C \\ &- 0.00003 \bullet T \bullet M \bullet C) \end{aligned} \qquad (2)$$

Back-transformed predicted adult population:

$$\text{PSURVCF or PSURVTC} = 70.5 \bullet \exp^{(\text{LSURVCF or LSURVTC})} - 0.5 \qquad (3)$$

where:

LSURVCF and LSURVTC are predicted logarithmic transformed adult populations of *C. ferrugineus* and *T. castaneum*, respectively;

W = time in wk,

T = temperature from 15 to 25 °C,

C = carbon dioxide concentration from 0.03 (ambient) to 10%,

M = moisture content from 12 to 15% (wb) in percent,

S = species effect factor taking a value of 1 for mixed-species and '0' for single-species combination,

PSURVCF and PSURVTC are predicted back-transformed adult populations from logarithmic populations LSURVCF and LSURVTC of *C. ferrugineus* and *T. castaneum*, respectively.

Based on the above models for the two species, the actual and predicted adult populations with relative mean percent error for each exposure interval were calculated and are shown in Tables 5.39 to 5.46 for each species in dry and wet grains. The observed and predicted adult population were plotted and are shown for all the treatments in Appendix A (Figs. A45 to A68).

Although, the R^2 value is reasonable, the model indicated greater variation at 15 °C at which there is no egg laying and the population does not multiply. Because the model was for temperature range of 15 to 25 °C, the prediction at 15 °C shows greater variation compared with other temperatures.

5.11 Comparison Between Single-species Population with Population at Ideal Conditions

A laboratory experiment using glass bottle jars was setup at optimum conditions of 30 °C and 70% RH at ambient CO_2 level using wheat (cv. AC Barrie) with 5% dockage added to it at two moisture contents of 12 and 15% wb. The two species, *C. ferrugineus* and

Table 5.39 Observed and predicted mean adult populations in single-species controls of *Cryptolestes ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*C. ferrugineus* Temperature (°C) 15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	60	64	7.4	72	69	4.9	87	73	15.5
	2	59	56	5.9	58	62	6.9	60	70	16.0
	5	55	44	19.6	57	54	5.1	51	65	26.8
	10	26	30	17.3	46	42	9.7	40	58	44.9
4	0.03	58	59	1.8	69	67	1.5	124	77	38.0
	2	44	44	1.1	55	55	1.7	58	70	19.8
	5	39	28	27.7	47	41	11.7	43	60	39.6
	10	10	13	28.8	37	25	32.9	34	47	38.4
6	0.03	45	55	21.3	68	66	2.6	107	80	24.8
	2	35	35	0.5	47	49	4.3	51	70	37.3
	5	31	17	42.7	42	31	25.3	46	56	21.9
	10	5	5	18.4	22	15	32.5	36	39	7.6
8	0.03	42	50	19.6	59	65	9.7	115	84	27.0
	2	31	28	10.4	42	44	3.8	48	70	46.4
	5	33	11	67.0	38	24	37.3	41	52	27.7
	10	2	2	36.0	18	9	51.6	28	32	14.5

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.40 Observed and predicted mean adult populations in single-species controls of *Cryptolestes ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*C. ferrugineus*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	63	69	11.1	80	77	3.1	125	85	31.8
	2	70	68	3.8	78	73	5.8	90	79	11.8
	5	65	65	0.2	69	68	1.7	73	71	3.1
	10	53	61	13.7	63	60	4.8	64	59	7.9
4	0.03	62	69	11.6	109	85	22.3	258	104	59.6
	2	69	65	5.4	98	77	21.4	96	90	6.5
	5	58	60	4.0	64	66	2.8	82	72	12.4
	10	58	52	9.4	51	51	0.4	63	50	21.6
6	0.03	54	68	27.1	104	93	9.9	268	127	52.6
	2	68	63	7.4	77	80	4.5	73	102	39.4
	5	60	56	6.9	62	64	2.9	59	73	23.8
	10	33	45	39.2	48	43	8.5	46	42	8.3
8	0.03	55	68	24.4	79	103	30.7	232	155	33.1
	2	72	61	15.8	53	84	58.4	55	116	110.5
	5	64	52	18.8	48	62	28.1	47	74	57.7
	10	31	39	26.2	39	37	5.6	42	35	16.4

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.41 Observed and predicted mean adult populations in mixed-species combination of *Cryptolestes ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*C. ferrugineus*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	62	62	0.1	65	66	1.2	80	70	11.9
	2	61	53	11.8	56	60	7.9	75	67	10.4
	5	56	42	24.5	57	52	9.6	53	62	19.0
	10	26	29	11.7	43	40	5.6	38	55	47.7
4	0.03	56	55	2.2	53	62	17.6	110	71	35.3
	2	44	41	7.1	65	51	20.9	63	64	2.3
	5	37	26	31.0	52	38	27.1	37	56	51.8
	10	5	12	163.8	32	23	28.4	24	44	80.6
6	0.03	48	48	0.9	34	59	74.3	146	71	51.0
	2	23	31	33.0	54	44	18.6	60	62	2.7
	5	19	15	16.3	42	28	33.7	39	50	26.8
	10	2	5	167.6	33	13	60.3	35	35	1.1
8	0.03	42	43	2.0	40	55	40.5	91	72	21.1
	2	11	23	113.6	45	37	16.4	34	59	73.4
	5	18	9	49.3	37	20	45.2	43	44	3.3
	10	1	2	67.1	26	7	71.8	27	27	3.1

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.42 Observed and predicted mean adult populations in mixed-species combination of *Cryptolestes ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*C. ferrugineus*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	55	67	20.8	77	74	3.8	100	82	18.1
	2	69	65	6.2	78	70	10.0	82	76	6.9
	5	66	62	5.6	73	65	10.7	69	68	0.4
	10	58	58	0.8	64	57	10.3	60	57	5.2
4	0.03	63	64	1.8	85	78	7.6	156	96	38.2
	2	70	60	13.6	89	71	20.0	79	83	5.3
	5	58	56	3.9	56	61	9.5	71	67	6.6
	10	43	48	11.8	46	47	1.8	55	46	17.1
6	0.03	61	61	0.3	88	83	5.6	165	113	31.3
	2	70	56	19.5	96	71	25.4	51	91	77.0
	5	58	49	14.8	69	57	18.2	45	65	44.2
	10	32	40	25.5	52	39	25.4	43	37	13.8
8	0.03	49	58	18.1	77	88	14.5	155	132	14.4
	2	69	52	24.5	55	72	30.3	64	99	54.5
	5	59	44	25.1	46	53	14.7	52	63	22.3
	10	34	33	2.6	42	32	24.7	32	30	6.4

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.43 Observed and predicted mean adult populations in single-species controls of *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*T. castaneum* Temperature (°C) 15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	67	64	5.0	70	76	8.9	136	91	33.5
	2	67	69	3.1	67	77	15.0	135	87	36.0
	5	66	78	19.3	65	79	22.1	90	81	9.9
	10	64	96	50.0	64	83	29.2	84	72	14.9
4	0.03	66	66	0.7	74	85	14.7	138	109	20.6
	2	65	66	2.4	66	81	23.2	136	100	26.2
	5	53	67	25.6	66	77	16.0	78	88	13.1
	10	51	68	35.1	64	69	7.8	70	70	0.8
6	0.03	64	76	19.3	68	97	42.1	136	122	10.1
	2	58	61	5.7	67	81	22.5	137	108	20.7
	5	56	44	21.7	63	63	0.1	101	90	11.2
	10	51	25	51.0	60	41	32.2	79	66	16.7
8	0.03	65	101	54.9	61	113	87.2	193	127	34.1
	2	52	55	6.6	71	78	10.3	137	110	19.7
	5	51	22	57.1	63	44	30.8	68	87	28.1
	10	1	4	253.0	42	17	59.9	55	59	8.4

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.44 Observed and predicted mean adult populations in single-species controls of *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*T. castaneum*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	60	67	11.0	92	83	9.6	151	102	32.1
	2	69	67	2.5	75	80	6.7	109	96	12.4
	5	69	68	1.6	67	77	15.0	96	87	9.5
	10	66	69	4.9	74	71	4.2	86	73	14.9
4	0.03	66	66	0.4	74	94	26.6	289	133	54.0
	2	69	67	3.1	66	89	34.6	142	118	16.6
	5	71	68	4.4	64	82	27.4	112	99	11.7
	10	63	69	9.6	61	71	17.6	97	74	23.8
6	0.03	65	67	3.6	72	102	41.9	392	154	60.6
	2	67	68	0.9	69	95	37.9	169	132	21.4
	5	70	69	0.7	65	85	30.3	117	105	10.5
	10	62	71	15.5	62	71	14.9	83	71	14.9
8	0.03	62	70	14.4	69	106	54.9	389	160	58.9
	2	67	71	6.9	74	98	32.8	163	134	17.8
	5	67	72	8.2	66	86	30.7	107	102	4.6
	10	61	74	22.1	63	70	10.4	74	65	12.2

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.45 Observed and predicted mean adult populations in mixed-species combination of *Tribolium castaneum* in dry (12% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*T. castaneum*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	64	57	10.7	70	68	2.6	90	81	9.1
	2	66	62	6.5	64	69	9.3	64	78	22.3
	5	65	70	7.9	66	71	8.0	62	72	17.7
	10	51	86	68.2	66	74	13.3	63	64	2.6
4	0.03	62	53	14.9	61	68	12.2	81	88	8.2
	2	61	53	12.1	64	66	1.9	61	81	32.7
	5	63	54	13.8	65	62	4.8	61	71	16.7
	10	47	55	17.6	60	56	7.0	54	57	5.4
6	0.03	62	55	11.0	64	70	10.0	104	88	15.0
	2	48	44	7.3	65	59	9.0	62	78	27.3
	5	58	32	45.7	62	45	27.1	51	65	26.9
	10	31	18	42.5	53	29	44.7	50	48	3.6
8	0.03	61	65	7.1	66	74	12.3	84	83	0.9
	2	26	36	36.1	60	50	15.9	56	71	26.4
	5	46	14	69.1	58	28	51.2	50	57	13.0
	10	3	3	17.0	9	11	25.4	36	38	8.3

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

Table 5.46 Observed and predicted mean adult populations in mixed-species combination of *Tribolium castaneum* in wet (15% wb) grain at 15, 20, and 25°C at selected exposure intervals and ambient (0.03%), 2, 5, and 10% levels of CO_2 at selected time intervals.

Time (wk)	CO_2 level (%)	*T. castaneum*								
		Temperature (°C)								
		15			20			25		
		Observed	Predicted	P*	Observed	Predicted	P	Observed	Predicted	P
2	0.03	59	60	2.2	70	74	6.4	90	92	2.0
	2	69	60	12.5	65	72	11.3	72	86	19.8
	5	69	61	11.3	63	69	9.3	69	78	12.3
	10	67	62	7.6	63	64	1.4	64	66	3.3
4	0.03	56	53	4.3	63	75	19.4	83	107	29.2
	2	69	54	22.6	61	72	17.3	63	95	52.1
	5	67	54	18.1	58	66	14.2	66	80	21.5
	10	61	56	8.9	56	58	3.2	59	59	0.6
6	0.03	65	48	25.4	59	74	25.9	84	112	33.0
	2	69	49	28.5	65	69	6.3	81	96	18.3
	5	69	50	27.7	58	61	6.4	65	76	17.0
	10	57	51	10.4	53	51	3.8	57	51	10.6
8	0.03	58	46	21.7	63	69	9.7	92	104	12.9
	2	65	46	29.1	53	63	19.0	63	87	38.6
	5	67	47	30.1	53	56	4.7	53	66	24.7
	10	56	48	14.5	49	45	8.0	49	42	12.9

* P - relative percent error (absolute value of percent of difference between predicted and observed divided by observed populations).

T. castaneum, were reared in single and mixed-species combination at ambient (0.03%) CO_2 level. The insect density and observation period were the same as in the experiments at low temperatures and CO_2 levels. The adult survival at the end of 8 wk at optimum conditions was compared with adult survival at low temperatures and CO_2 levels to assess the stress of temperature, CO_2 level, and moisture content on the adult populations. The comparison between the adult population at optimum conditions and at lower temperatures and higher CO_2 levels is shown in Tables 5.47 and 5.48. Adult population at lower temperatures and higher CO_2 levels were significantly lower than the adult population at optimum conditions at low and high moisture contents in single and mixed-species combinations. All the three variables: temperature, CO_2 concentration, and moisture content have negative stress on adult survival compared with the optimum conditions. The mortality and decrease in the test species at cool temperatures and increased CO_2 levels have been quantified to demonstrate that keeping grain cool and dry inhibits insect growth and multiplication without significant deterioration in germination and thus maintaining the quality of grain.

5.12 Comparison of Single-species Adult Population of *C. ferrugineus* with Kawamoto's model

The mean adult survival in single-species controls of *C. ferrugineus* at low temperatures in dry (12% wb) and wet(15% wb) grain at various CO_2 levels was compared with predicted adult survival from Kawamoto's model (Kawamoto et al. 1989b) at ambient CO_2 level. The observed mean adult survival was also compared with predicted adult population using the model arrived at in this study. The comparison among the observed adult populations with the two models is shown in Table 5.49.

Table 5.47 Comparison of mean adult populations in single-species controls of *Cryptolestes ferrugineus* and *Tribolium castaneum* at 30°C, 70% RH* with experimental tests at low temperatures and CO_2 levels in dry (12% wb) and wet (15% wb) grain at the end of 8 wk.

Moisture content (% wb)	CO_2 (%)	*C. ferrugineus* Temperature (°C)				*T. castaneum* Temperature (°C)			
		30	25	20	15	30	25	20	15
Dry (12%)	0.03	60	115	59	42	331	193	61	65
	2		48	42	31		137	71	52
	5		41	38	33		68	63	51
	10		28	18	2		55	42	1
Wet (15%)	0.03	902	232	79	55	387	389	69	62
	2		55	53	72		163	74	67
	5		47	48	64		107	66	67
	10		42	39	31		74	63	61

Table 5.48 Comparison of mean adult populations in mixed-species combination of *Cryptolestes ferrugineus* and *Tribolium castaneum* at 30°C, 70% RH* with experimental tests at low temperatures and CO_2 levels in dry (12% wb) and wet (15% wb) grain at the end of 8 wk.

Moisture content (% wb)	CO_2 (%)	*C. ferrugineus* Temperature (°C)				*T. castaneum* Temperature (°C)			
		30	25	20	15	30	25	20	15
Dry (12%)	0.03	76	91	40	42	106	84	66	61
	2		34	45	11		56	60	26
	5		43	37	18		50	58	46
	10		27	26	1		36	9	3
Wet (15%)	0.03	770	155	77	49	158	92	63	58
	2		64	55	69		63	53	65
	5		52	46	59		53	53	67
	10		32	42	34		49	49	56

* the experiment at these conditions also had the same initial number of adult population (i.e. insect density) as in the experimental tests at low temperatures and CO_2 concentrations.

Table 5.49 Comparison of adult populations of *Cryptolestes ferrugineus* predicted by Kawamoto's model in ambient CO_2 conditions at 15, 20, 25, and 30°C with observed and predicted mean adult populations at test temperatures and CO_2 levels in this study in dry (12% wb) and wet (15% wb) grain at the end of 8 wk.

Moisture content (% wb)	CO_2 levels (%)	*C. ferrugineus*										
		Temperature (°C)										
		30		25			20			15		
		P_K*	O_S†	P_K	P_S☼	O_S	P_K	P_S	O_S	P_K	P_S	O_S
Dry (12%)	0.03	2071	902	910	84	115	351	65	59	70	50	42
	2				70	48		44	42		28	31
	5				52	41		24	38		11	33
	10				32	28		9	18		2	2
Wet (15%)	0.03	3485	60	1022	155	232	351	103	79	70	68	55
	2				116	55		84	53		61	72
	5				74	47		62	48		52	64
	10				35	42		37	39		39	31

* predicted adult population by Kawamoto et al. (1989b) model.
☼ predicted mean adult population from the model derived in this study.
† observed mean adult population in this study.

The comparison shows that at ambient CO_2 levels, Kawamoto's model over predicted the adult populations at 20 and 25°C whereas the model obtained in this study under predicted the adult population at 25°C and over predicted at 20°C. The mean adult populations at 2, 5, and 10% levels of CO_2 were lower than the predicted populations at ambient CO_2 level of both models, indicating the effect of CO_2 in reducing the adult population.

6. CONCLUSIONS

I outlined the objectives of this study in Chapter 2 and in short this study was an investigation into how *C. ferrugineus* and *T. castaneum*, the two common and economically important pests of Canadian stored-cereals survive and multiply by themselves and in combination, at low temperatures of 15, 20, and 25 °C and at low CO_2 concentrations of 2, 5, and 10% in dry (12% wb) and wet (15% wb) grain. The following conclusions can be drawn from this work:

1. The temperature range of 15 to 25 °C had a significant effect on the adult survival of both *C. ferrugineus* and *T. castaneum* in single-species as well as mixed-species combinations and multiplication generally increased with increasing temperature. At 15 °C, the survival decreased with time and there was no addition to the population as the incubation count was zero since no eggs were laid at this temperature in both the species in all treatments. At 25 °C, the second generation appeared in the first count for both of the species indicating that at 15 and 20 °C the insects do not multiply or that the hatching is delayed or inhibited due to the effect of CO_2. In general, the adult survival in mixed-species combination of two species was significantly lower than corresponding single-species controls. There was significant interaction between temperature and other variables like CO_2 levels, moisture content, species combination and time which also affected the adult survival.
2. The CO_2 concentrations of 2, 5, and 10% significantly affected the adult survival of both

T. castaneum and *C. ferrugineus* in single and mixed-species combinations. The adults from the first count, incubation count and total adult survival, decreased for all the treatments for both the species with increasing CO_2 concentrations compared to the ambient CO_2 level at constant test temperatures. An exception at the 2% CO_2 level was observed for single-species controls of *C. ferrugineus* at 15°C which is attributed to experimental error or biological variation within the replicates. The decrease in incubation count with increasing CO_2 levels in both the species indicates that probably CO_2 has an inhibiting or delaying effect on the egg laying. The mean adult mortality increased with time and increasing CO_2 levels at constant temperature for both the species at single and mixed-species combinations. At 5 and 10% CO_2 levels, significant adult mortality was observed after 6 wk at 20 and 25°C in both species. This observation could possibly be utilized in practice by mixing CO_2 with air when aerating or ventilating grain in bins for storage over prolonged periods or followed by sealing the bin.

3. The moisture content of grains determines the equilibrium relative humidity of the inter-granular space. The low (12% wb) and high (15% wb) moisture contents had significant effect on the adult survival of both the species in both single and mixed-species combinations. The adult survival was higher in wet grains compared to dry grains for both species in single and mixed-species combinations. Two way interaction between RH and CO_2 levels was highly significant with higher adult mortality in dry grains compared to wet grains with increasing levels of CO_2. A significant two-way interaction existed between the humidity and temperature reflects our current understanding that keeping the grain dry and cool would be an

ideal combination for safe storage.

4. The adult survival in mixed-species combination was significantly lower than the single-species populations at various treatments. Adult populations of both *C. ferrugineus* and *T. castaneum* were suppressed. The population suppression was less in *C. ferrugineus* compared with *T. castaneum*. The *C. ferrugineus* had a significant effect in inhibiting the population of *T. castaneum* in both dry and wet grain. The adult survival in mixed-species combination decreased with increase of CO_2 levels and both the species generally had significantly lower adult survival compared to their corresponding single-species controls.
5. The germination of wheat (cv. 'AC Barrie') was not significantly affected at 15 and 20°C because at these temperatures the metabolic activity in insects is low and they are less active and have easier access to dockage than consuming the whole grain. At 25°C, the germination was significantly affected and decreased with increasing time intervals.
6. Based on the data of adult survival for a range of temperatures, CO_2 levels, moisture contents (relative humidities), exposure time, and species combination, equations were developed to predict adult populations. One equation for each species was developed which also takes into account the species combination (single or mixed-species). The equations predicted the adult population with an initial population of 70 adults per 70 g (1000 adults per kg) over a period of 8 wk within the range of values of variables carried out in this study. The two models reasonably predicted the adult populations of two species with large errors at 15°C. The model needs to be validated with field data and further refined.

7. The adult survival at all the low temperatures and low CO_2 levels in dry and wet grain was compared with adult survival at 30°C and 70% RH for both the single and mixed-species combinations of two species. The comparison showed variables in this study namely temperature, moisture content, and CO_2 levels are stress factors and negatively affect the adult survival compared to ideal conditions at 30°C, 70% RH, and negligible CO_2. The comparison of observed adult survival in single-species controls of *C. ferrugineus* at various temperatures with predicted adult survivals in the present study and Kawamoto's model indicated variation stressing the need for validation and further refinement of the mathematical models.

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APPENDIX A

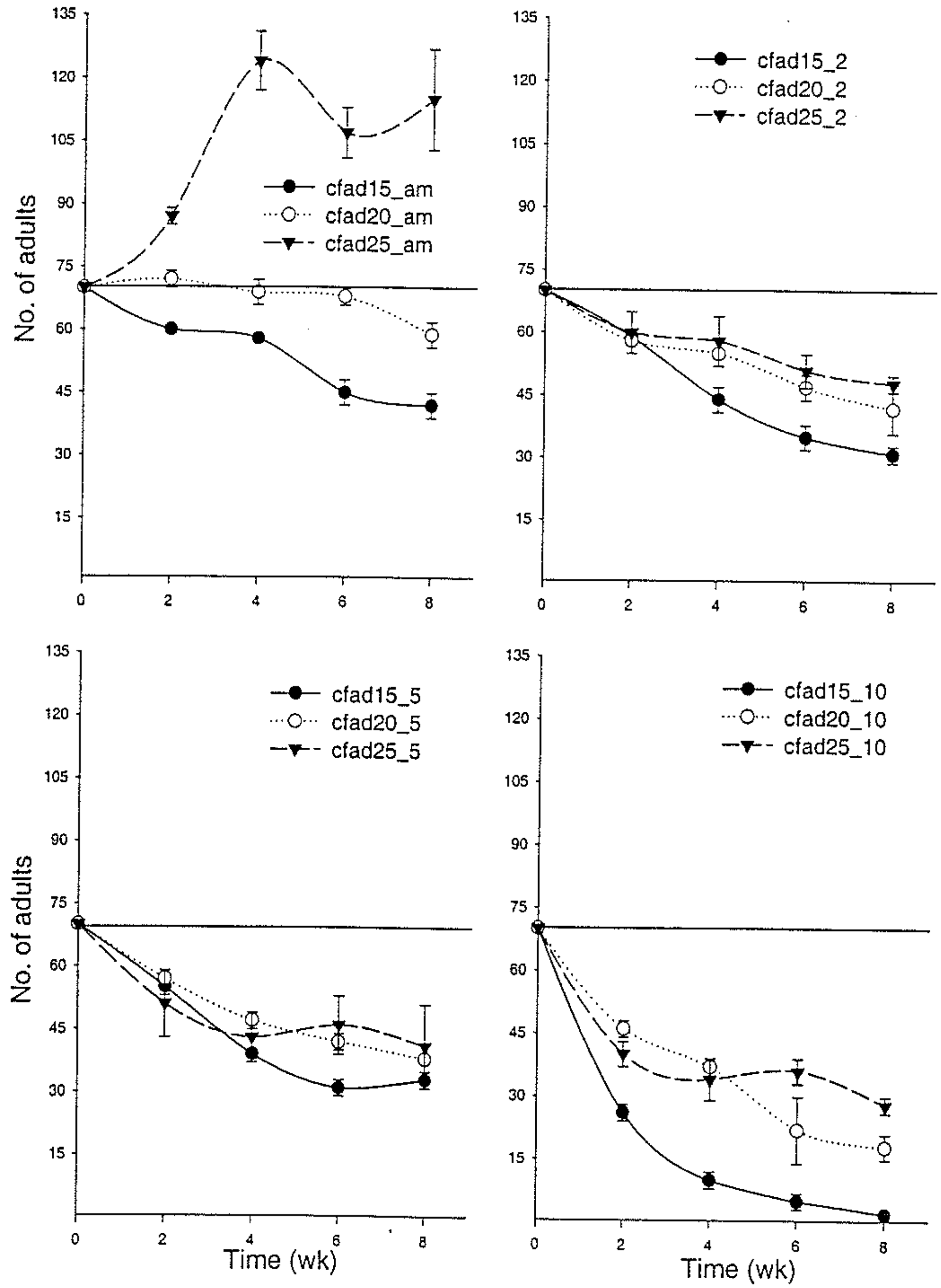

Fig. A1 Effect of temperature on mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

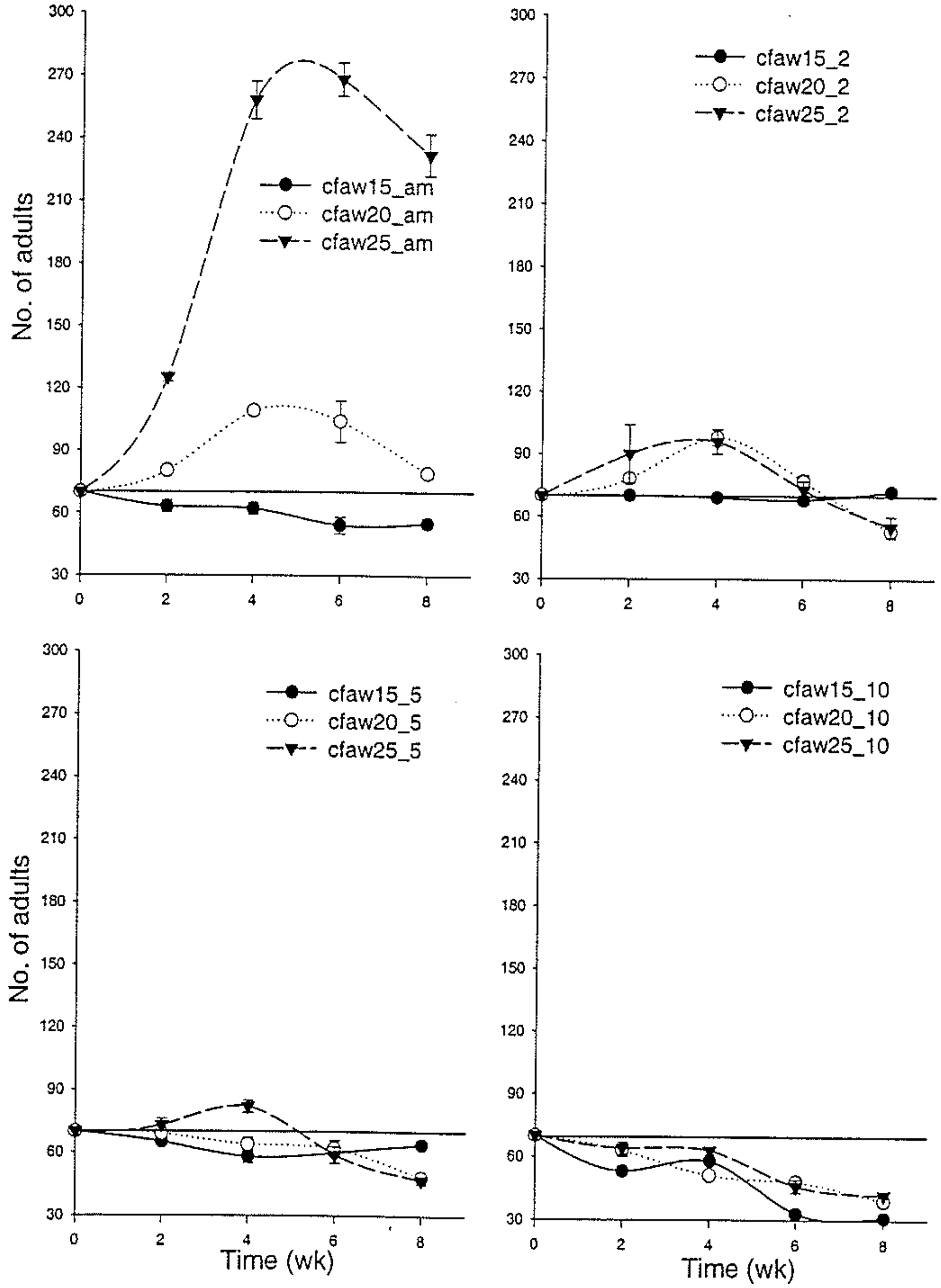

Fig. A2 Effect of temperature on mean adult survival in single-species controls of *C. ferrugineus* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

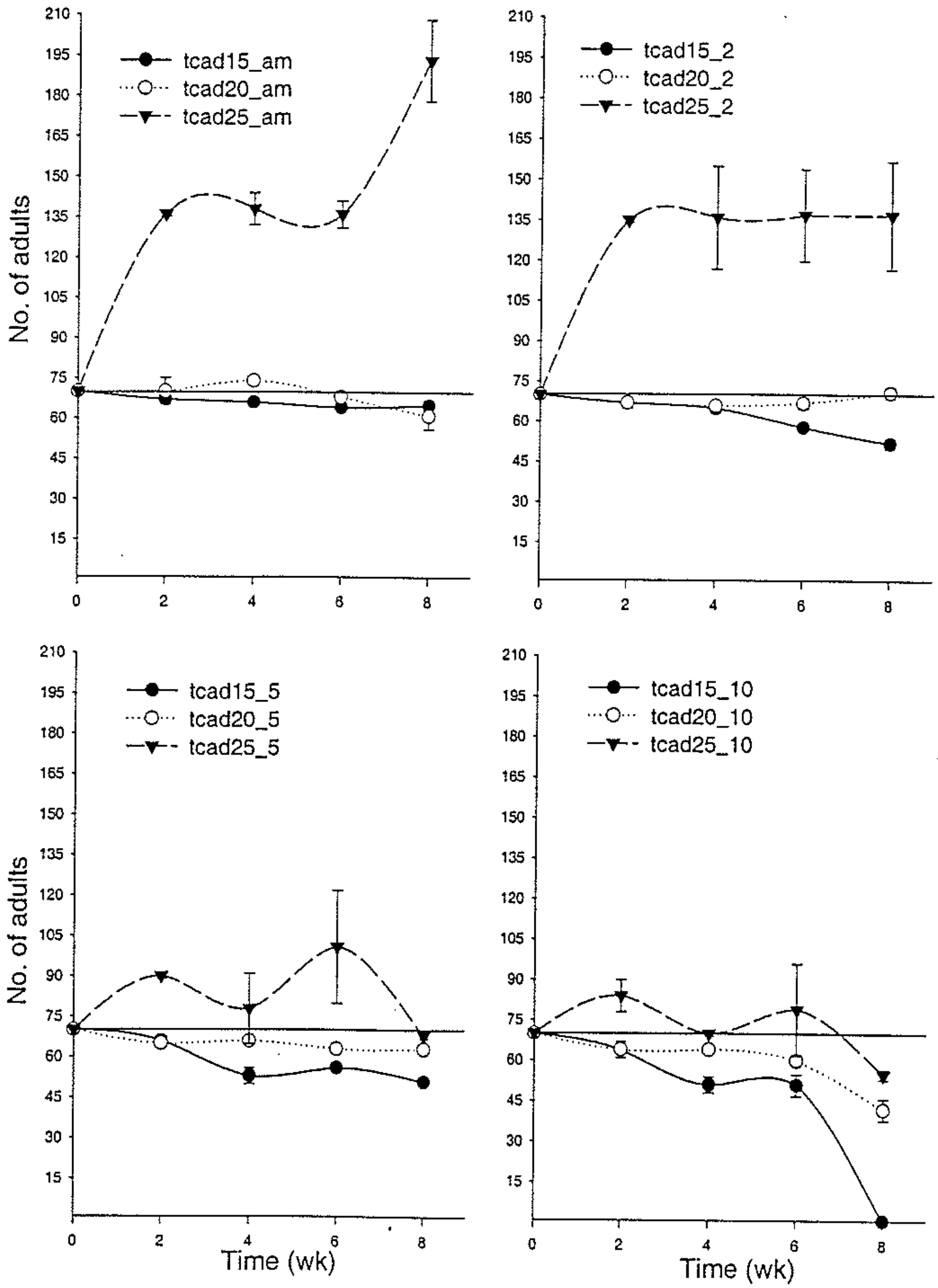

Fig. A3 Effect of temperature on mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

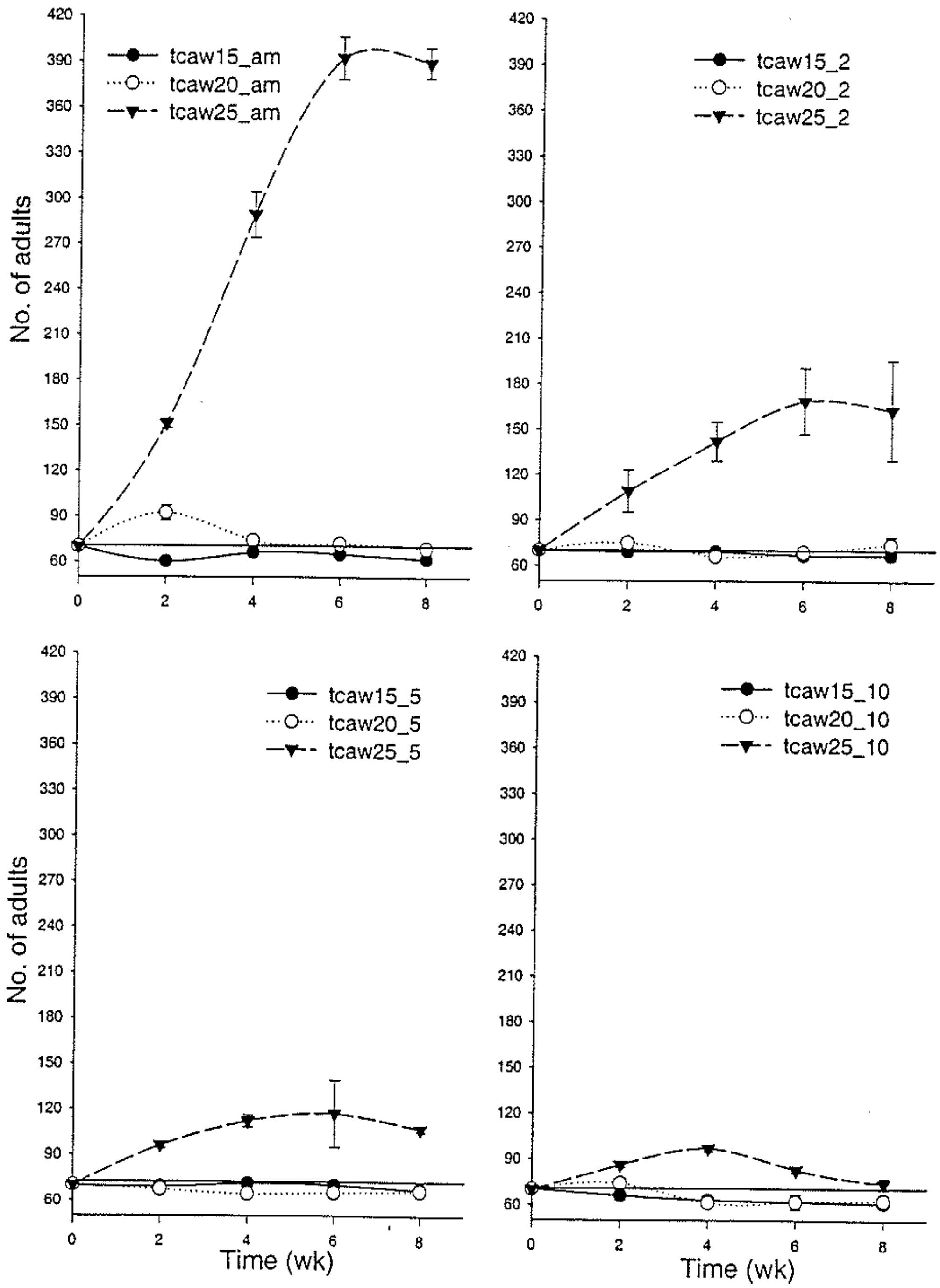

Fig. A4 Effect of temperature on mean adult survival in single-species controls of *T. castaneum* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

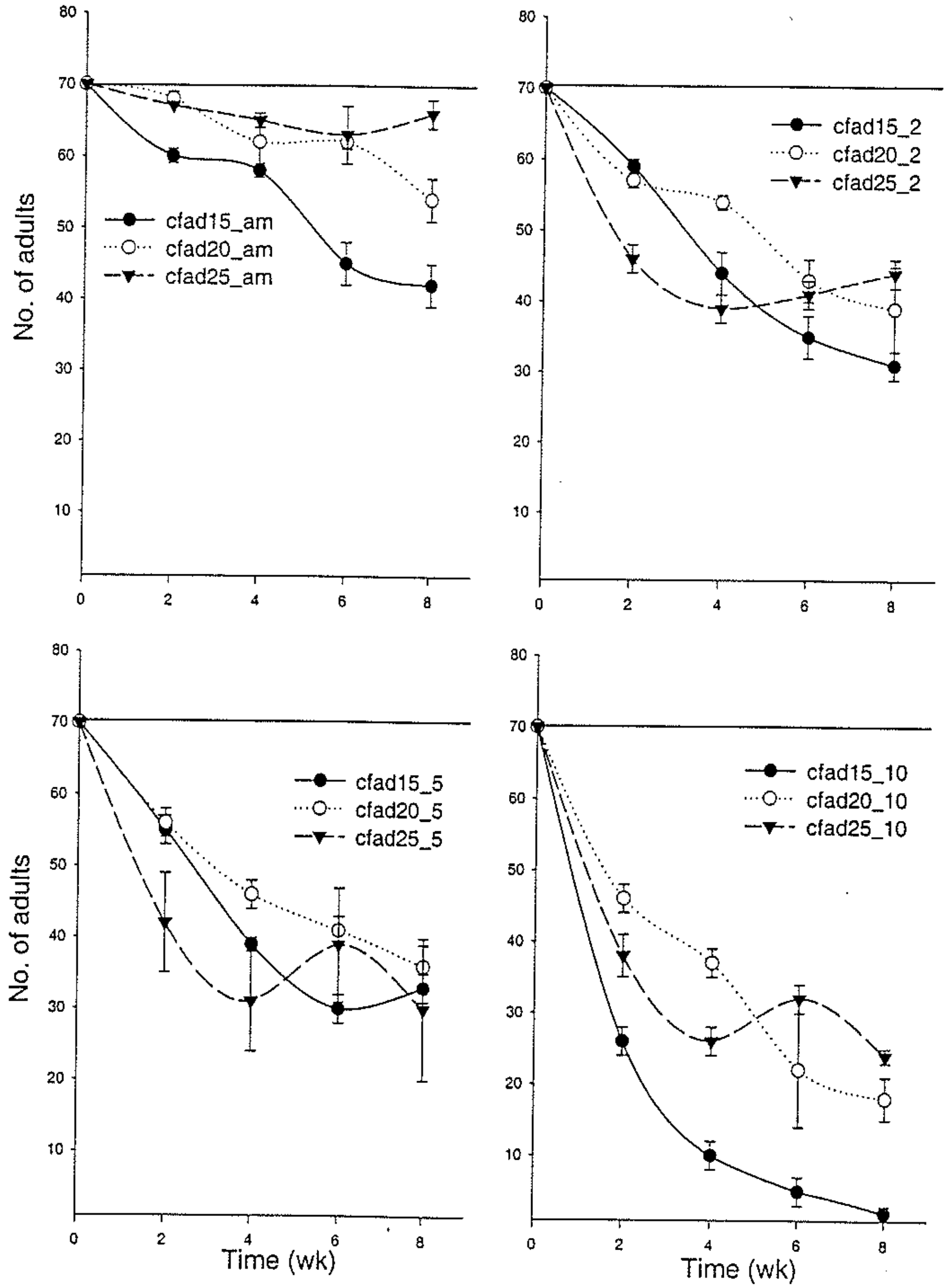

Fig. A5 Effect of temperature on mean adult survival from first count in single-species controls of *C. ferrugineus* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

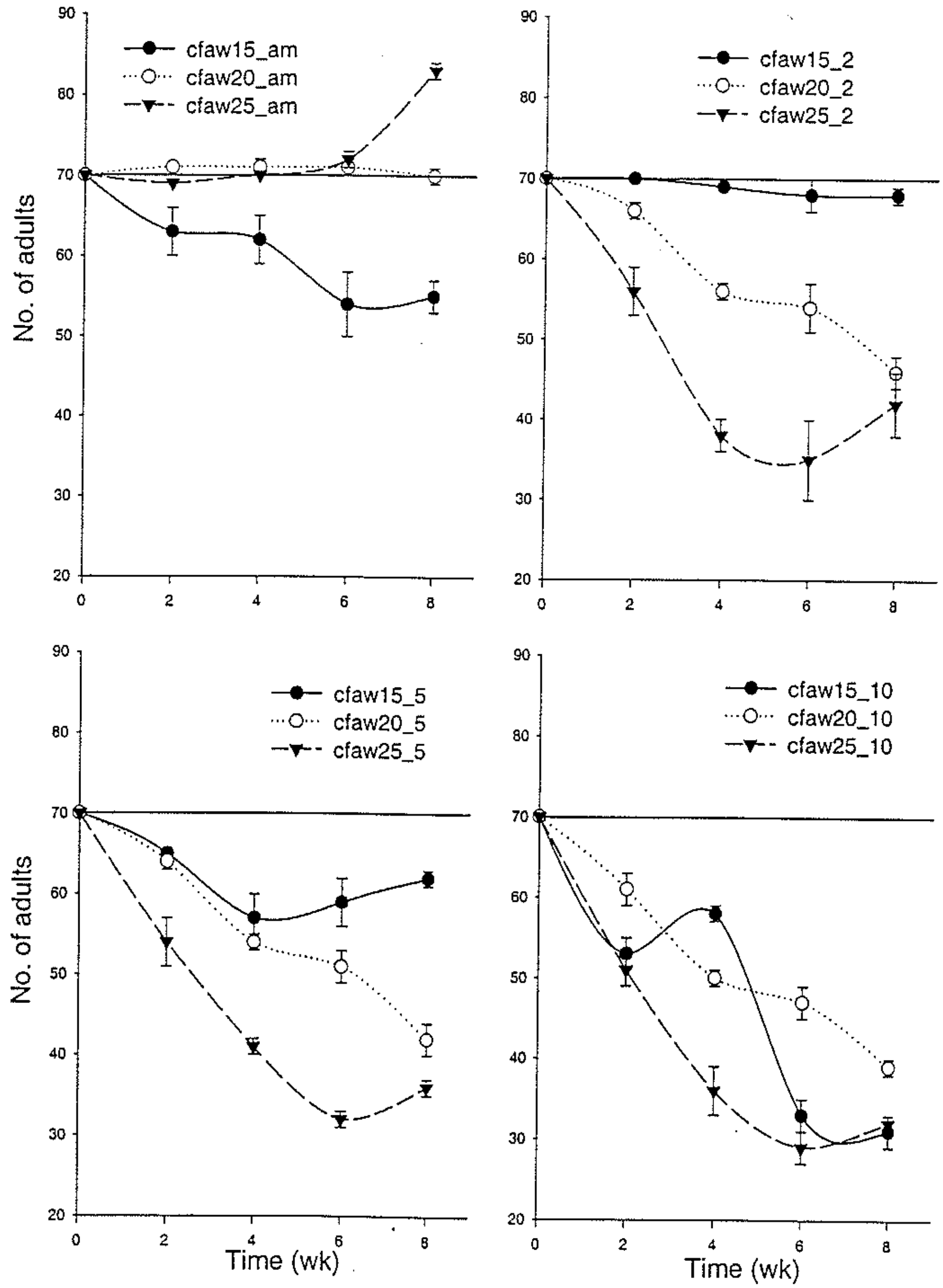

Fig. A6 Effect of temperature on mean adult survival from first count in single-species controls of *C. ferrugineus* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

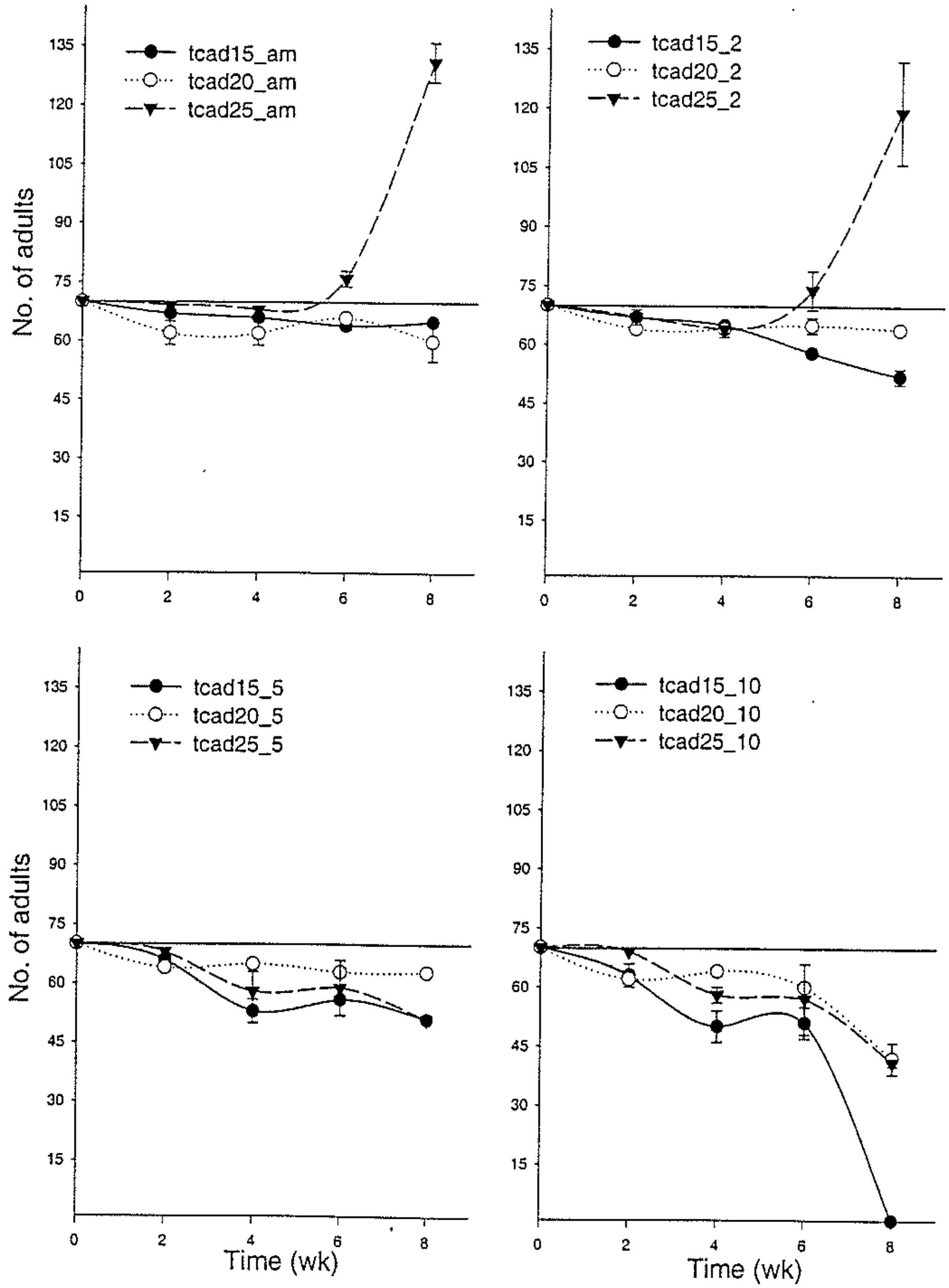

Fig. A7 Effect of temperature on mean adult survival from first count in single-species controls of *T. castaneum* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

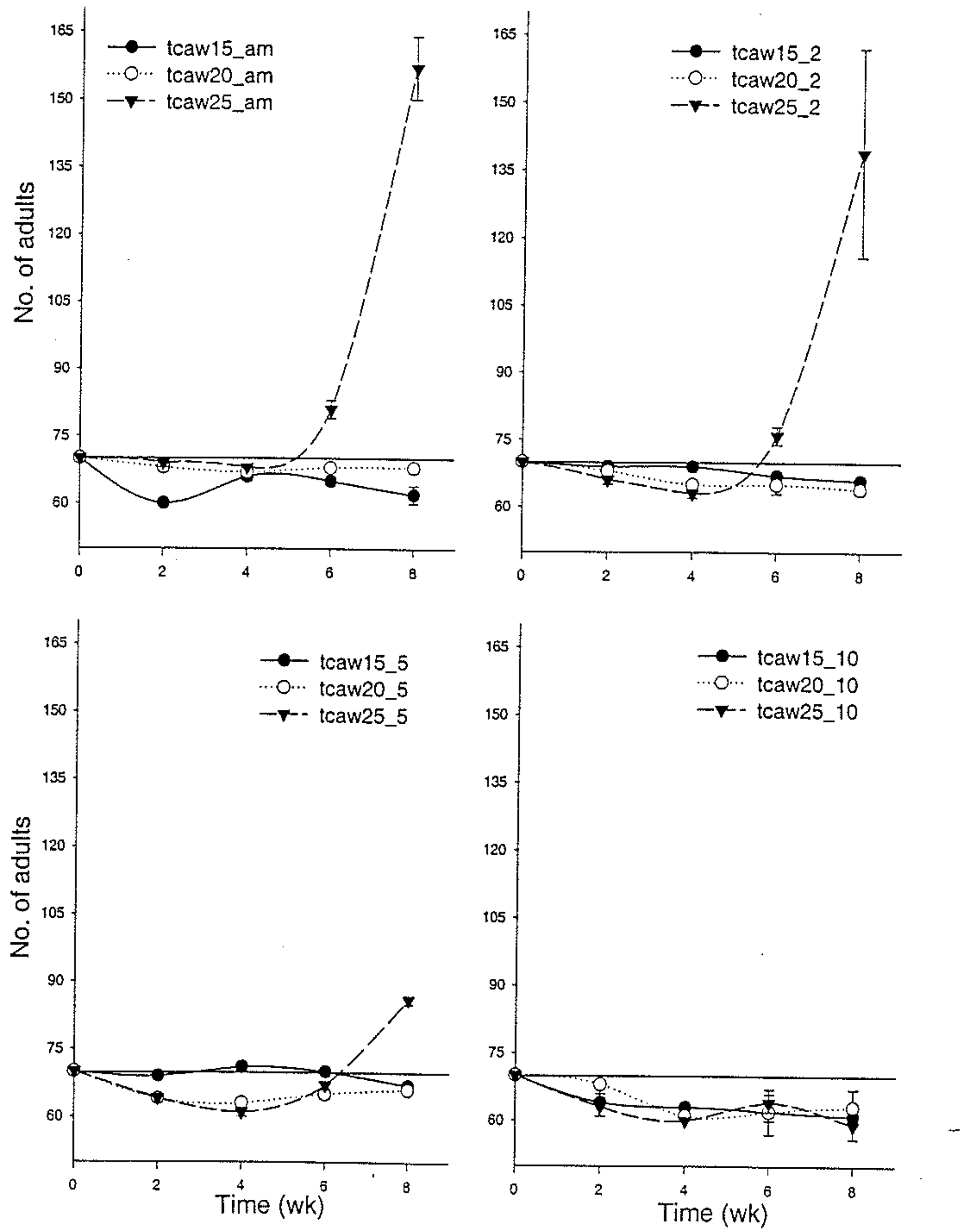

Fig. A8 Effect of temperature on mean adult survival from first count in single-species controls of *T. castaneum* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

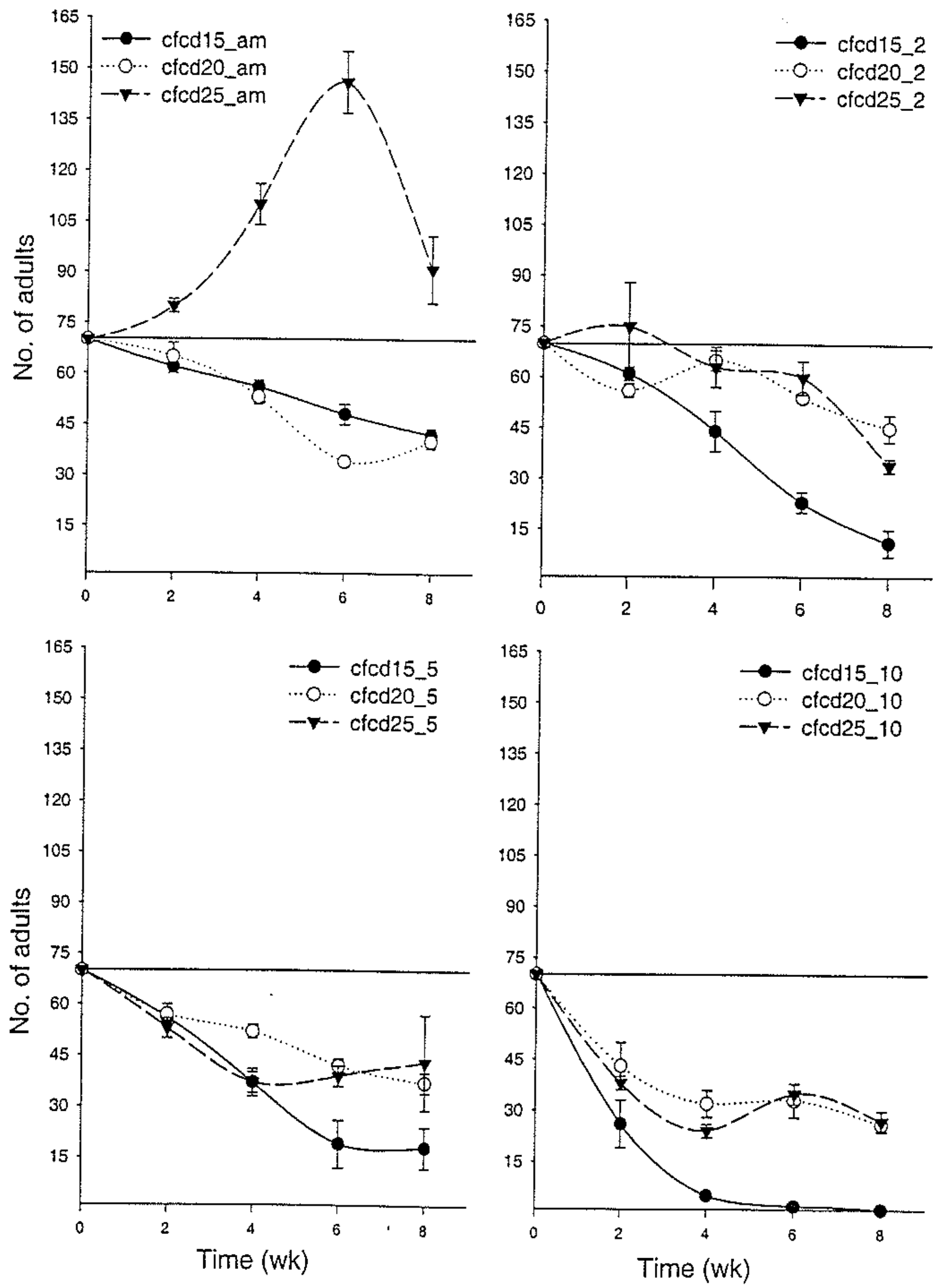

Fig. A9 Effect of temperature on mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

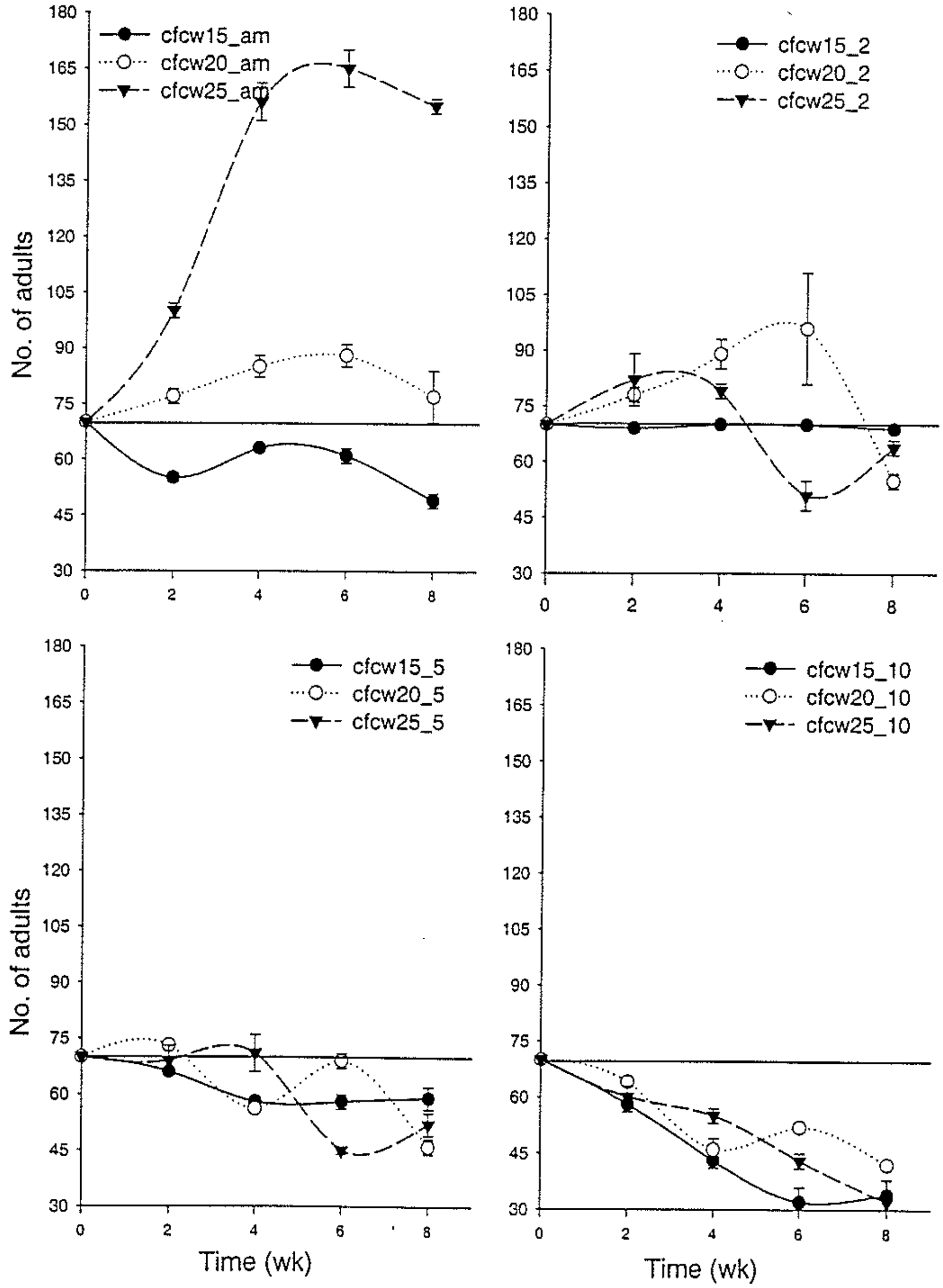

Fig. A10 Effect of temperature on mean adult survival in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

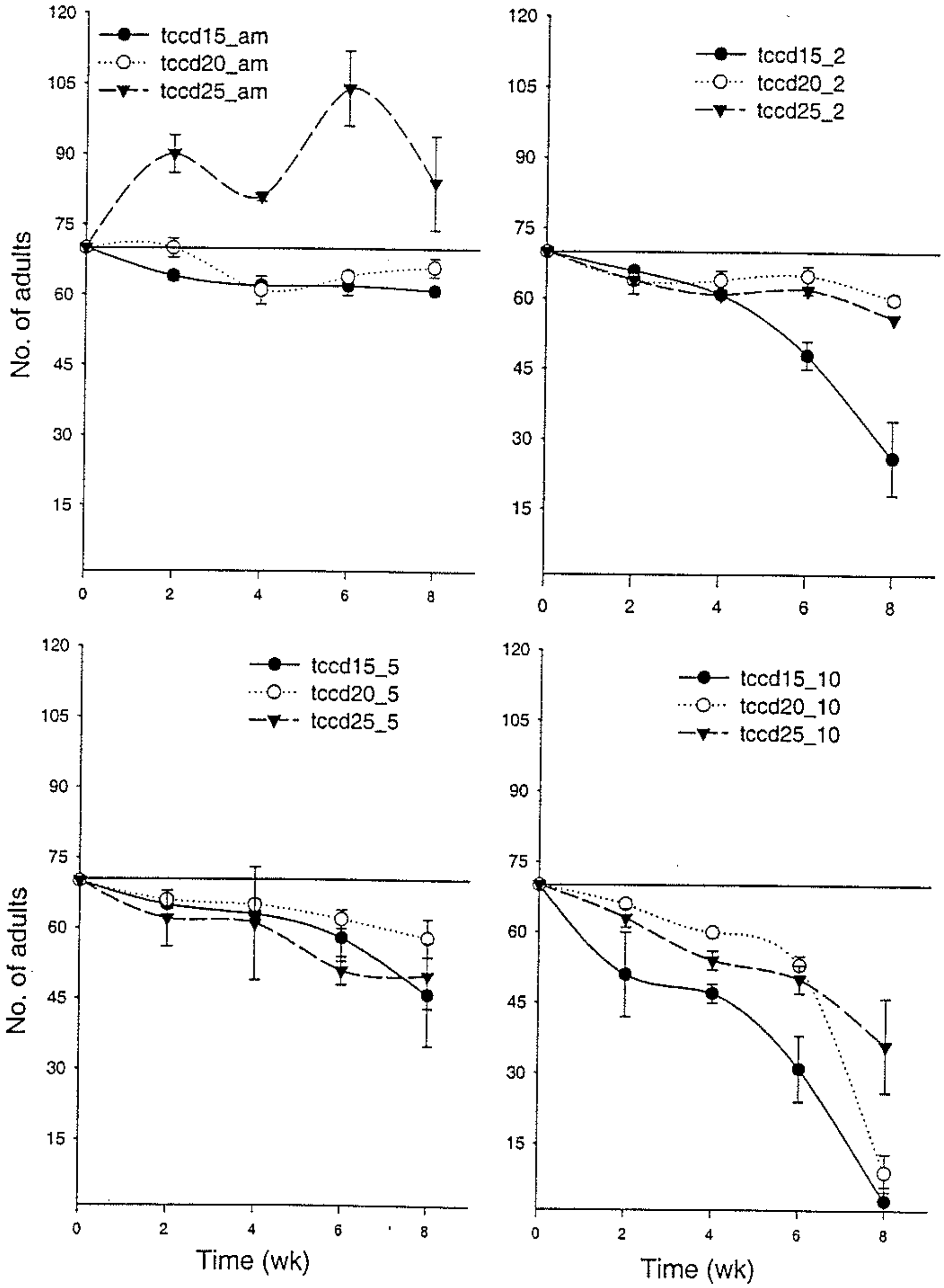

Fig. A11 Effect of temperature on mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

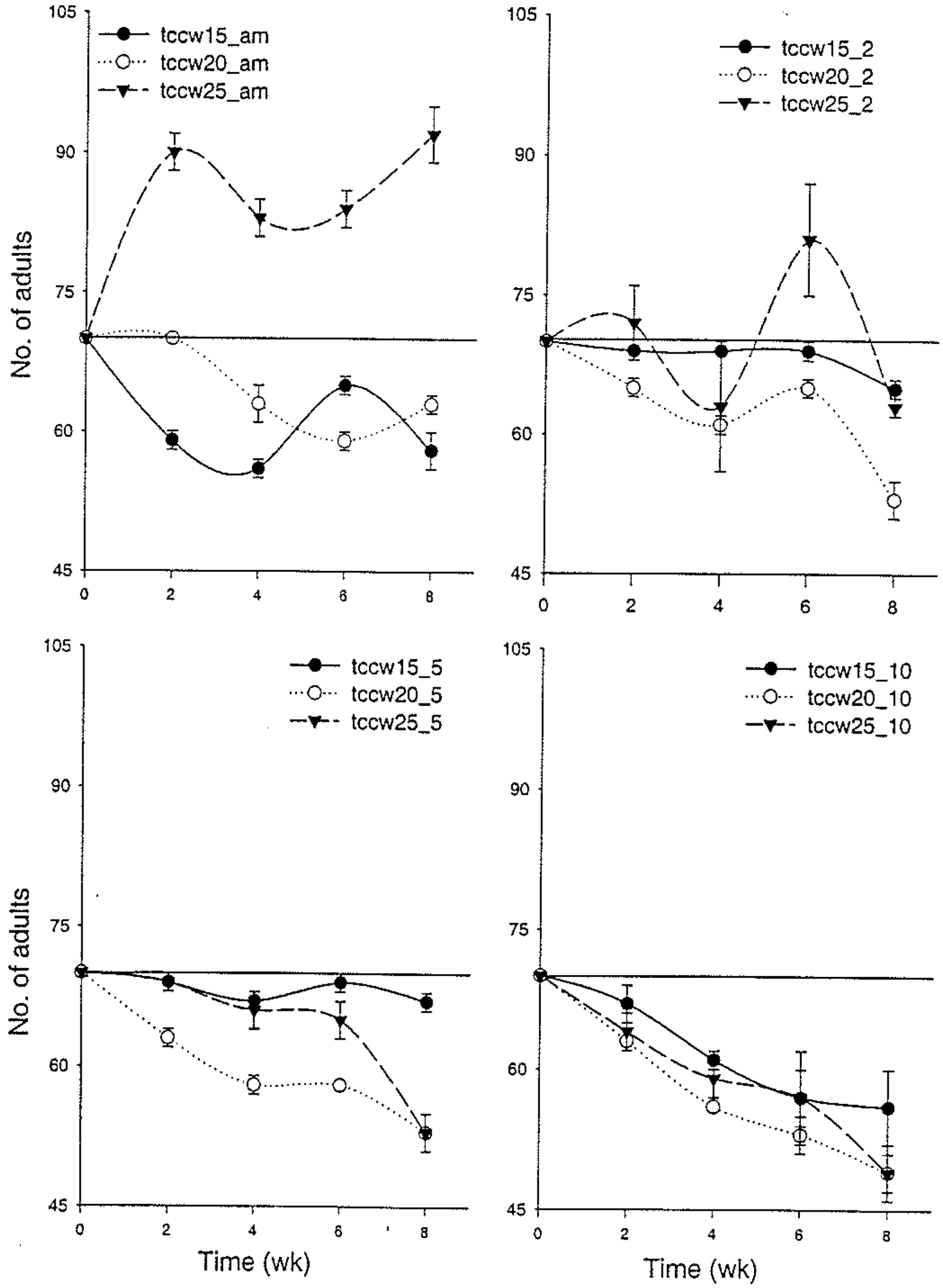

Fig. A12 Effect of temperature on mean adult survival in mixed-species combination of *T. castaneum* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

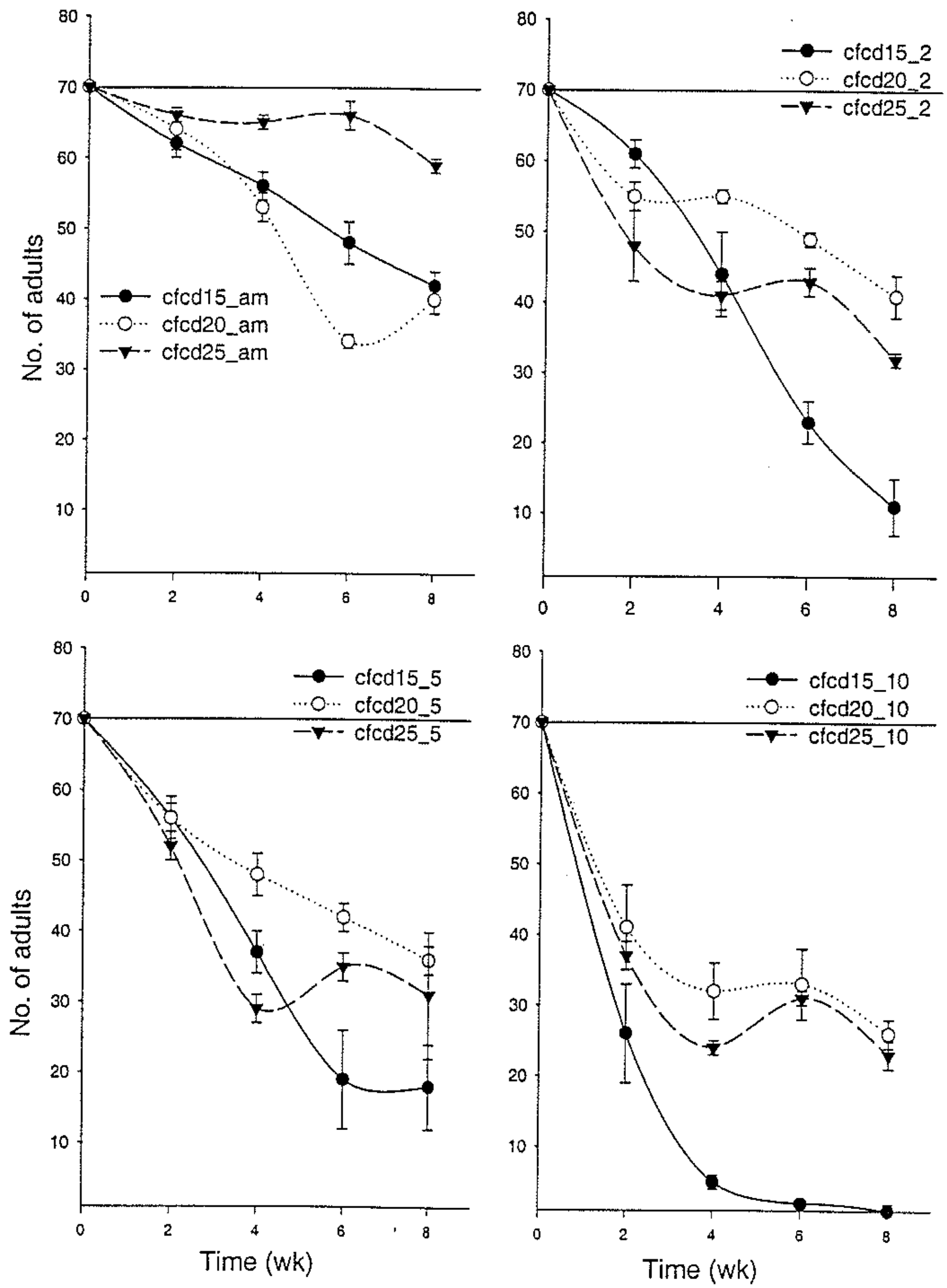

Fig. A13 Effect of temperature on mean adult survival from first count in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

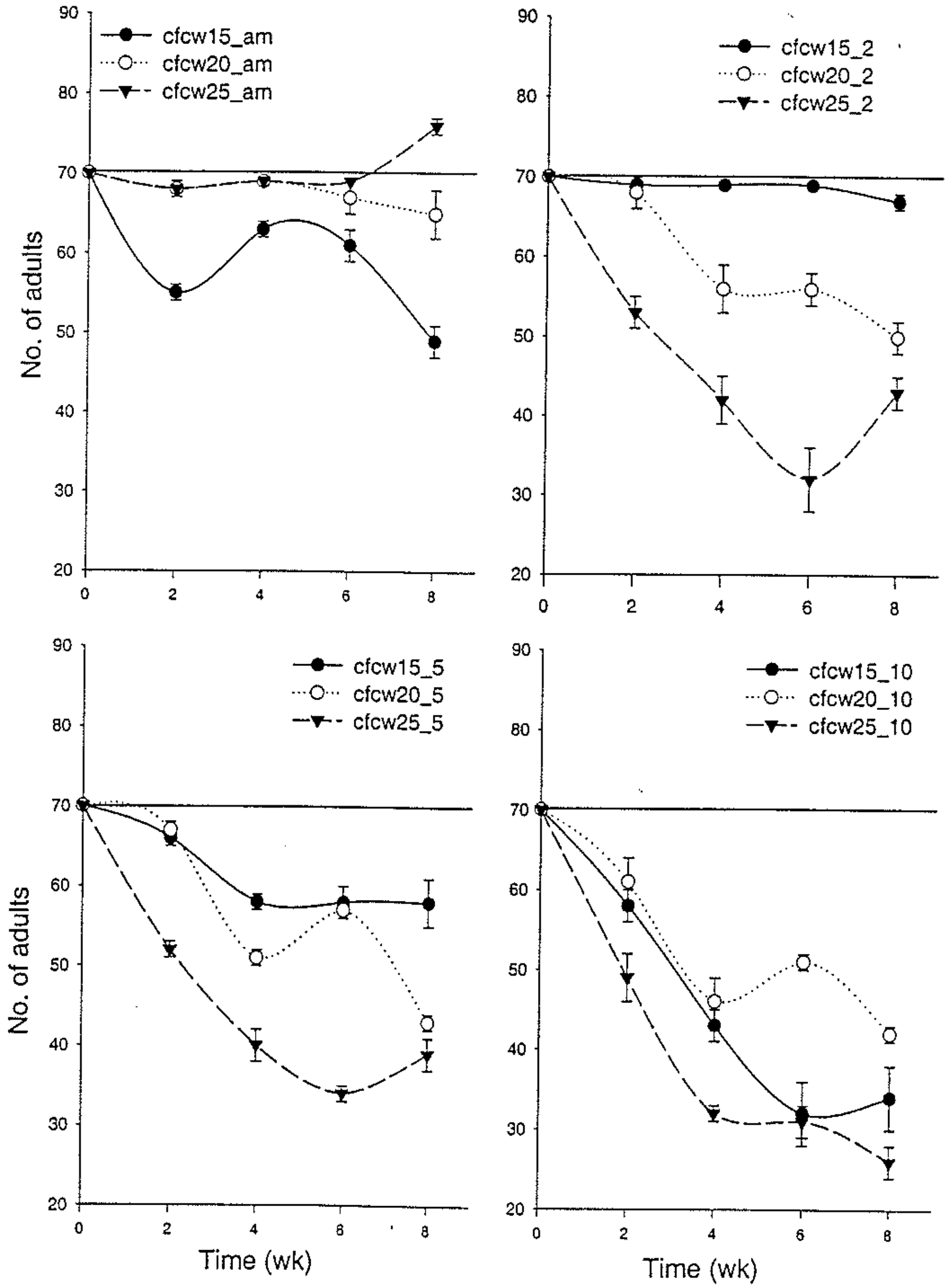

Fig. A14 Effect of temperature on mean adult survival from first count in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

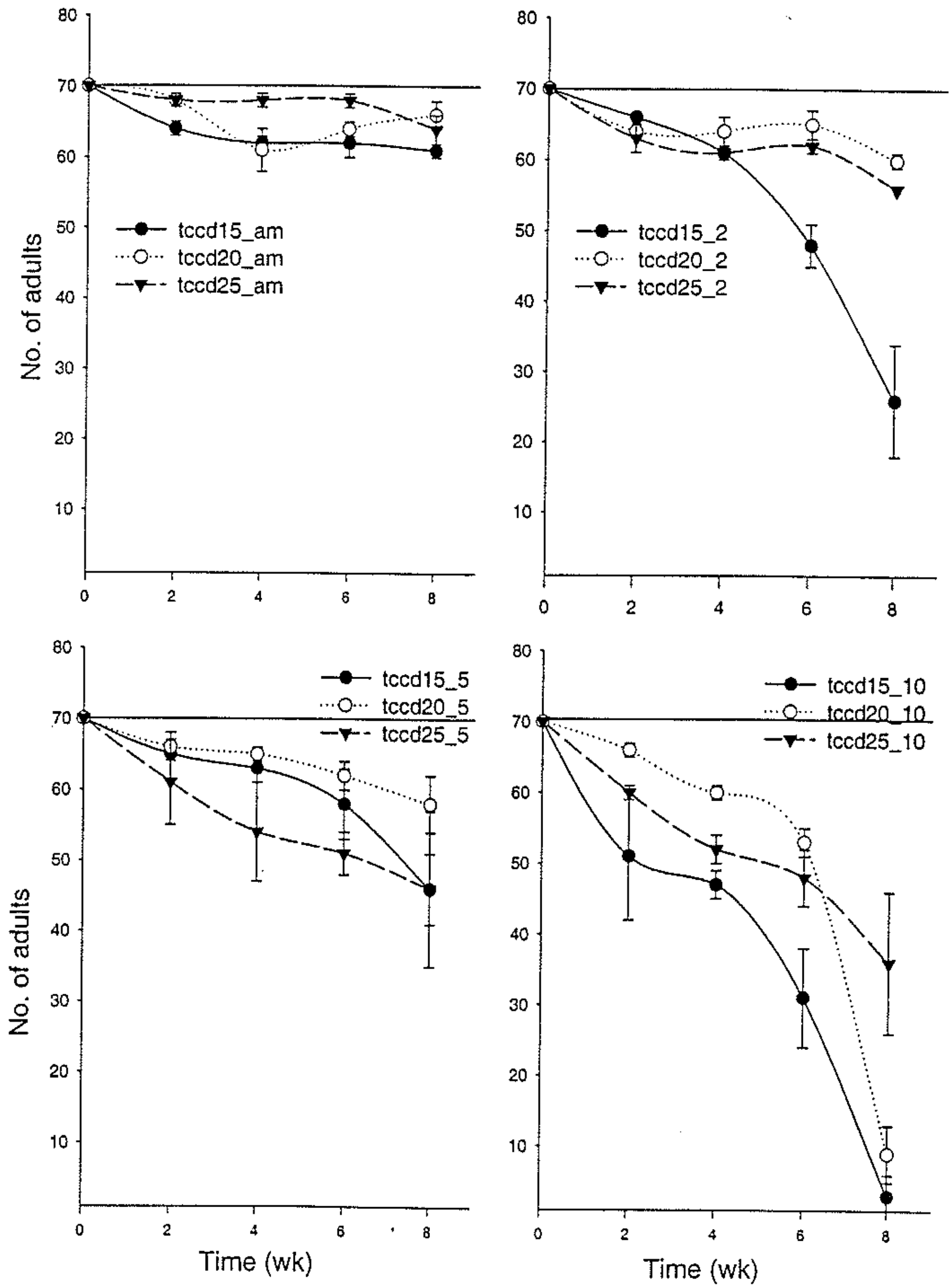

Fig. A15 Effect of temperature on mean adult survival from first count in mixed-species combination of *T. castaneum* in dry (12% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

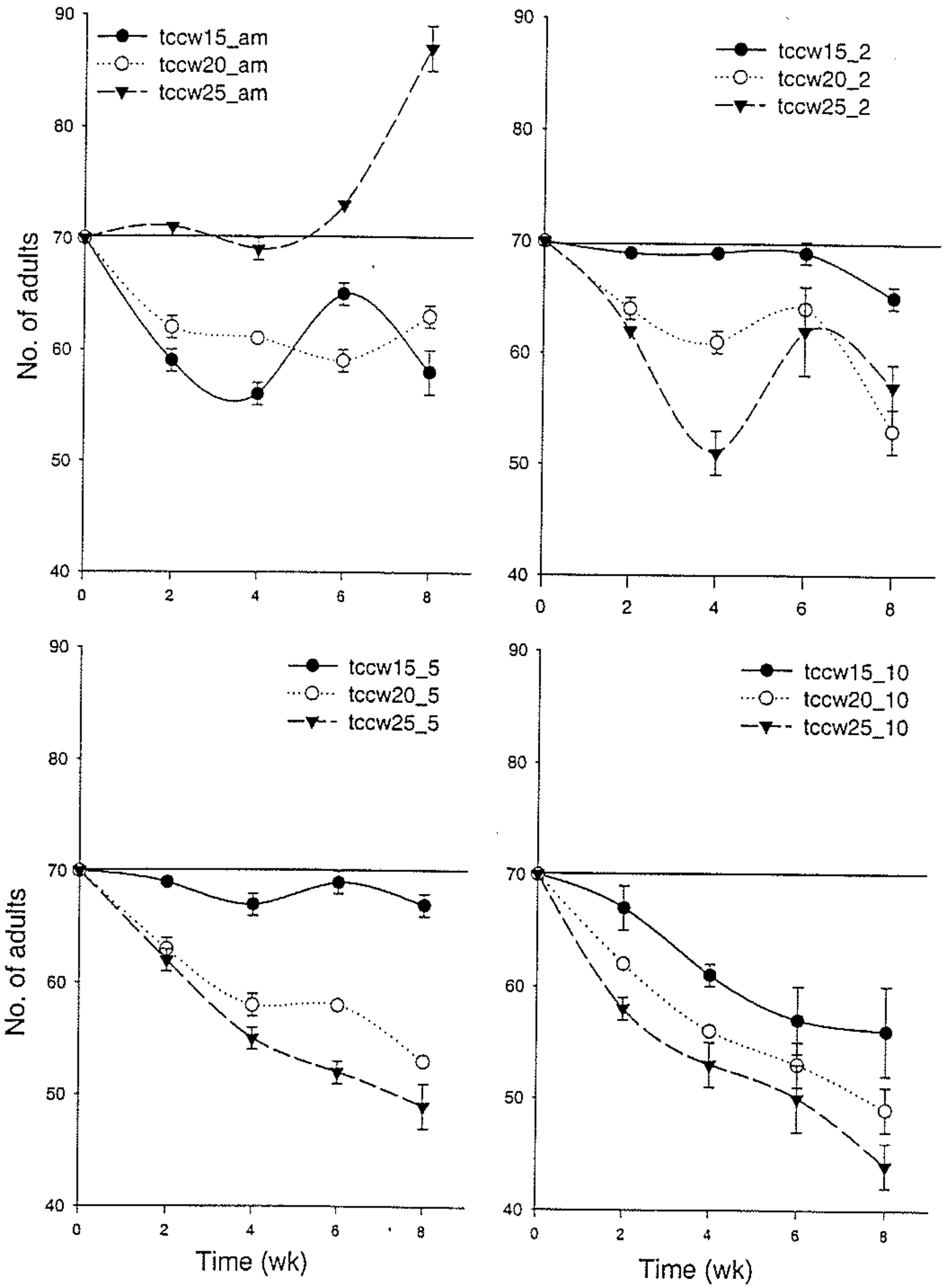

Fig. A16 Effect of temperature on mean adult survival from first count in mixed-species combination of *T. castaneum* in wet (15% wb) grain at ambient (am), 2, 5, and 10% levels of CO_2.

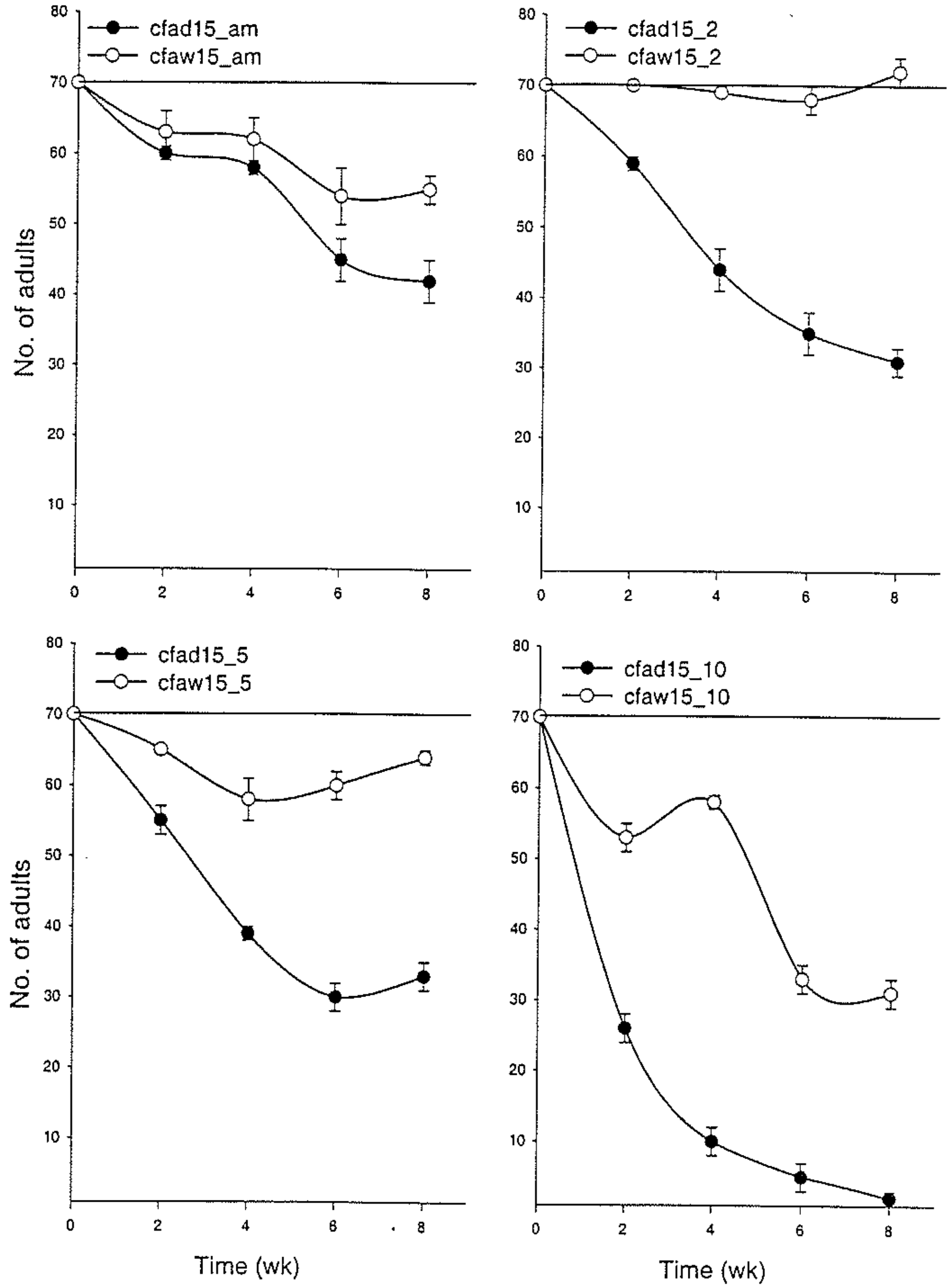

Fig. A17 Comparison of mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

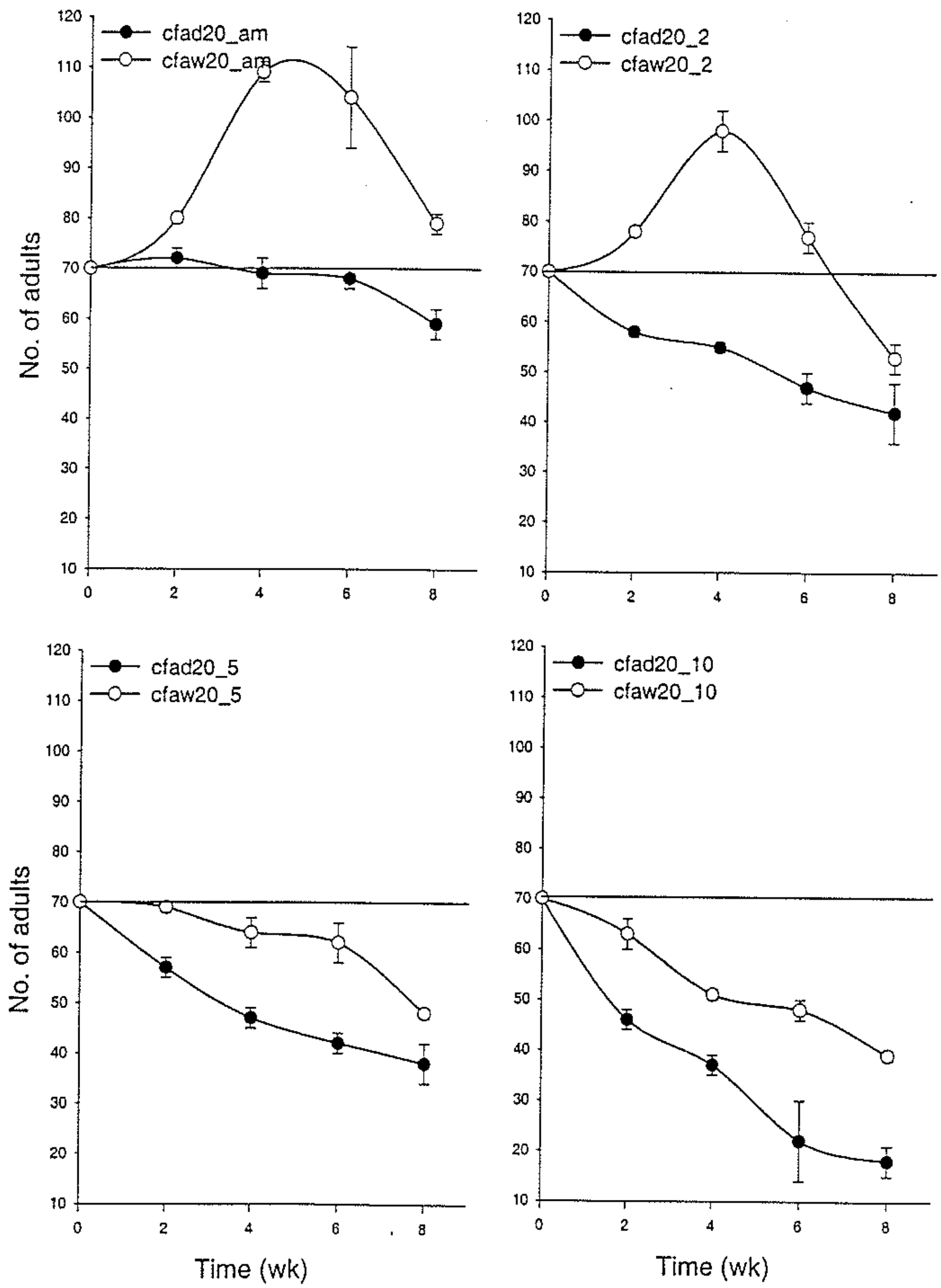

Fig. A18 Comparison of mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

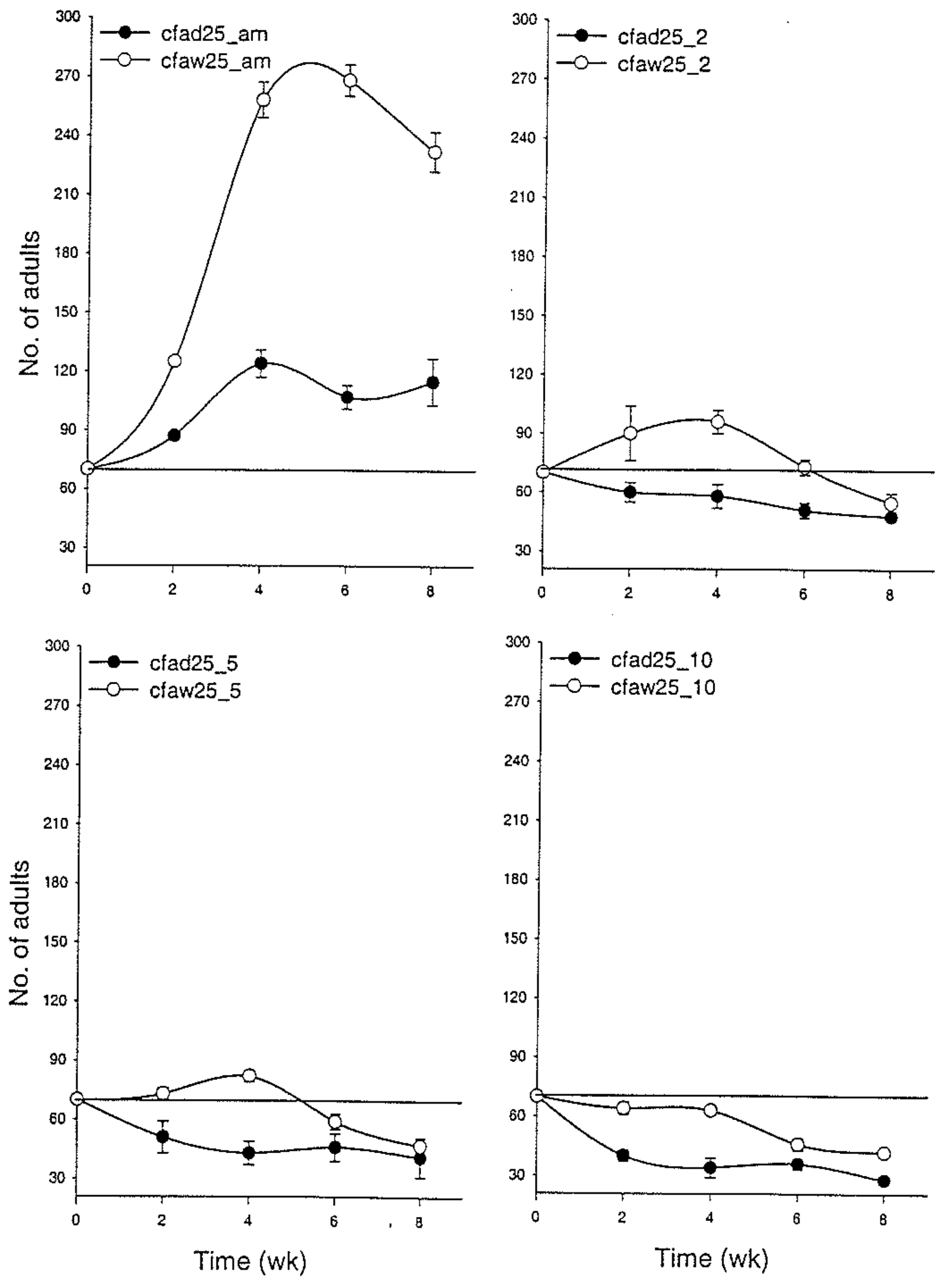

Fig. A19 Comparison of mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

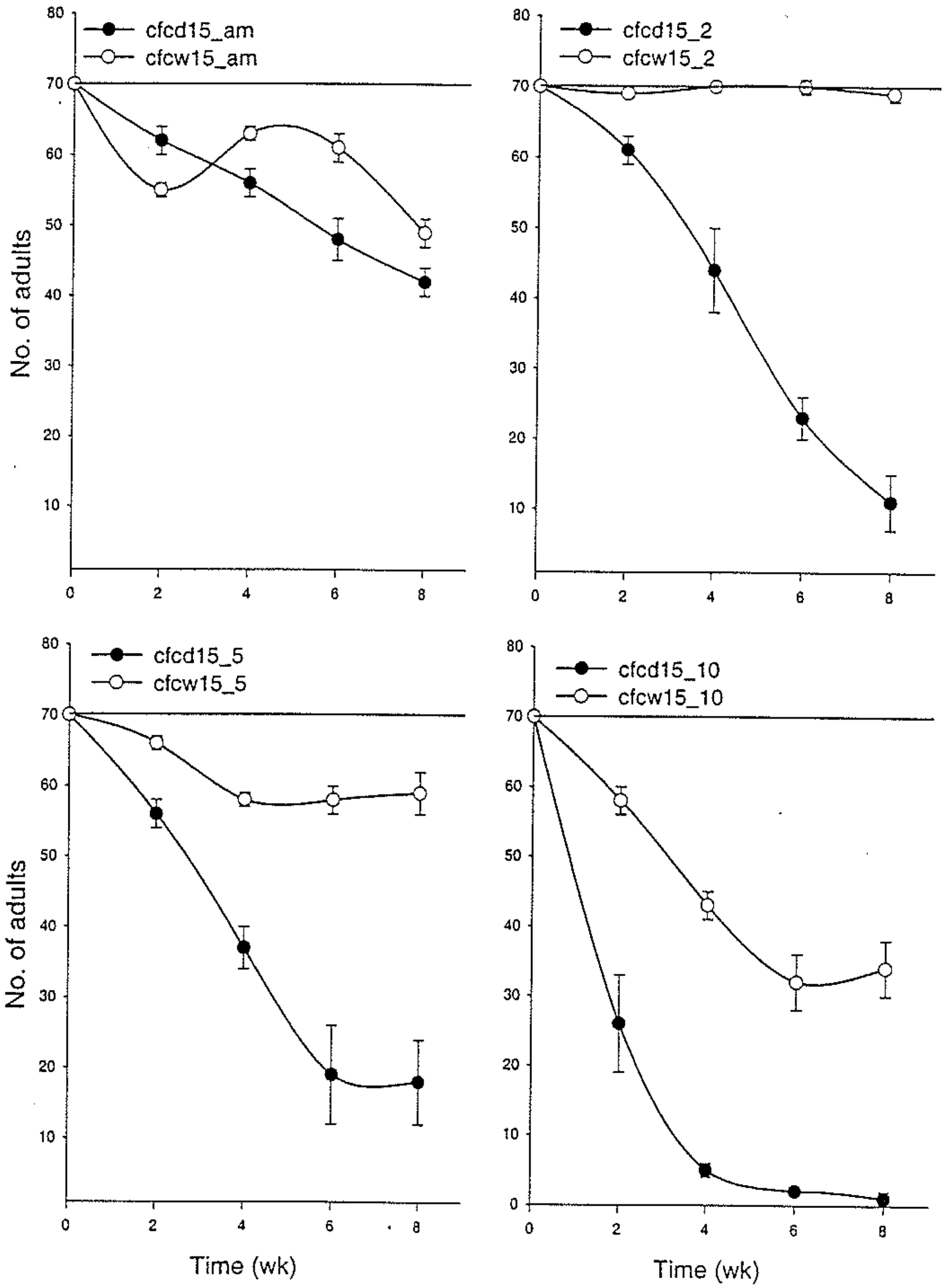

Fig. A20 Comparison of mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

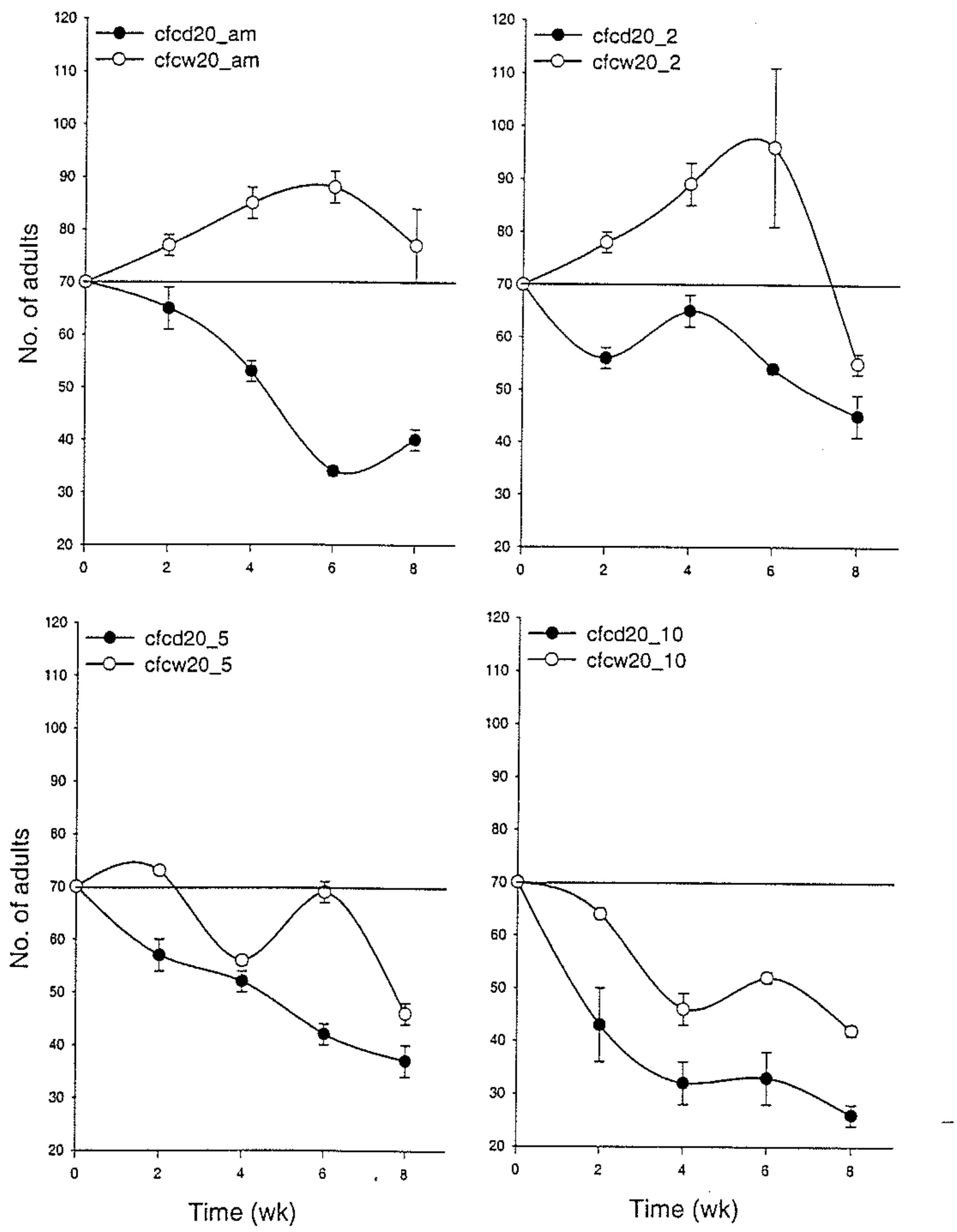

Fig. A21 Comparison of mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

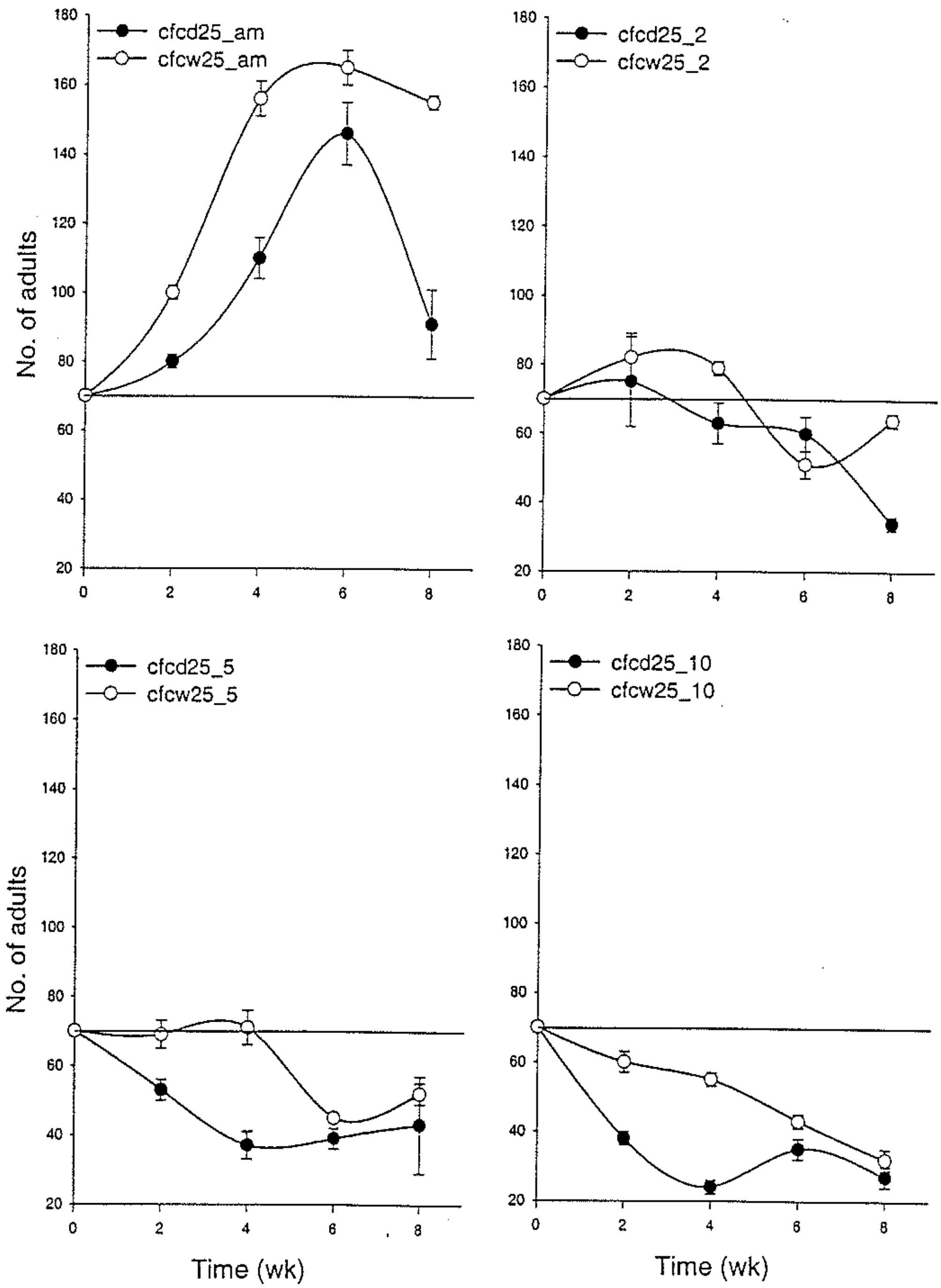

Fig. A22 Comparison of mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) and wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

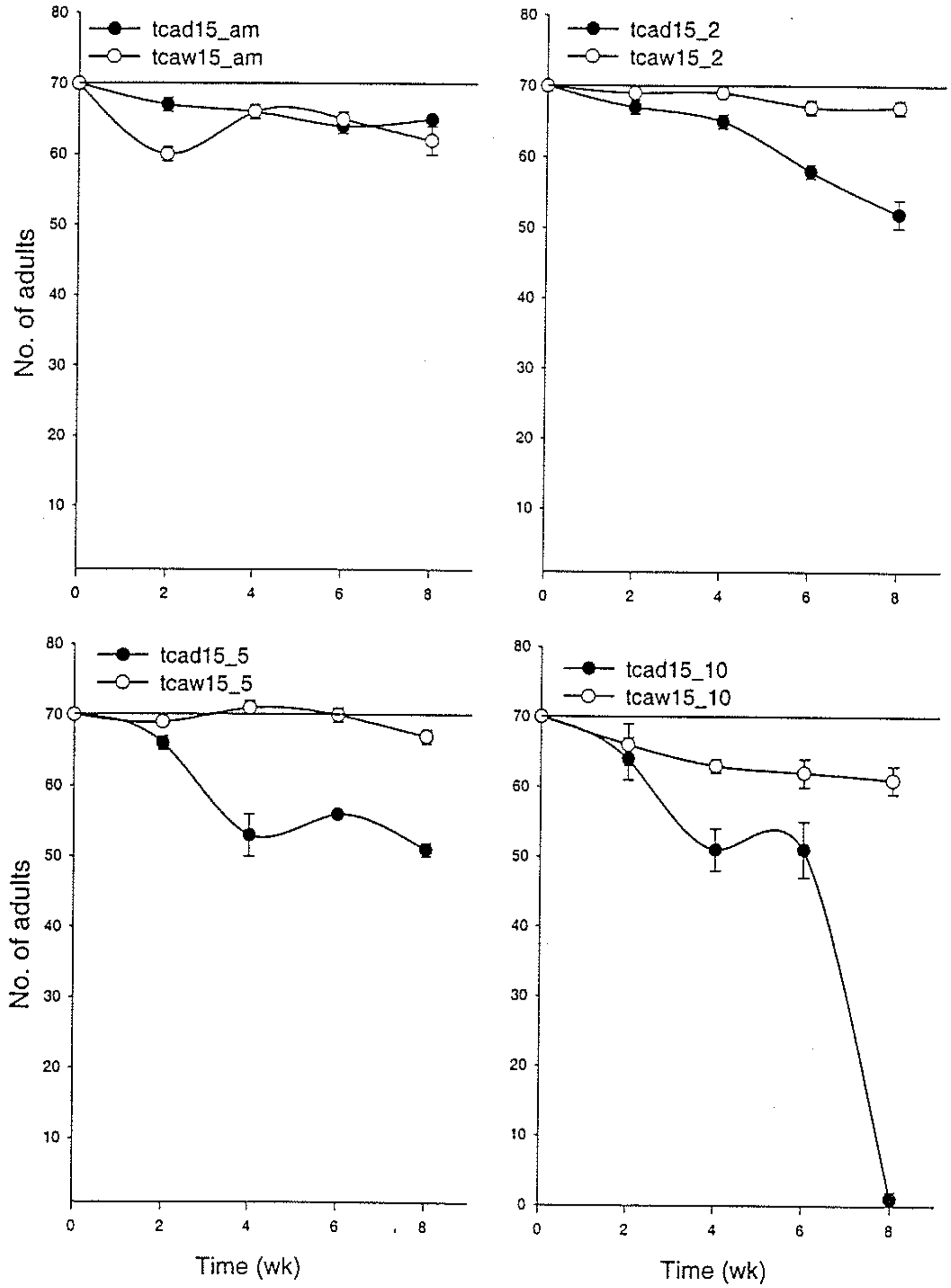

Fig. A23 Comparison of mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

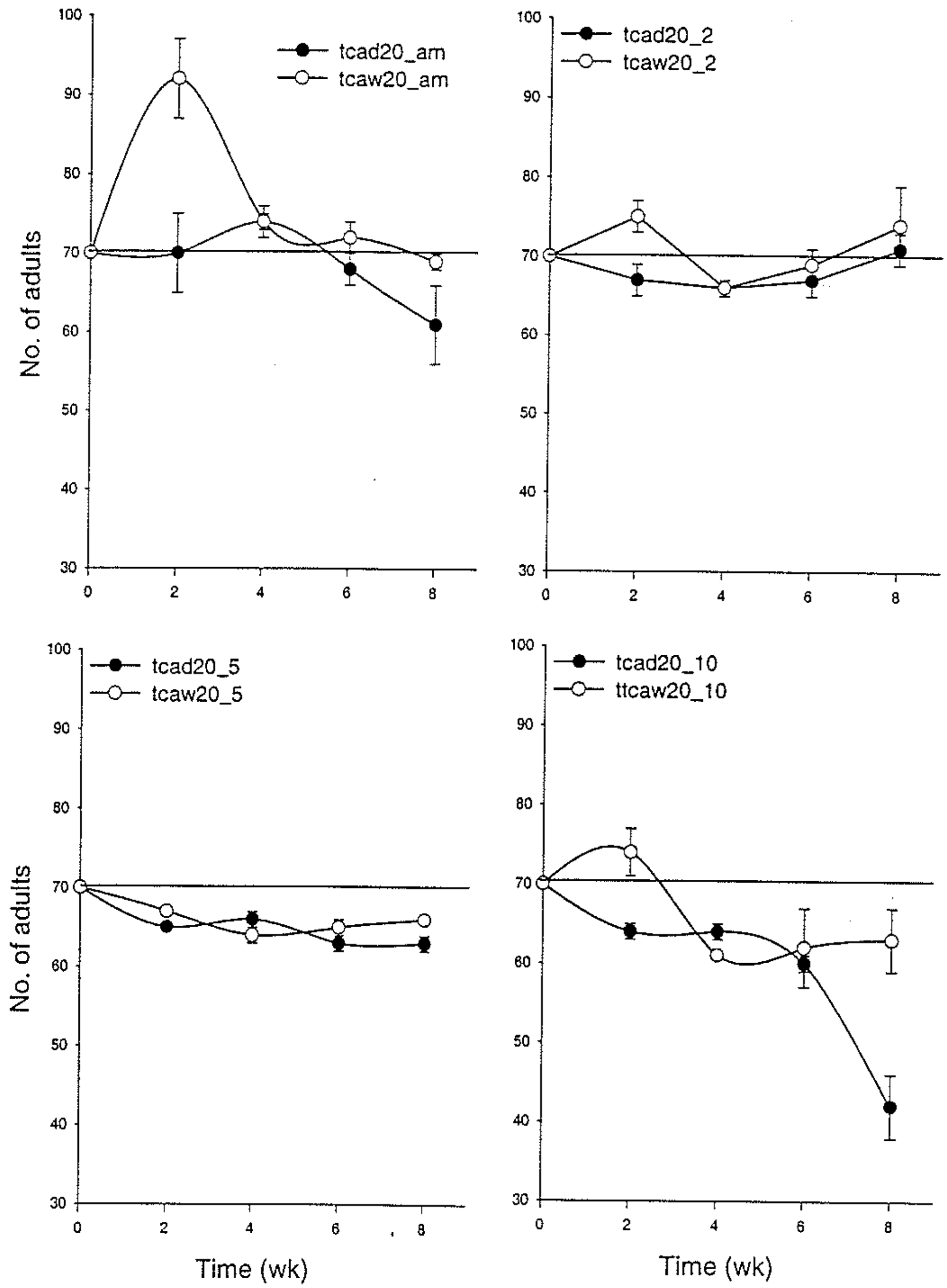

Fig. A24 Comparison of mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

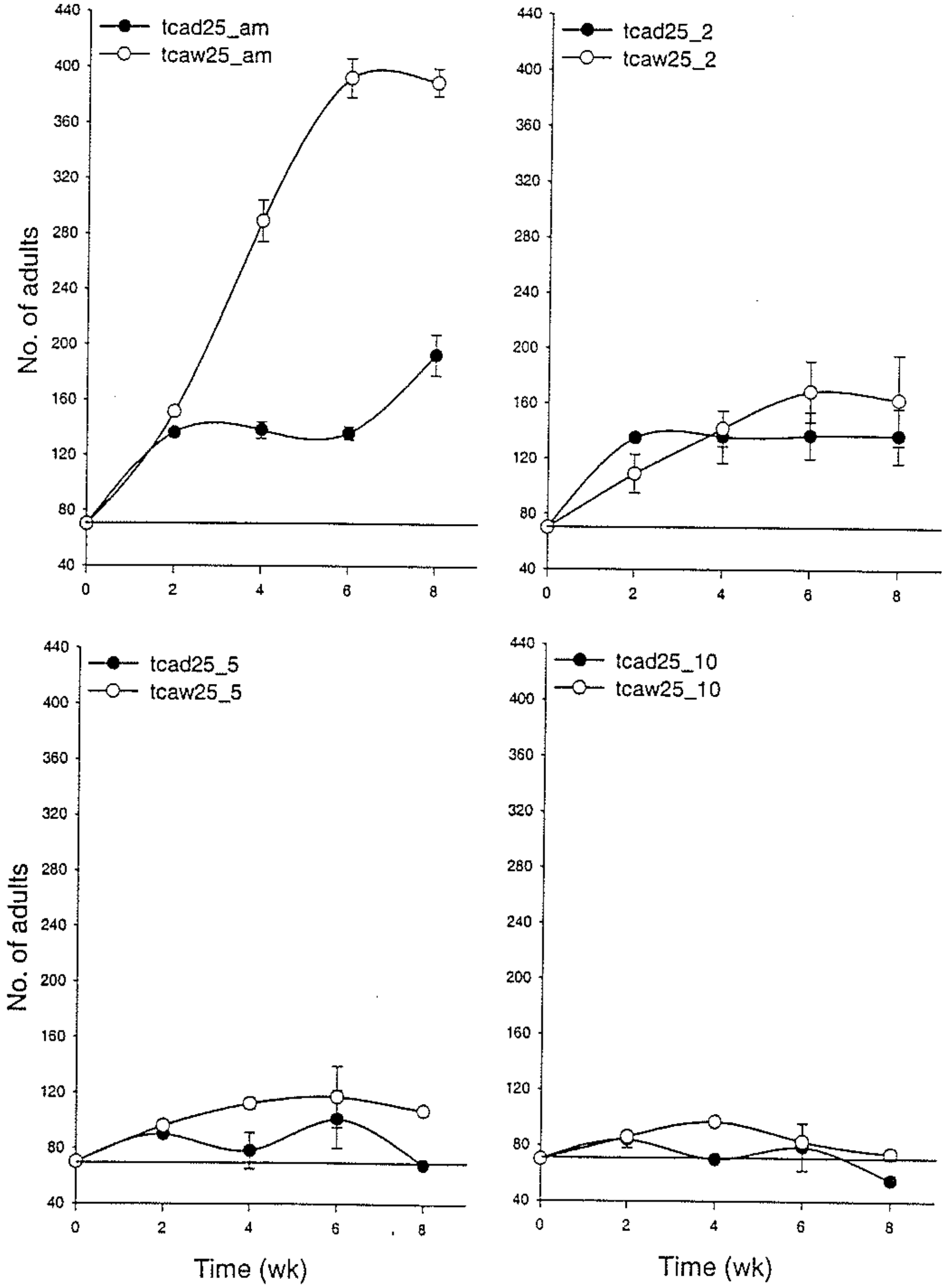

Fig. A25 Comparison of mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

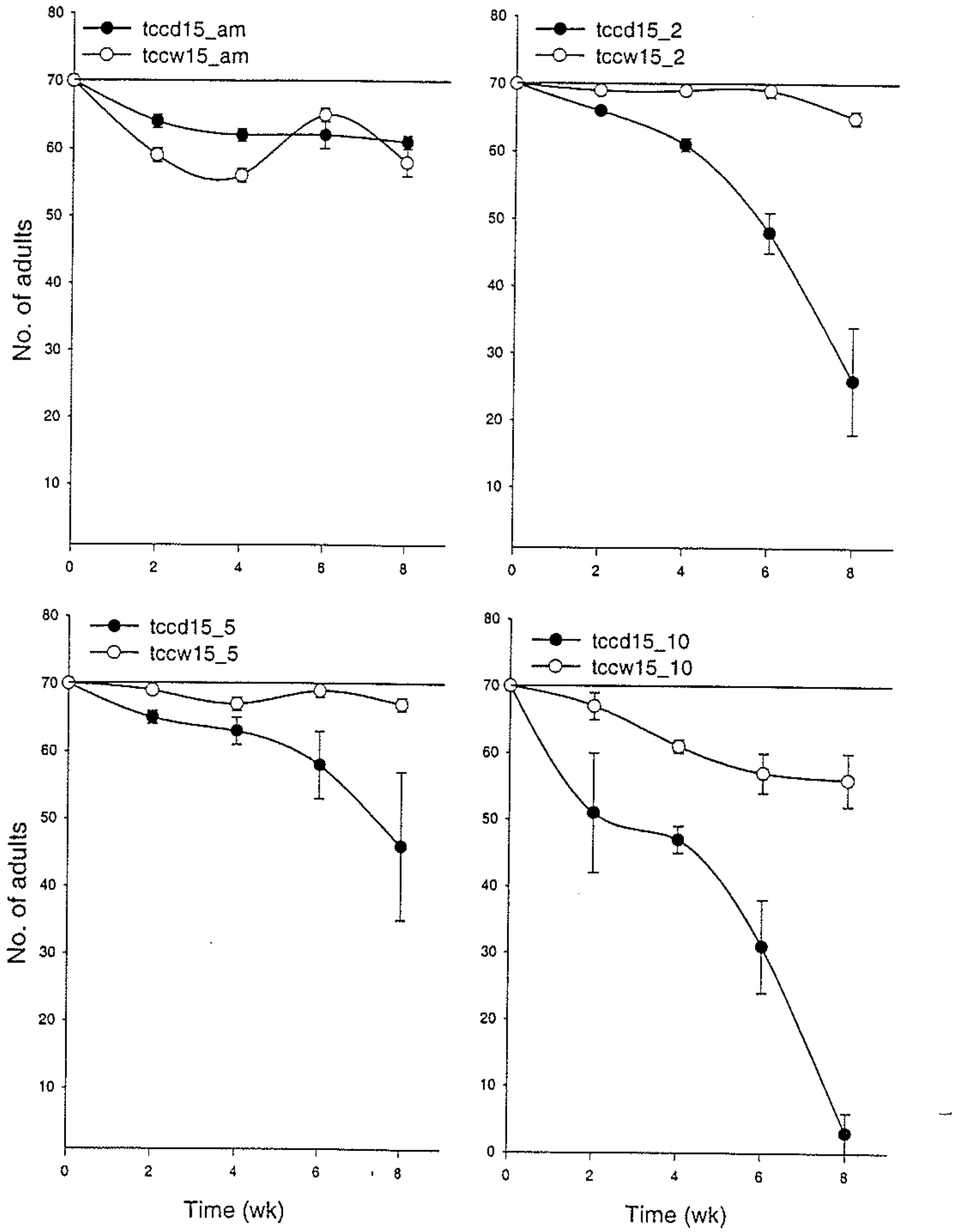

Fig. A26 Comparison of mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

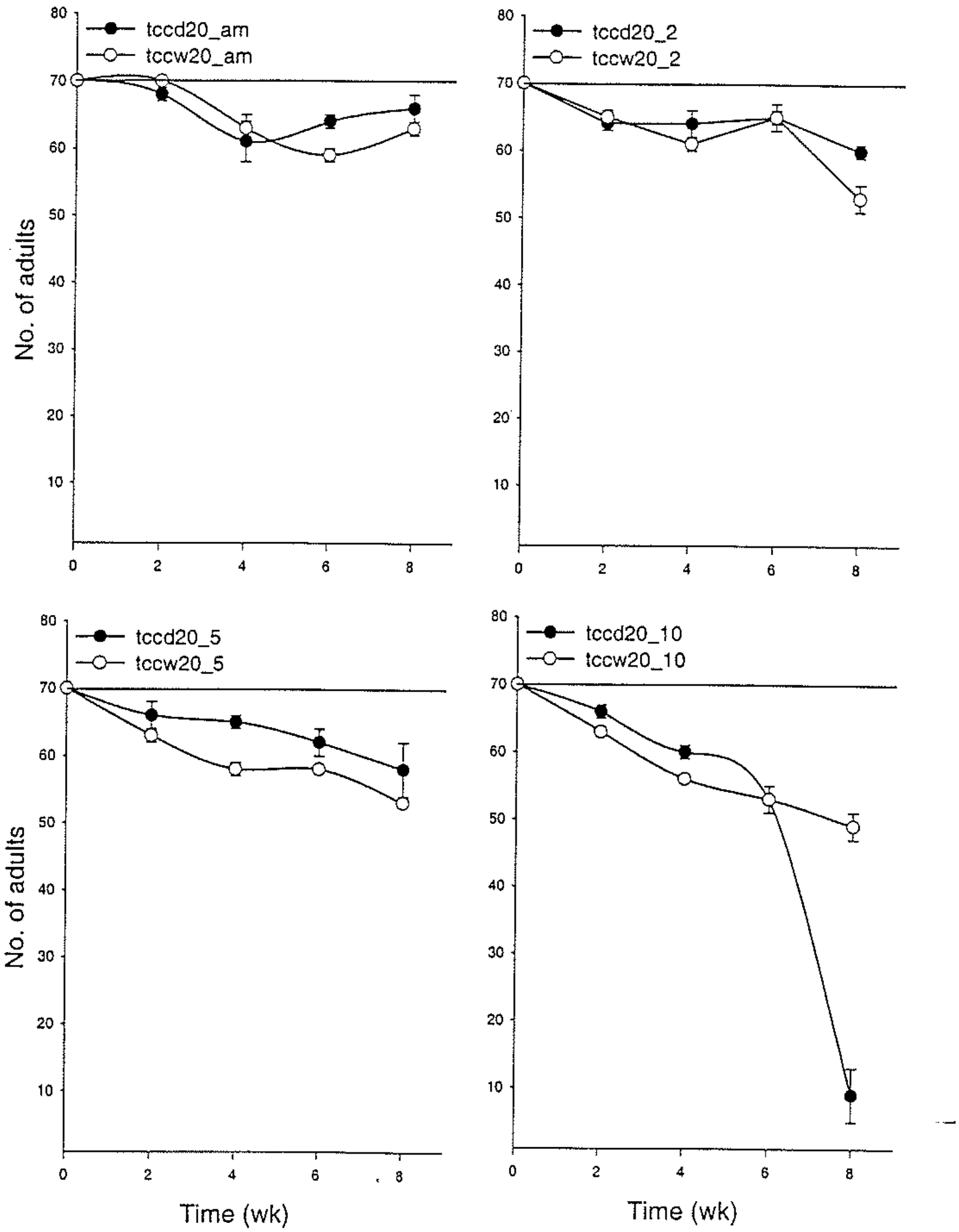

Fig. A27 Comparison of mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

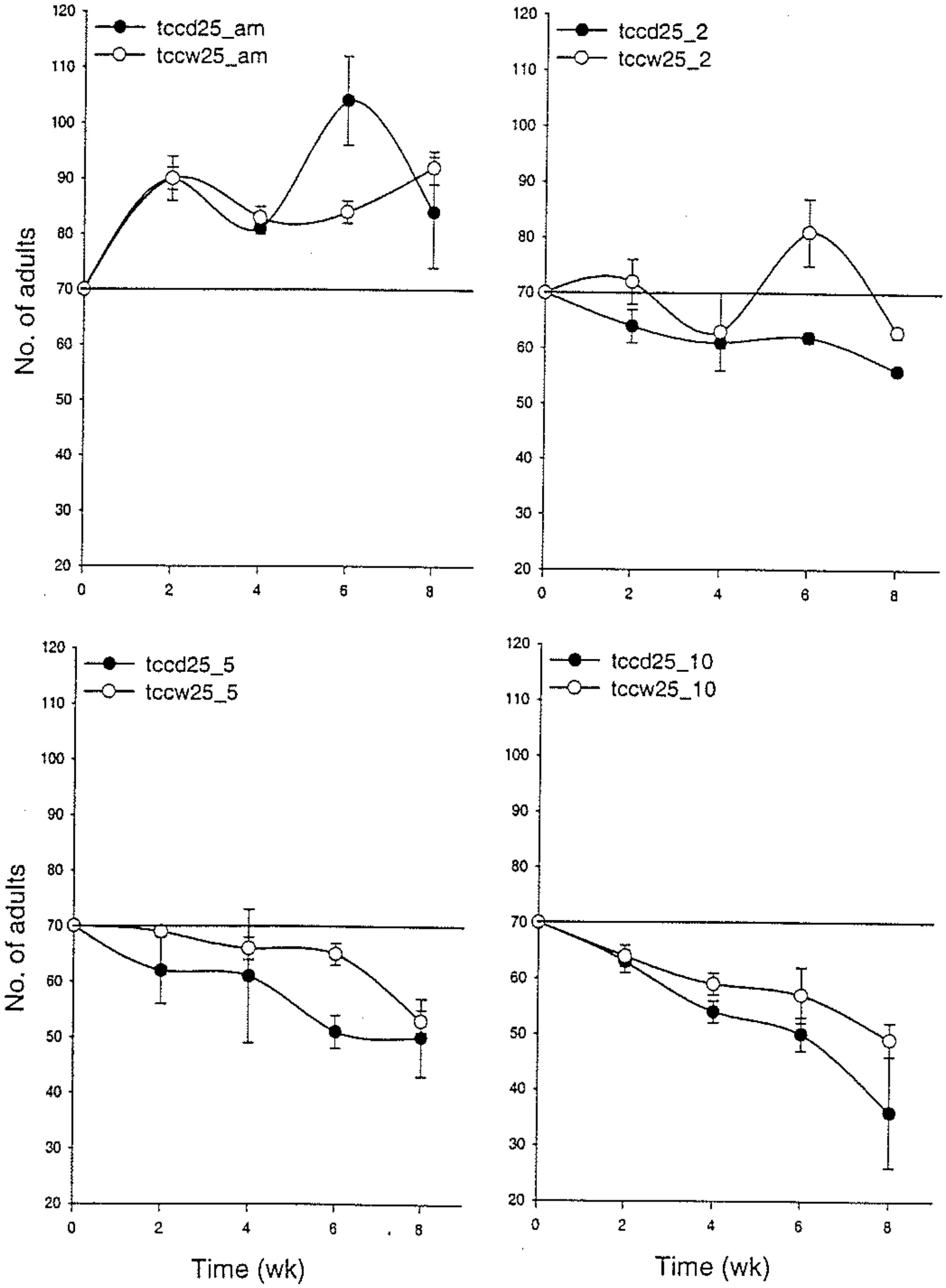

Fig. A28 Comparison of mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) and wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

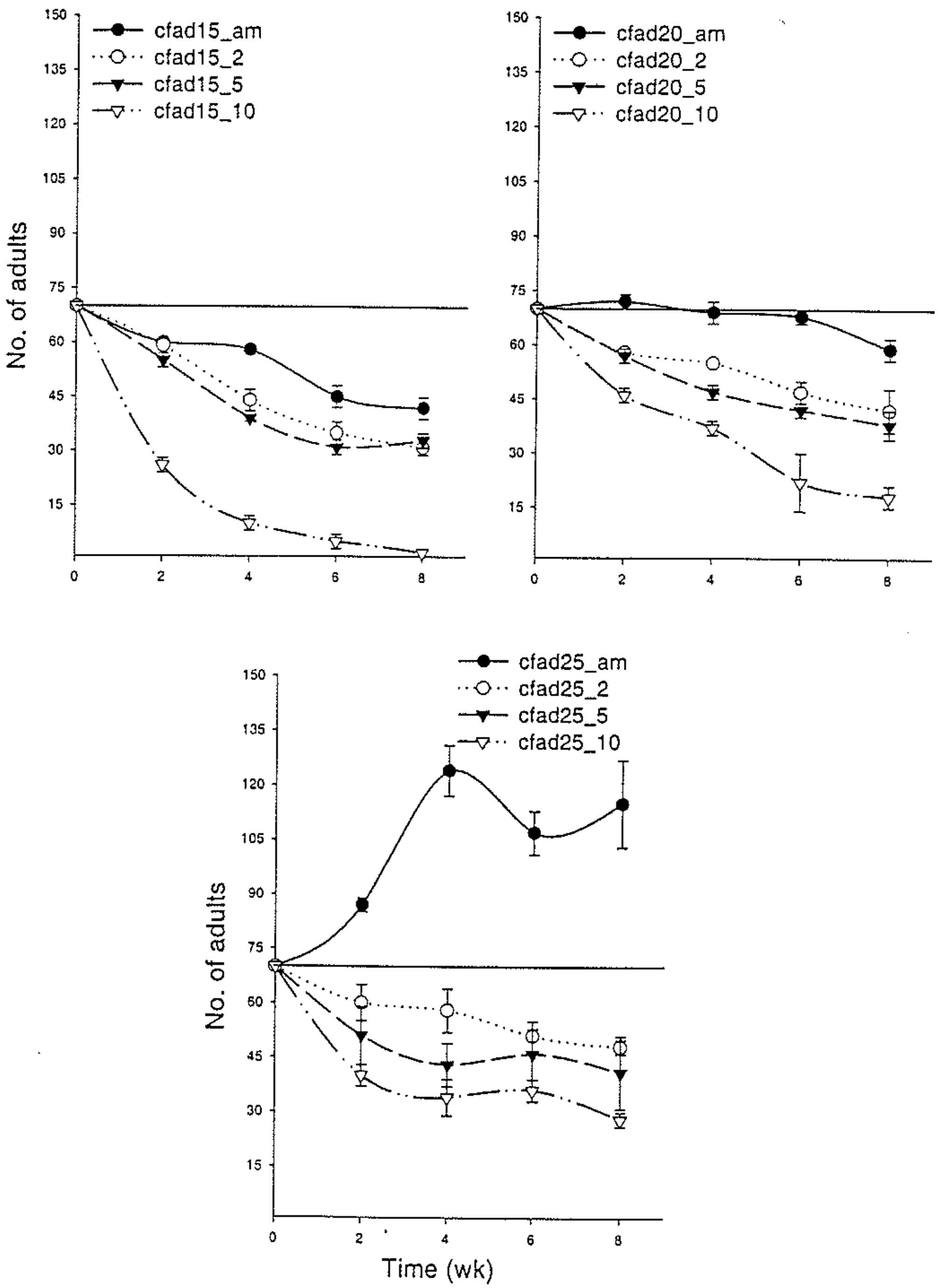

Fig. A29 Effect of CO_2 levels on mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C.

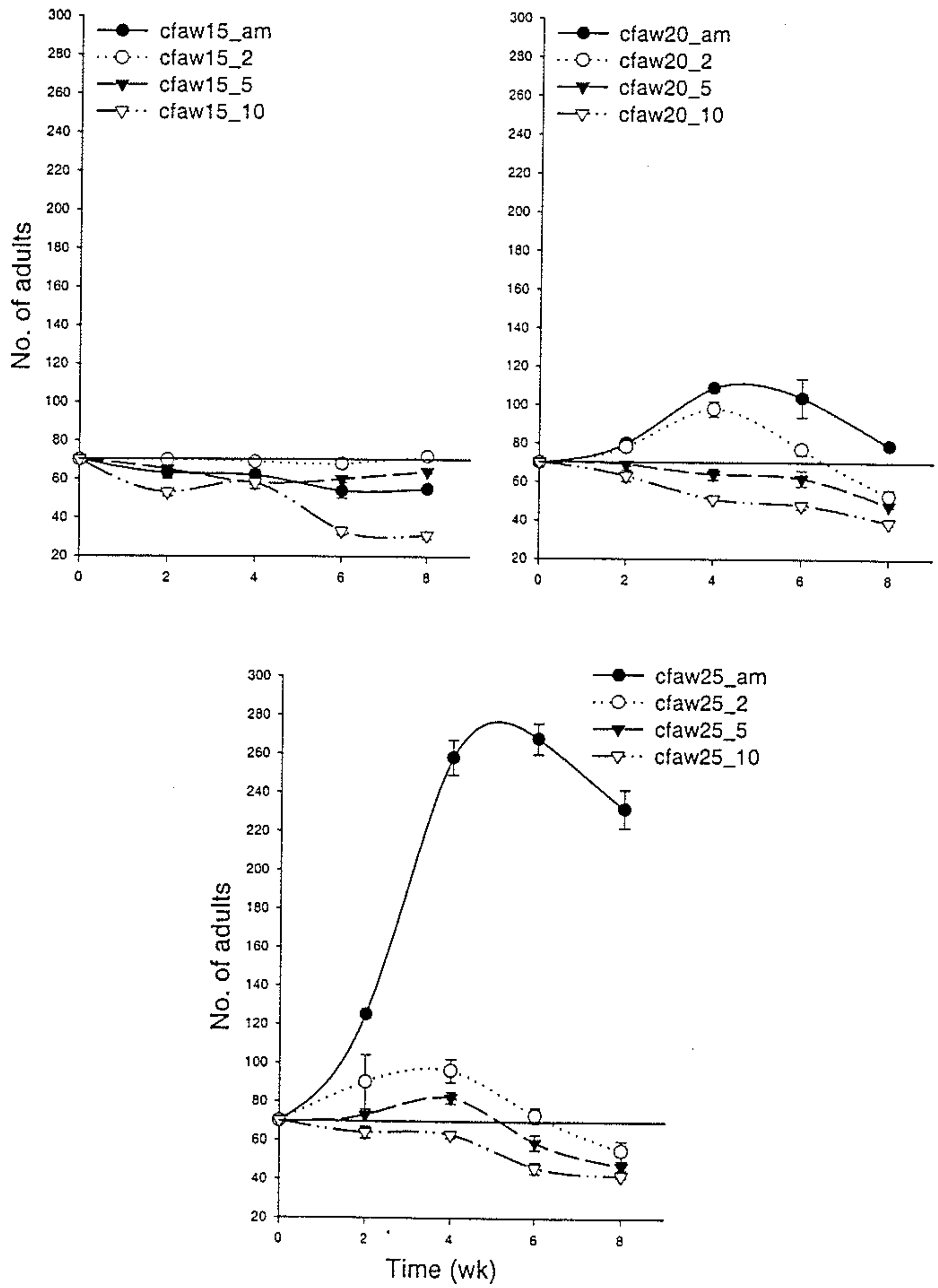

Fig. A30 Effect of CO_2 levels on mean adult survival in single-species controls of *C. ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C.

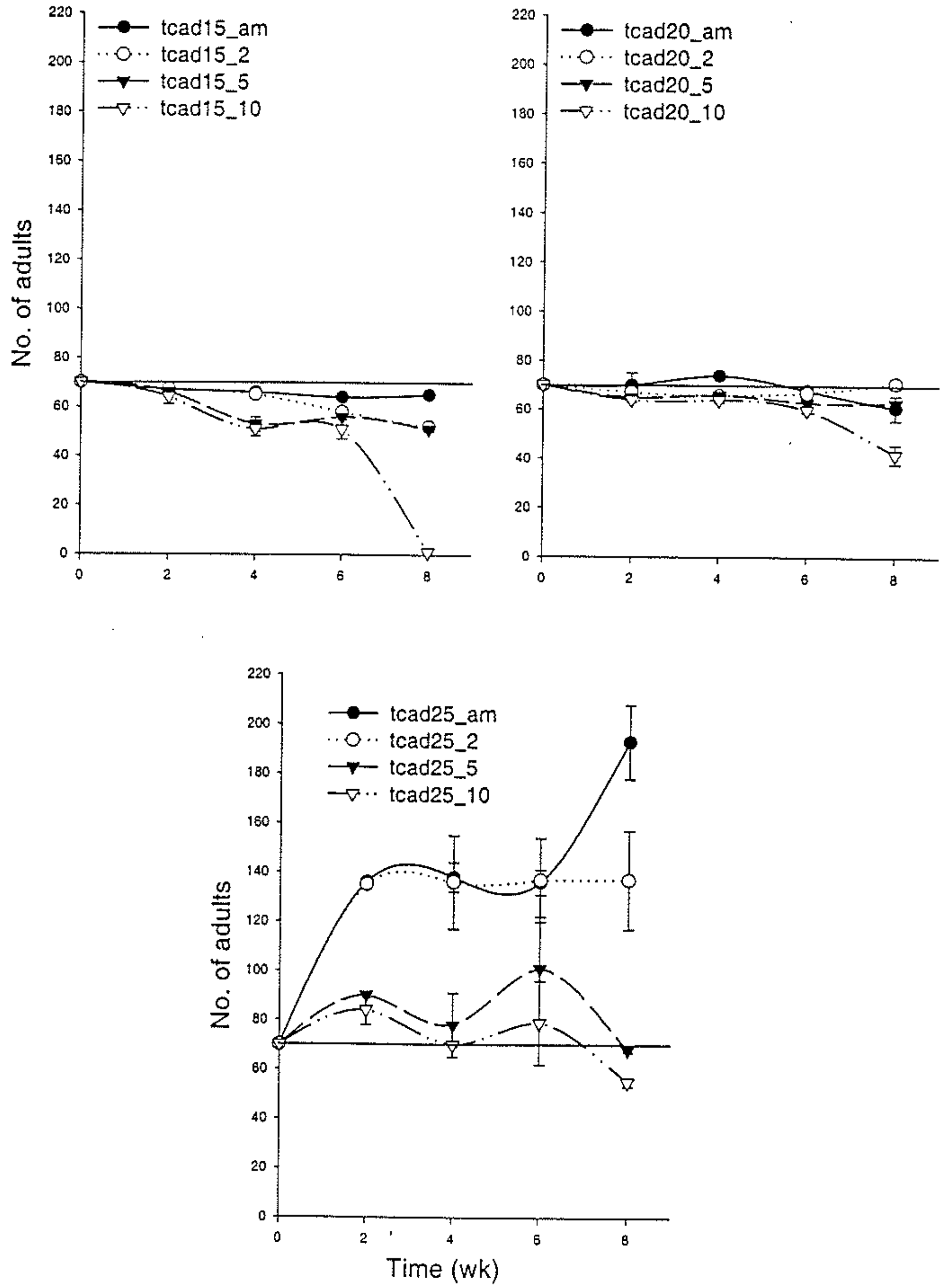

Fig. A31 Effect of CO_2 levels on mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) grain at 15, 20, and 25°C.

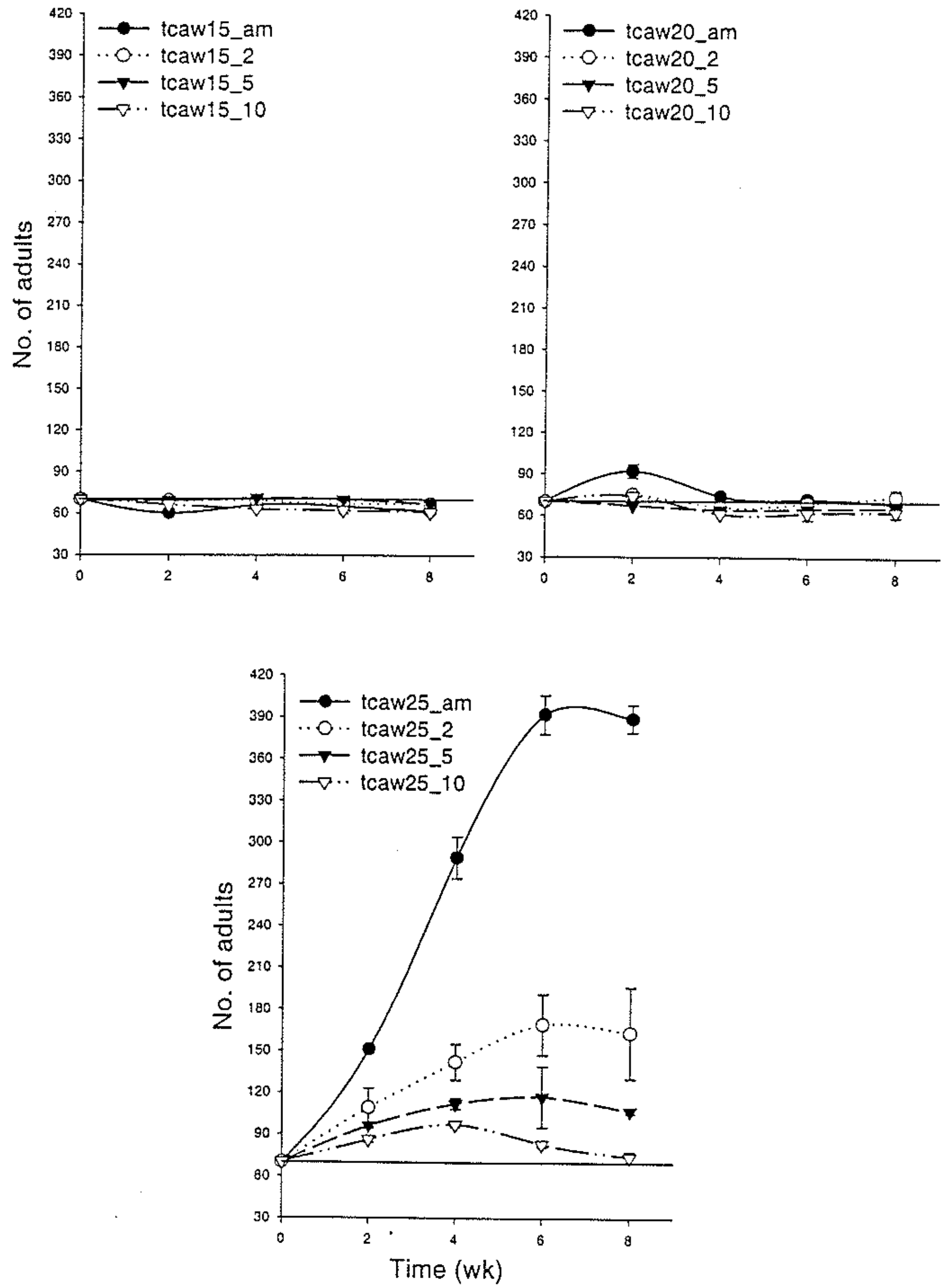

Fig. A32 Effect of CO_2 levels on mean adult survival in single-species controls of *T. castaneum* in wet (15% wb) grain at 15, 20, and 25°C.

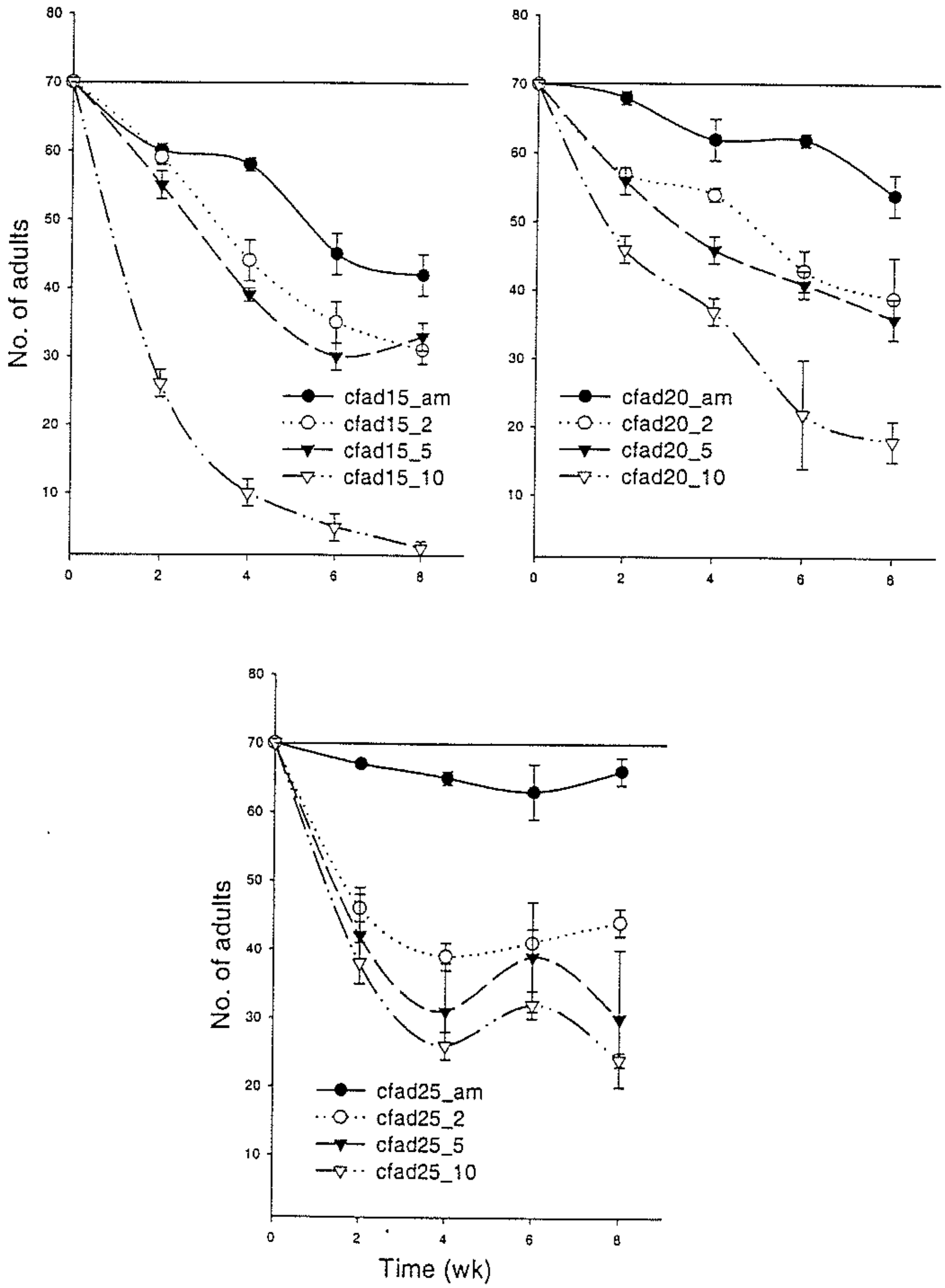

Fig. A33 Effect of CO_2 levels on mean adult survival from first count in single-species controls of *C. ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C.

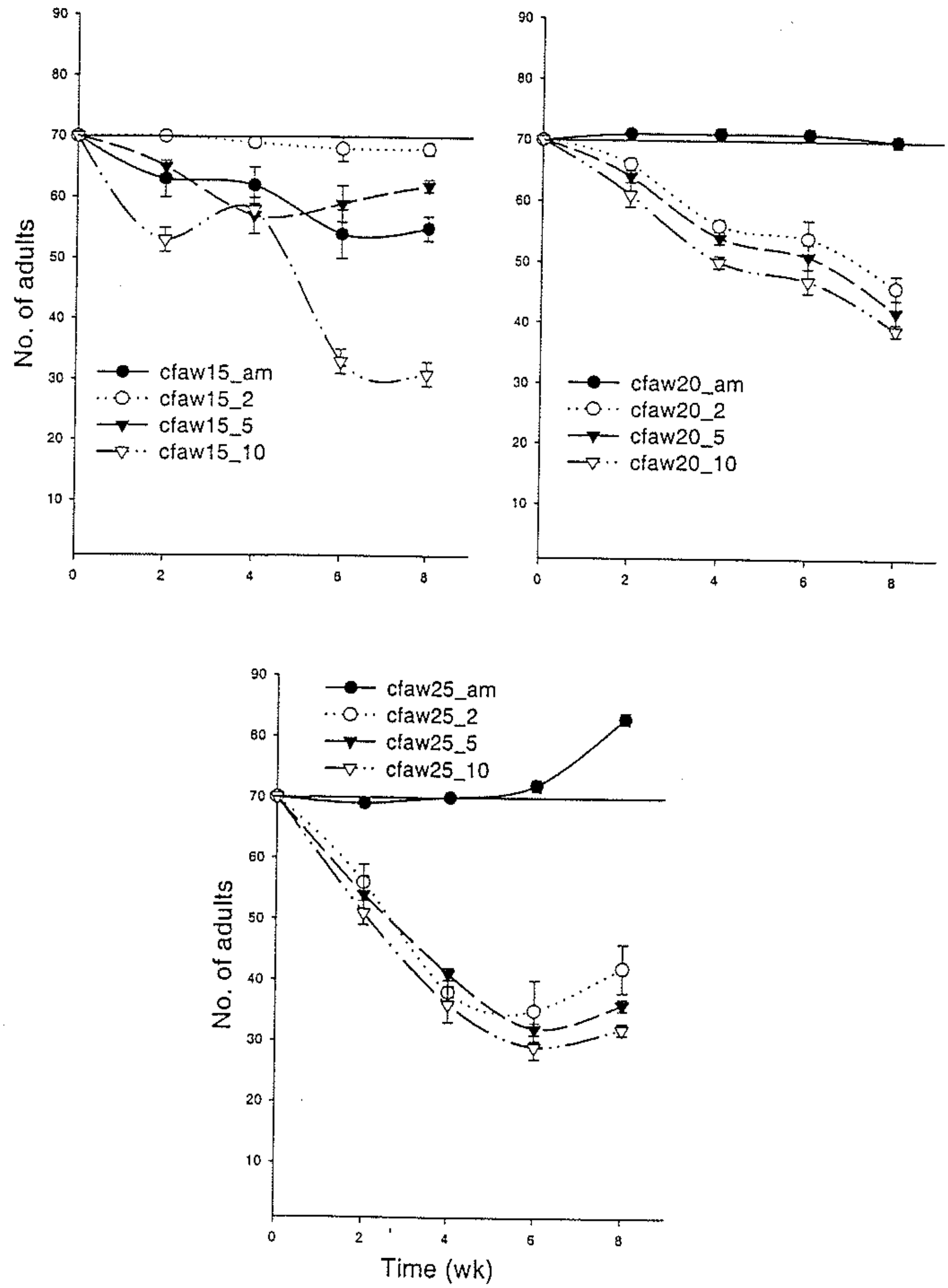

Fig. A34 Effect of CO_2 levels on mean adult survival from first count in single-species controls of *C. ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C.

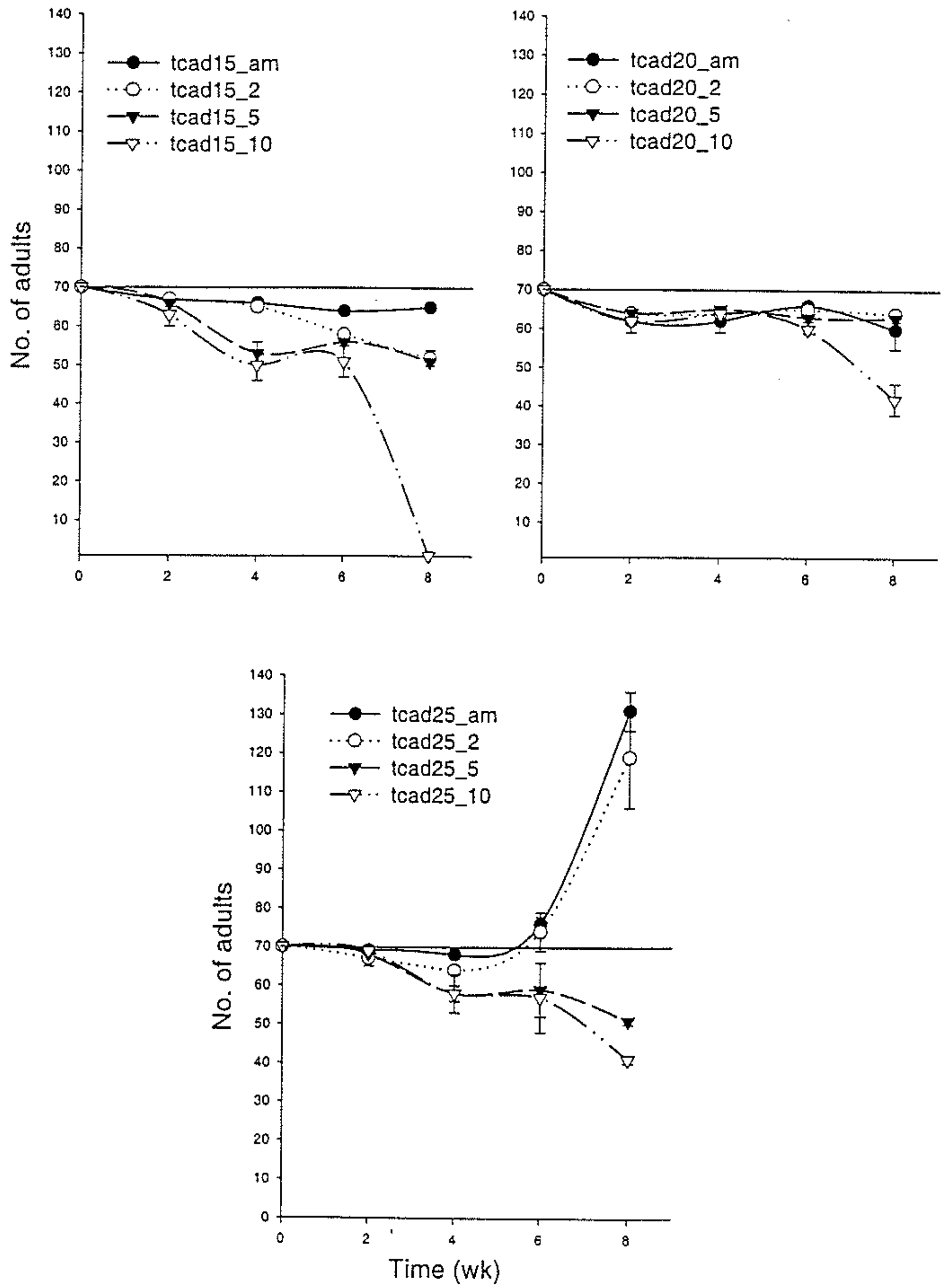

Fig. A35 Effect of CO_2 levels on mean adult survival from first count in single-species controls of *T. castaneum* in dry (12% wb) grain at 15, 20, and 25°C.

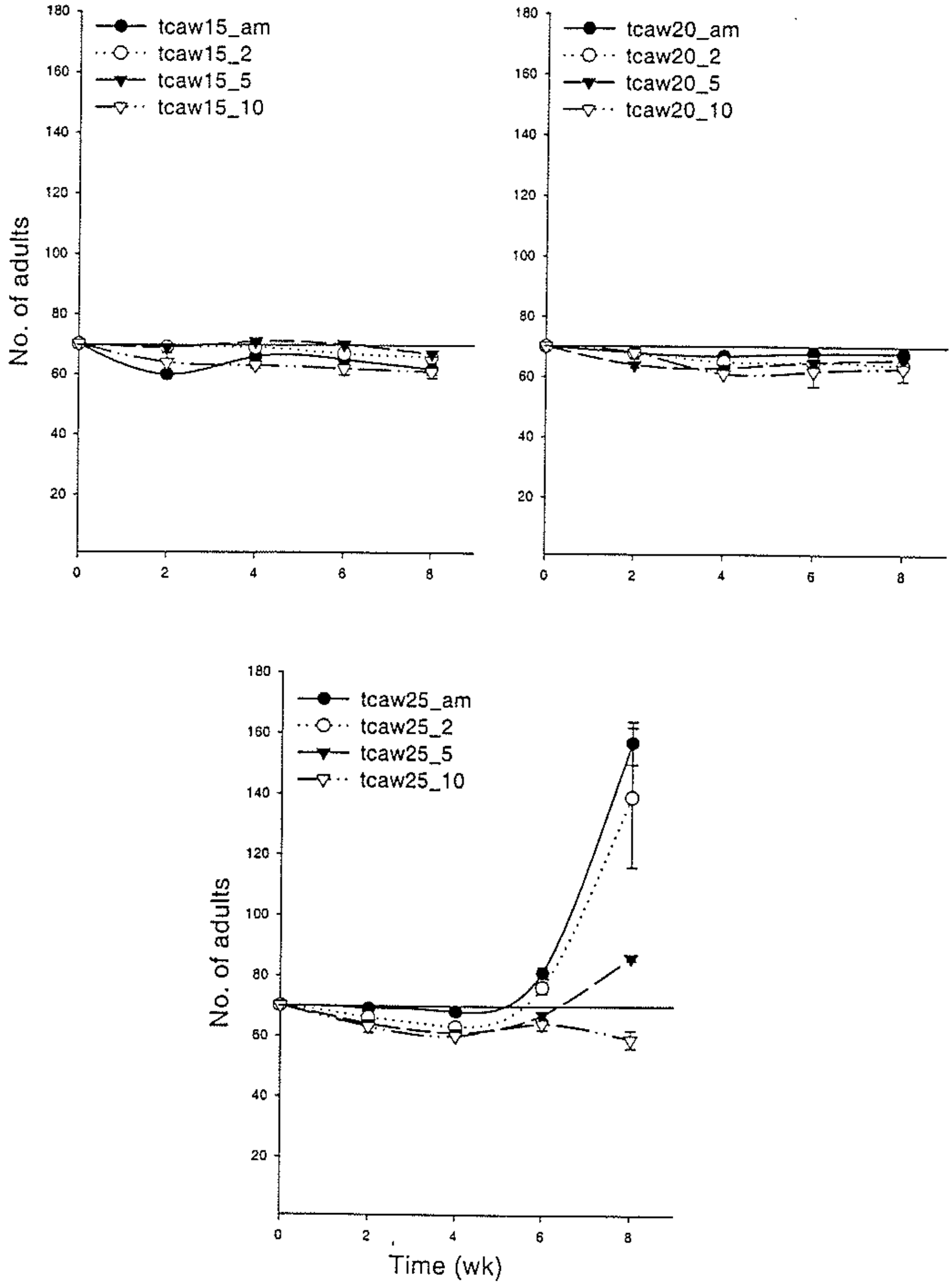

Fig. A36 Effect of CO_2 levels on mean adult survival from first count in single-species controls of *T. castaneum* in wet (15% wb) grain at 15, 20, and 25°C.

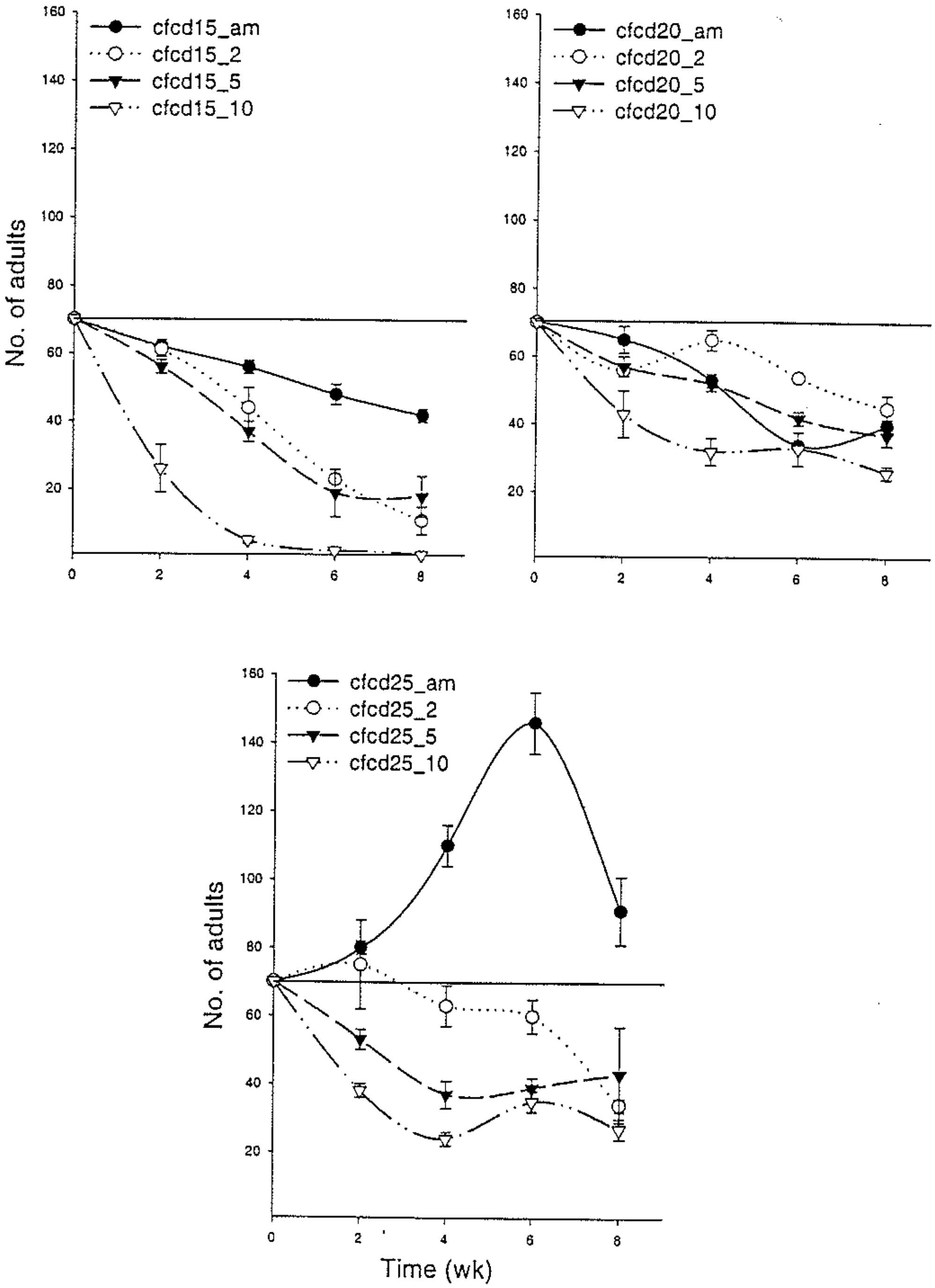

Fig. A37 Effect of CO_2 levels on mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C.

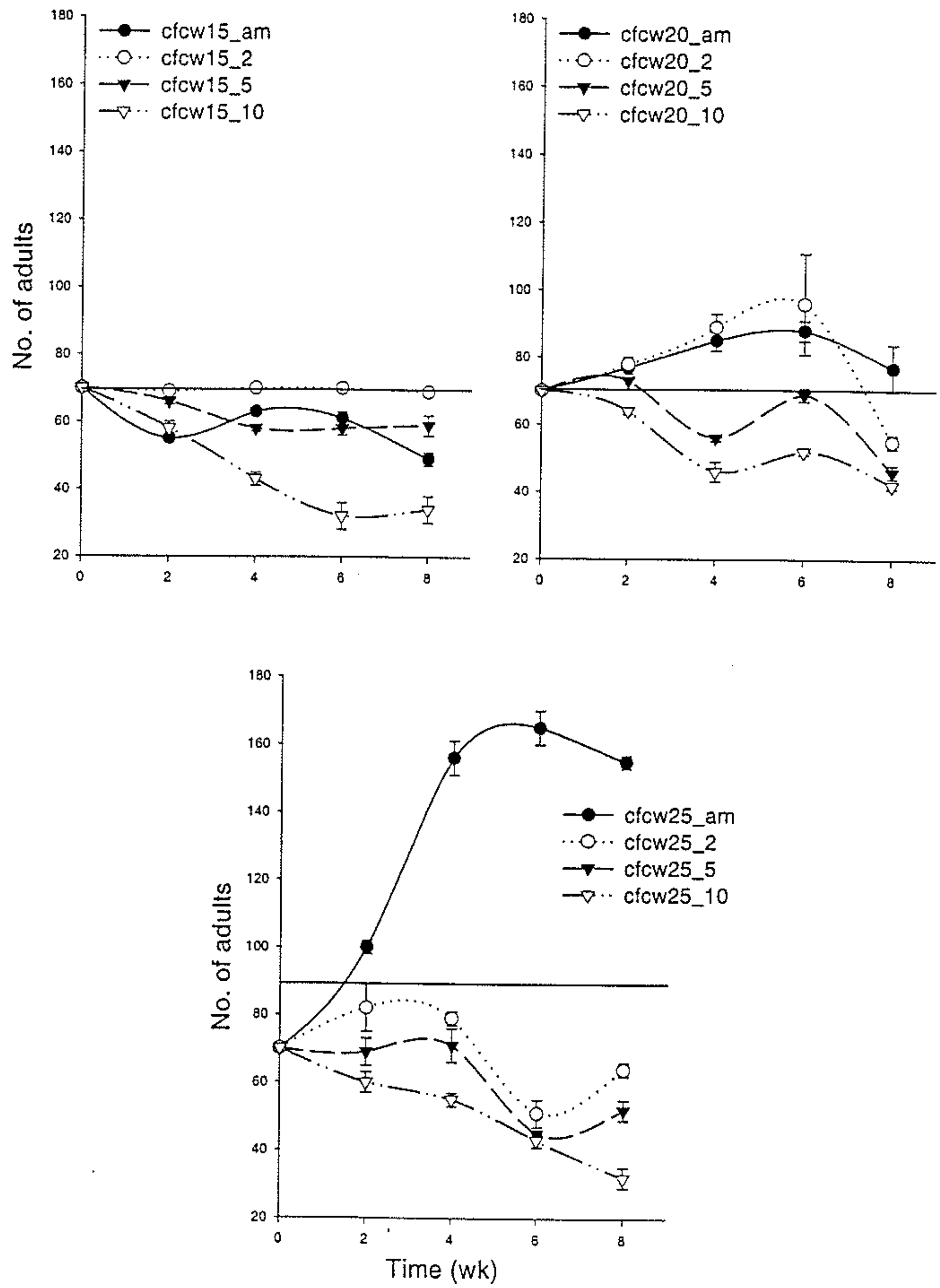

Fig. A38 Effect of CO_2 levels on mean adult survival in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C.

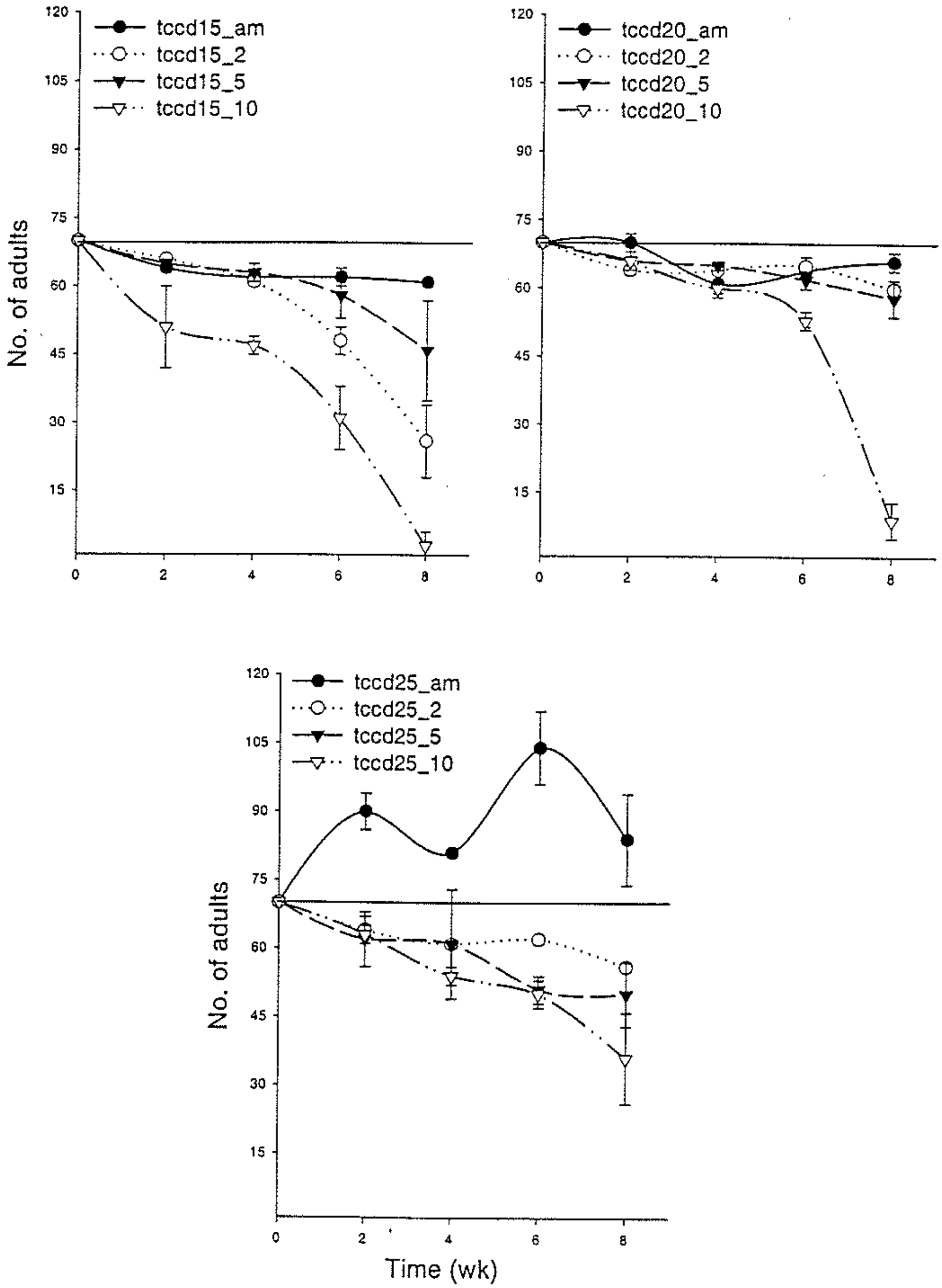

Fig. A39 Effect of CO_2 levels on mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) grain at 15, 20, and 25°C.

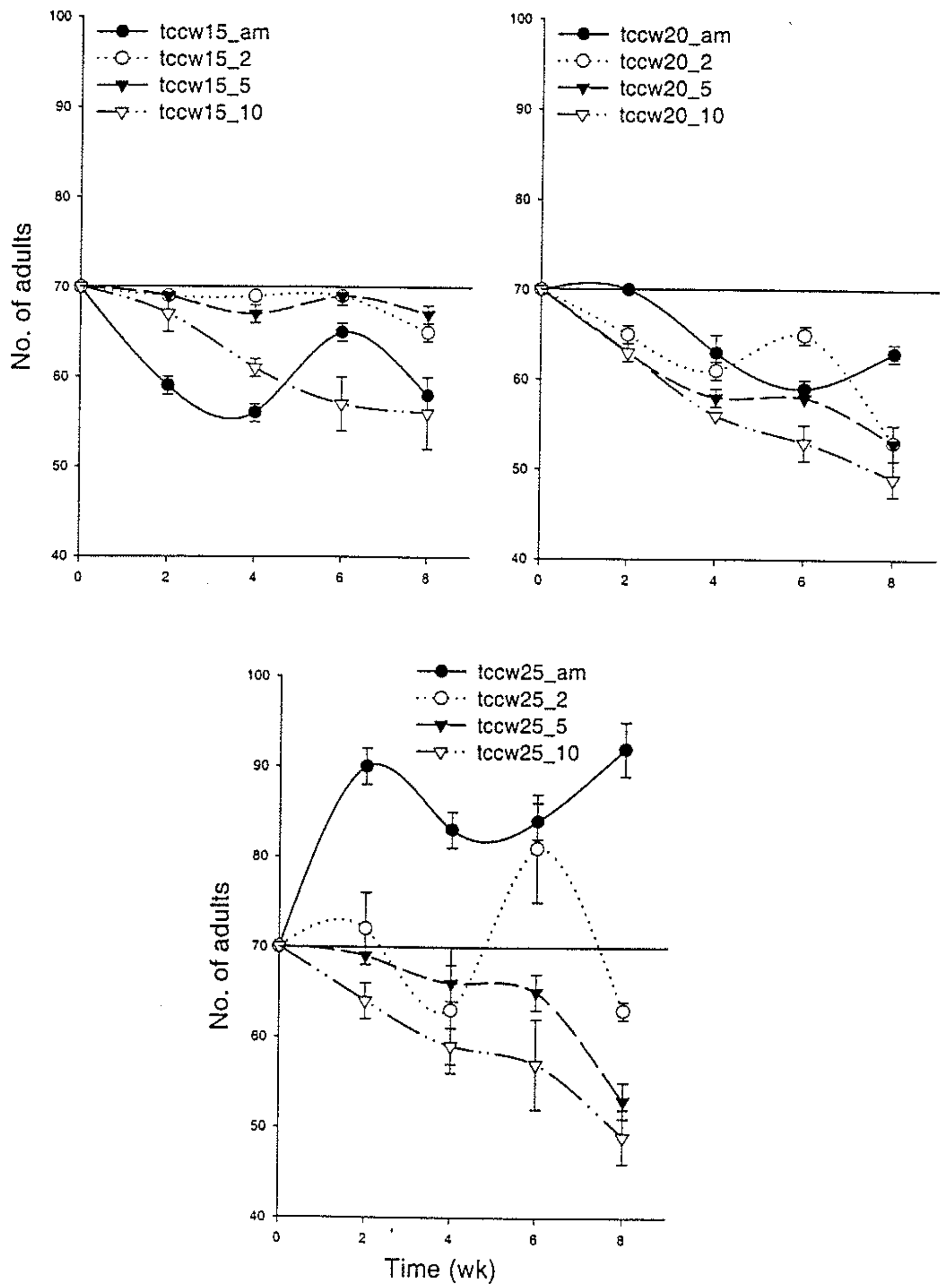

Fig. A40 Effect of CO_2 levels on mean adult survival in mixed-species combination of *T. castaneum* in wet (15% wb) grain at 15, 20, and 25°C.

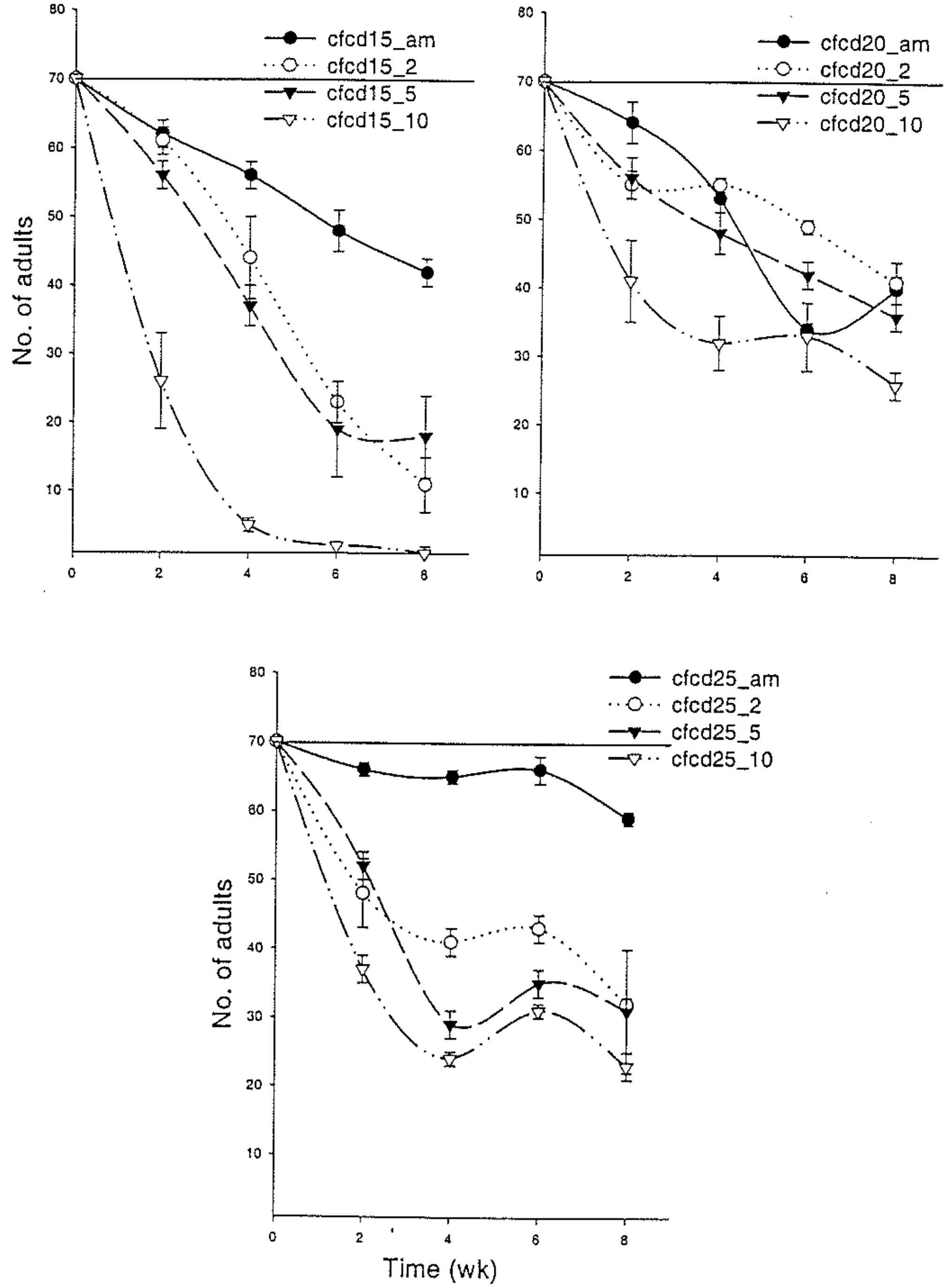

Fig. A41 Effect of CO_2 levels on mean adult survival from first count in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at 15, 20, and 25°C.

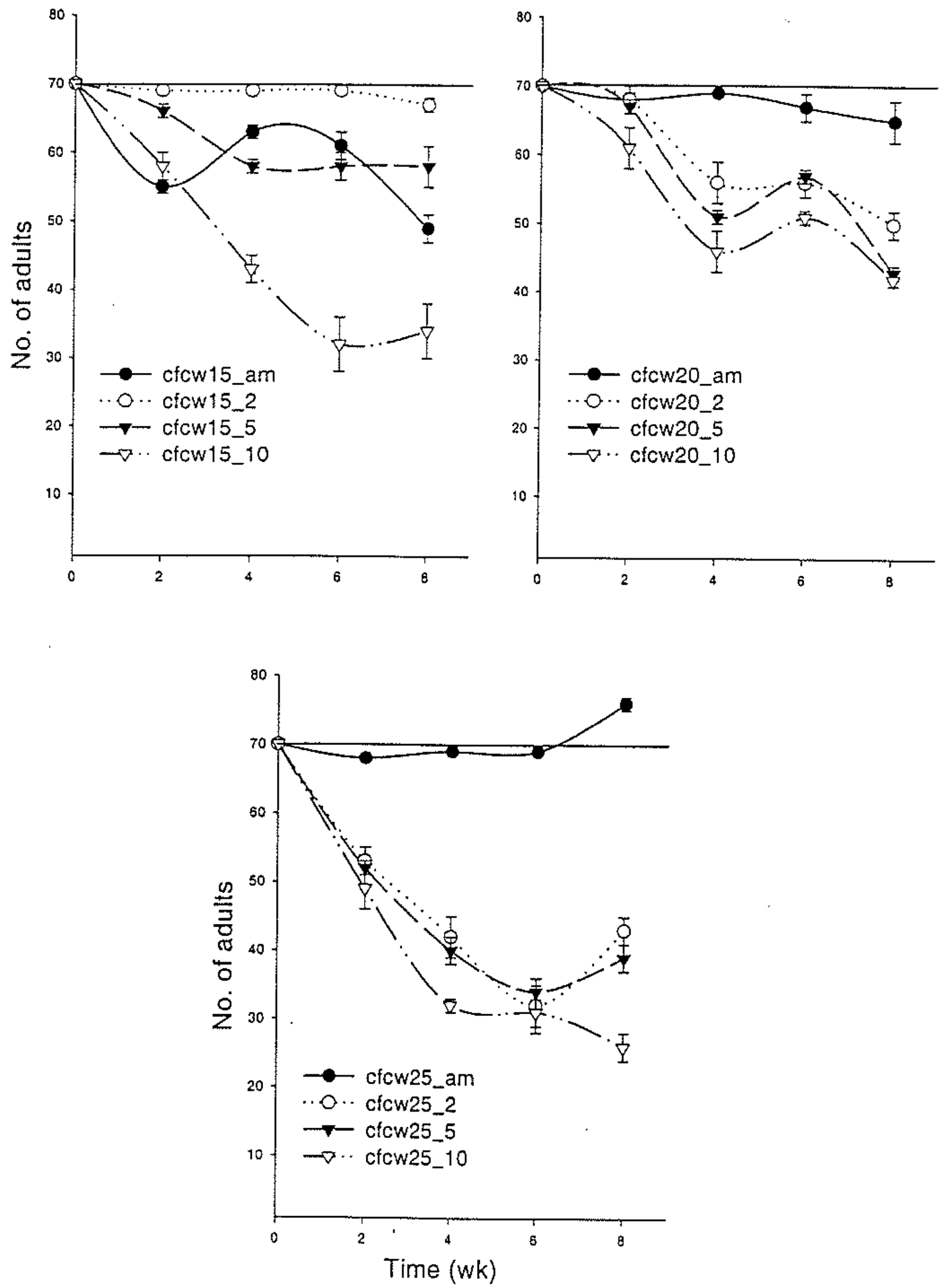

Fig. A42 Effect of CO_2 levels on mean adult survival from first count in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at 15, 20, and 25°C.

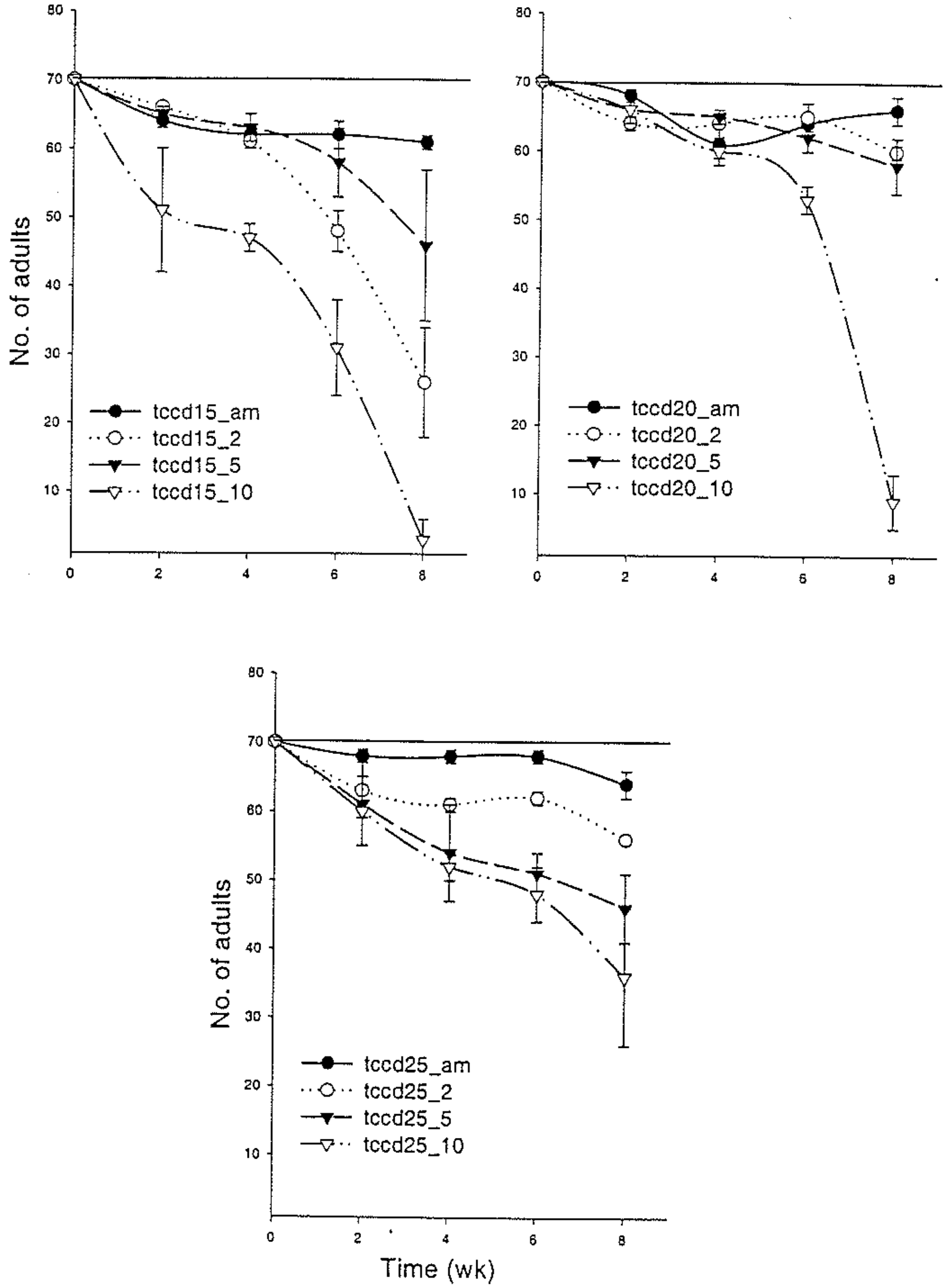

Fig. A43 Effect of CO_2 levels on mean adult survival from first count in mixed-species combination of *T. castaneum* in dry (12% wb) grain at 15, 20, and 25°C.

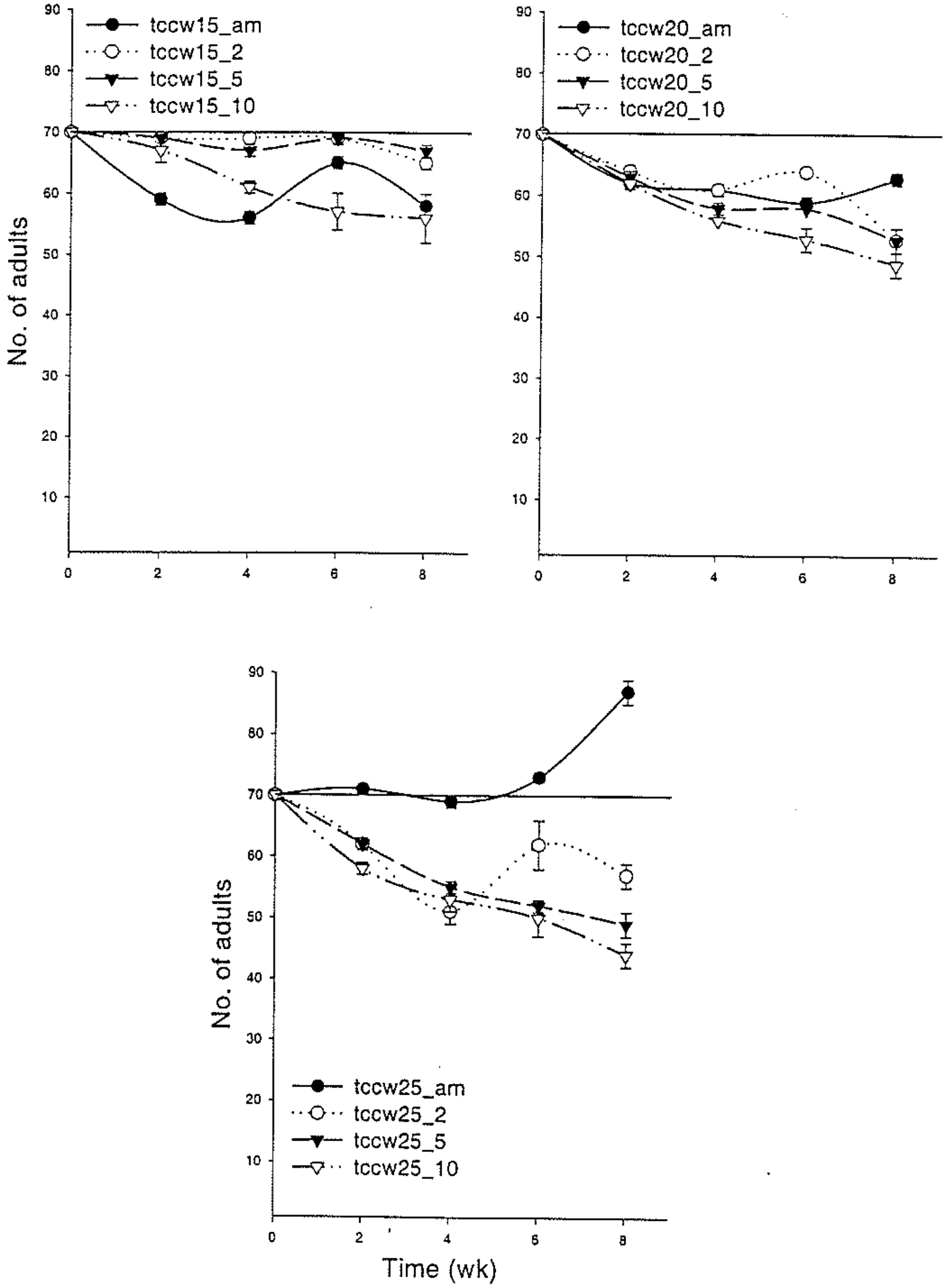

Fig. A44 Effect of CO_2 levels on mean adult survival from first count in mixed-species combination of *T. castaneum* in wet (15% wb) grain at 15, 20, and 25°C.

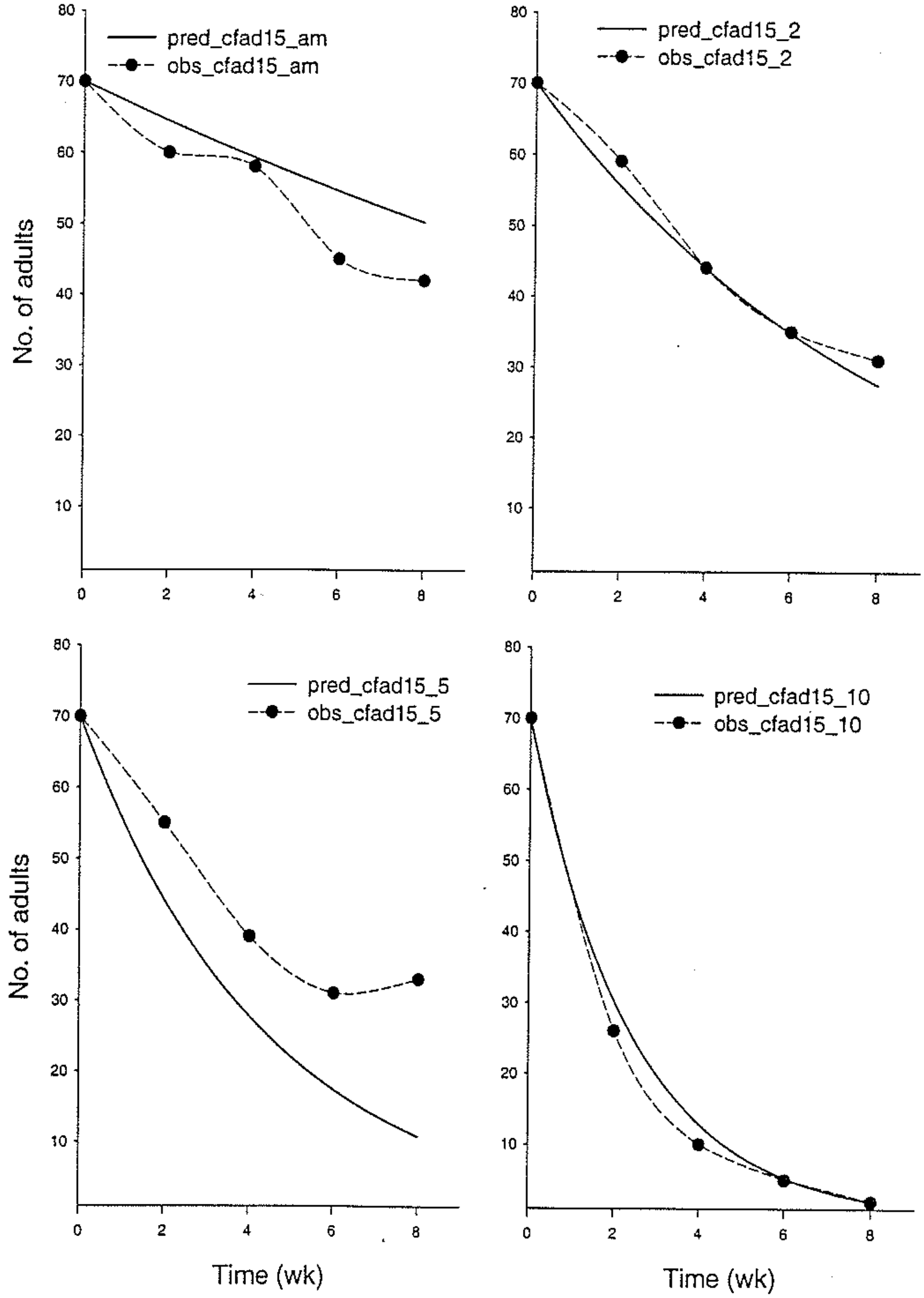

Fig. A45 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

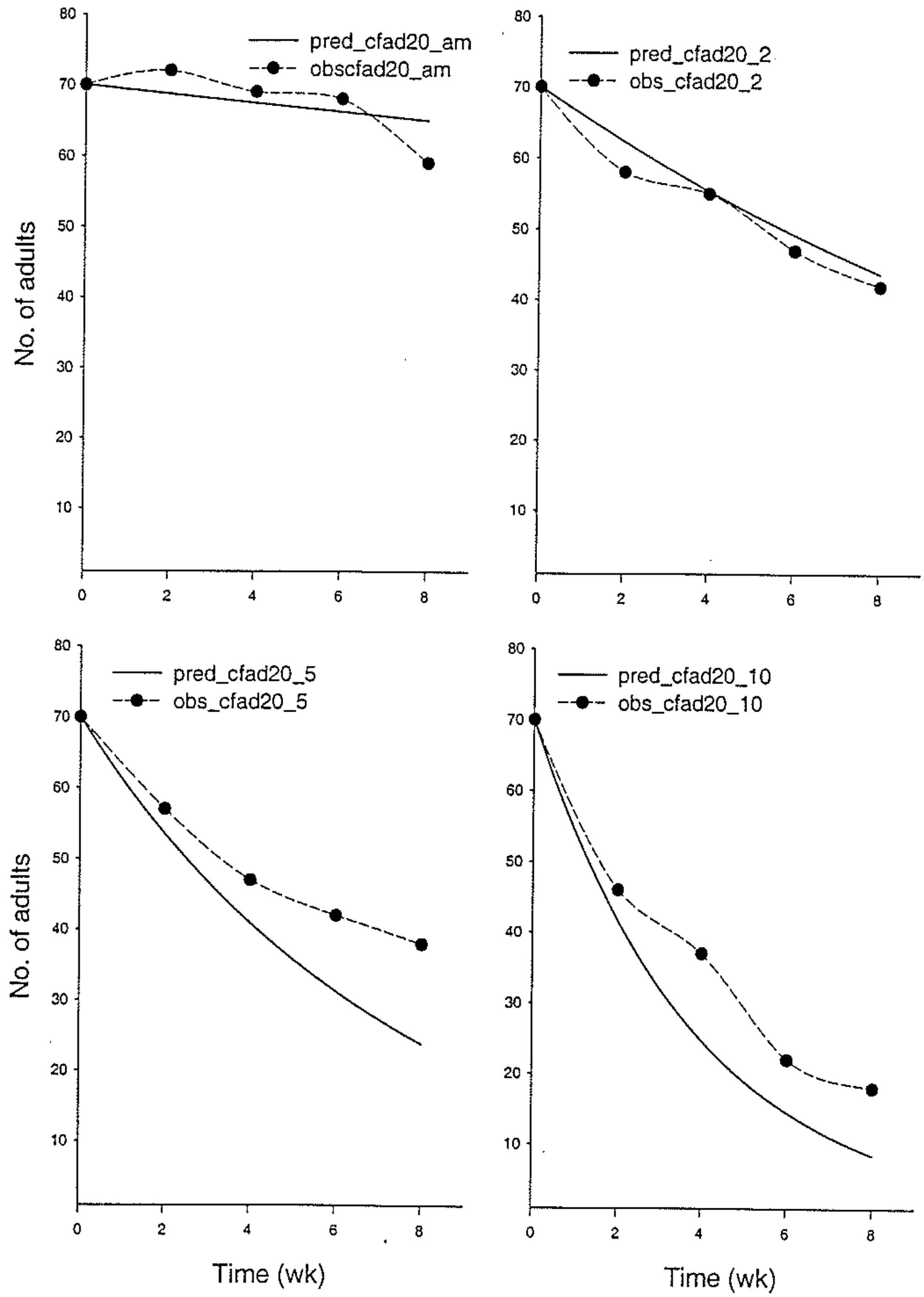

Fig. A46 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

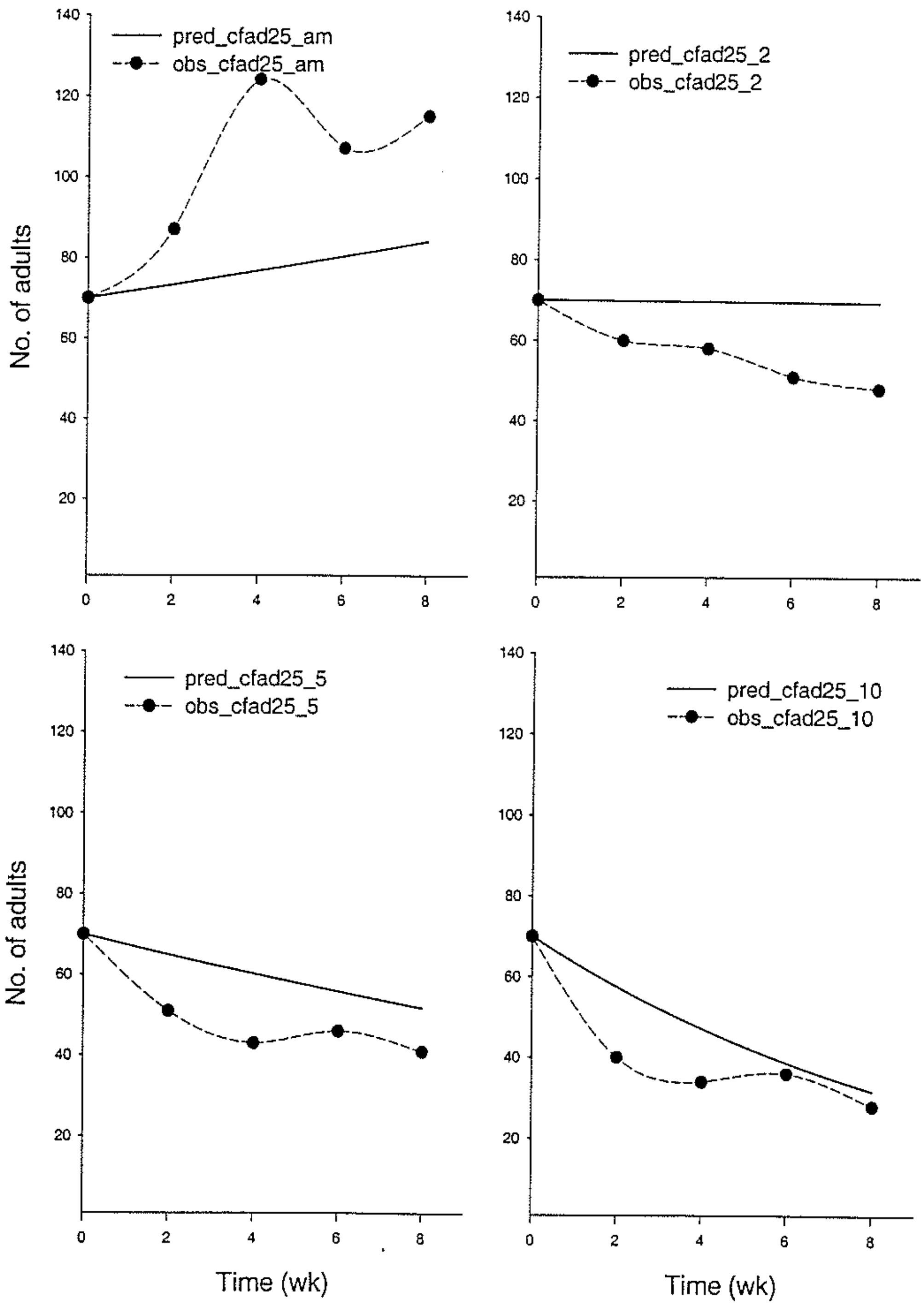

Fig. A47 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in dry (12% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

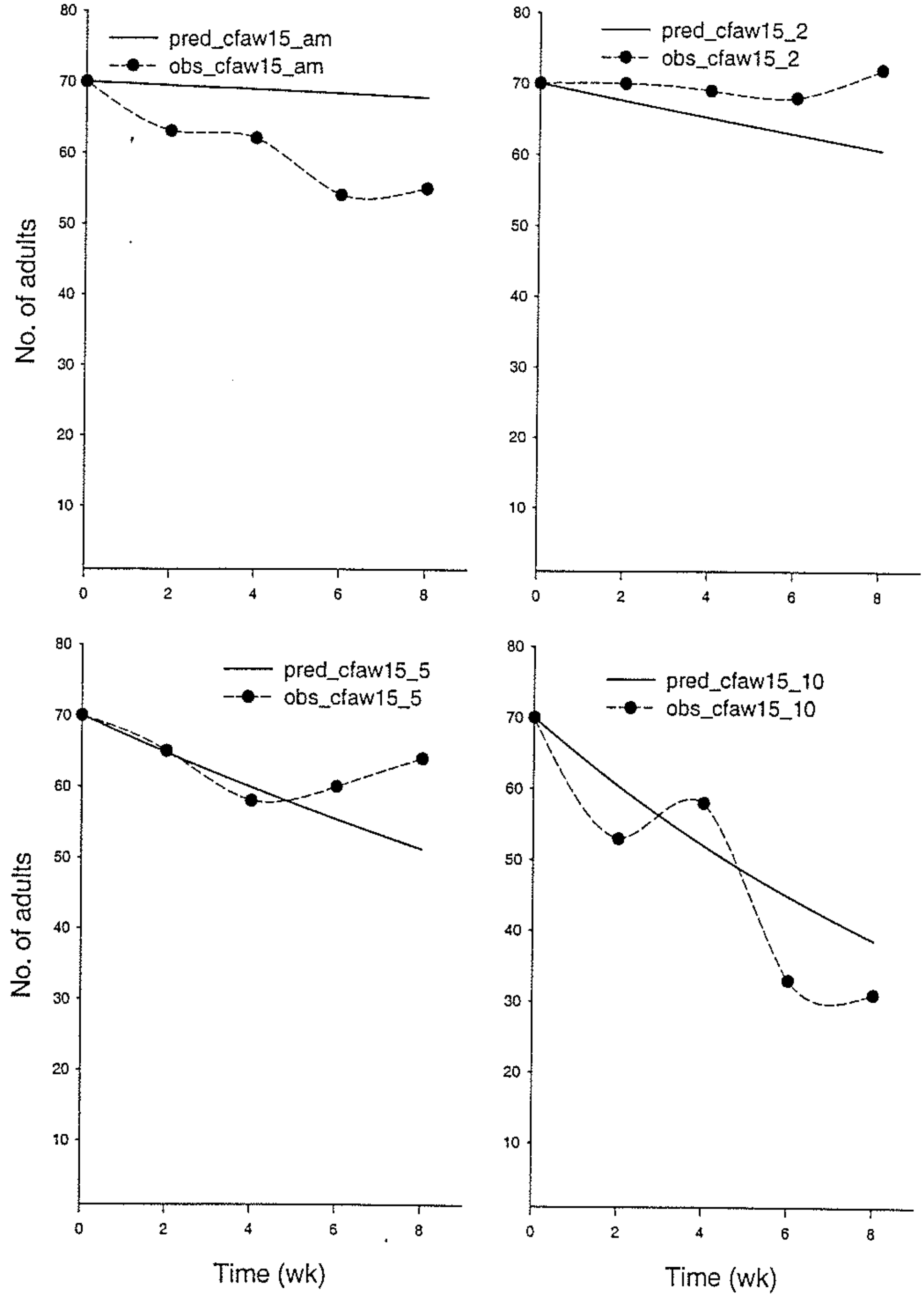

Fig. A48 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

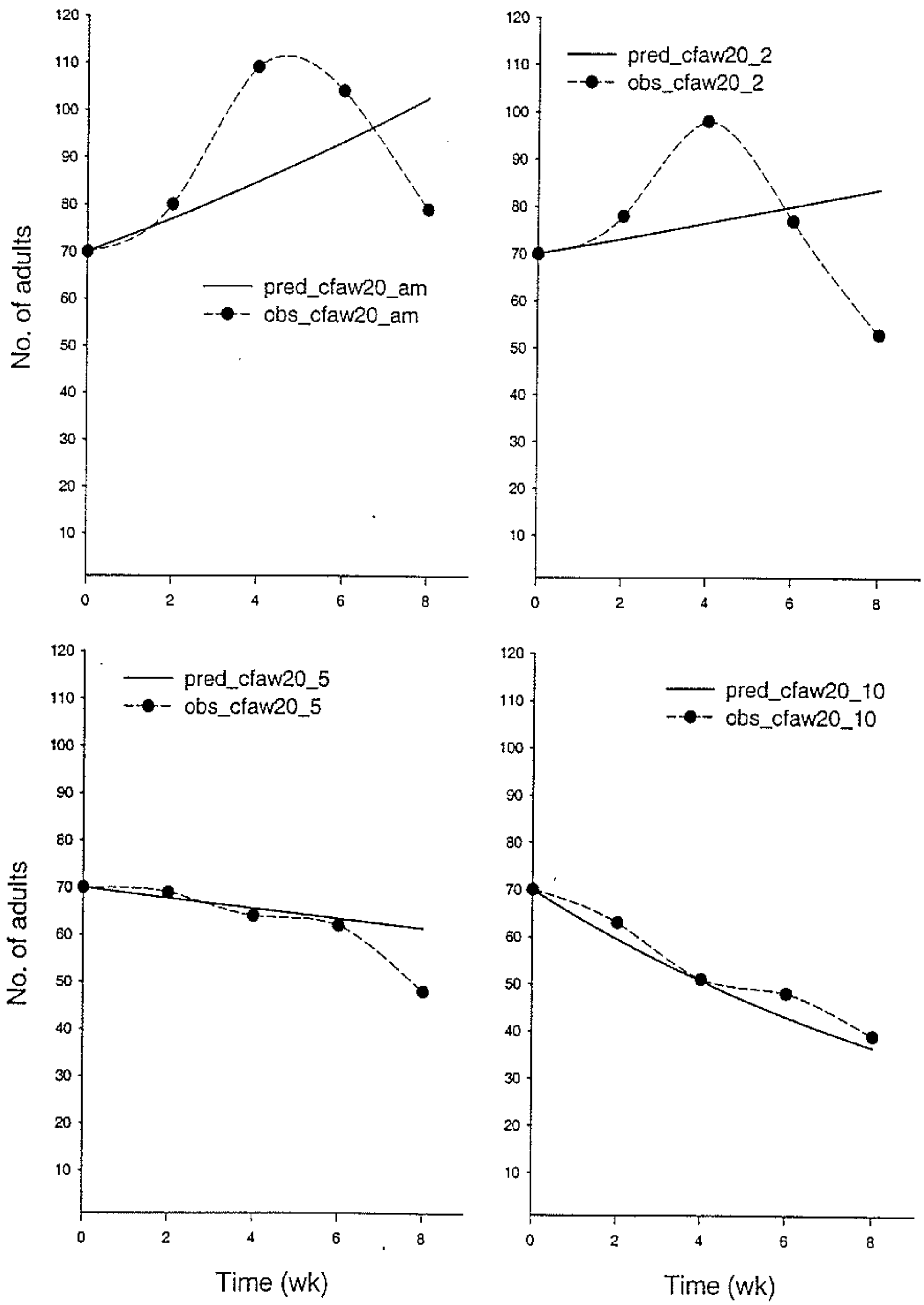

Fig. A49 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

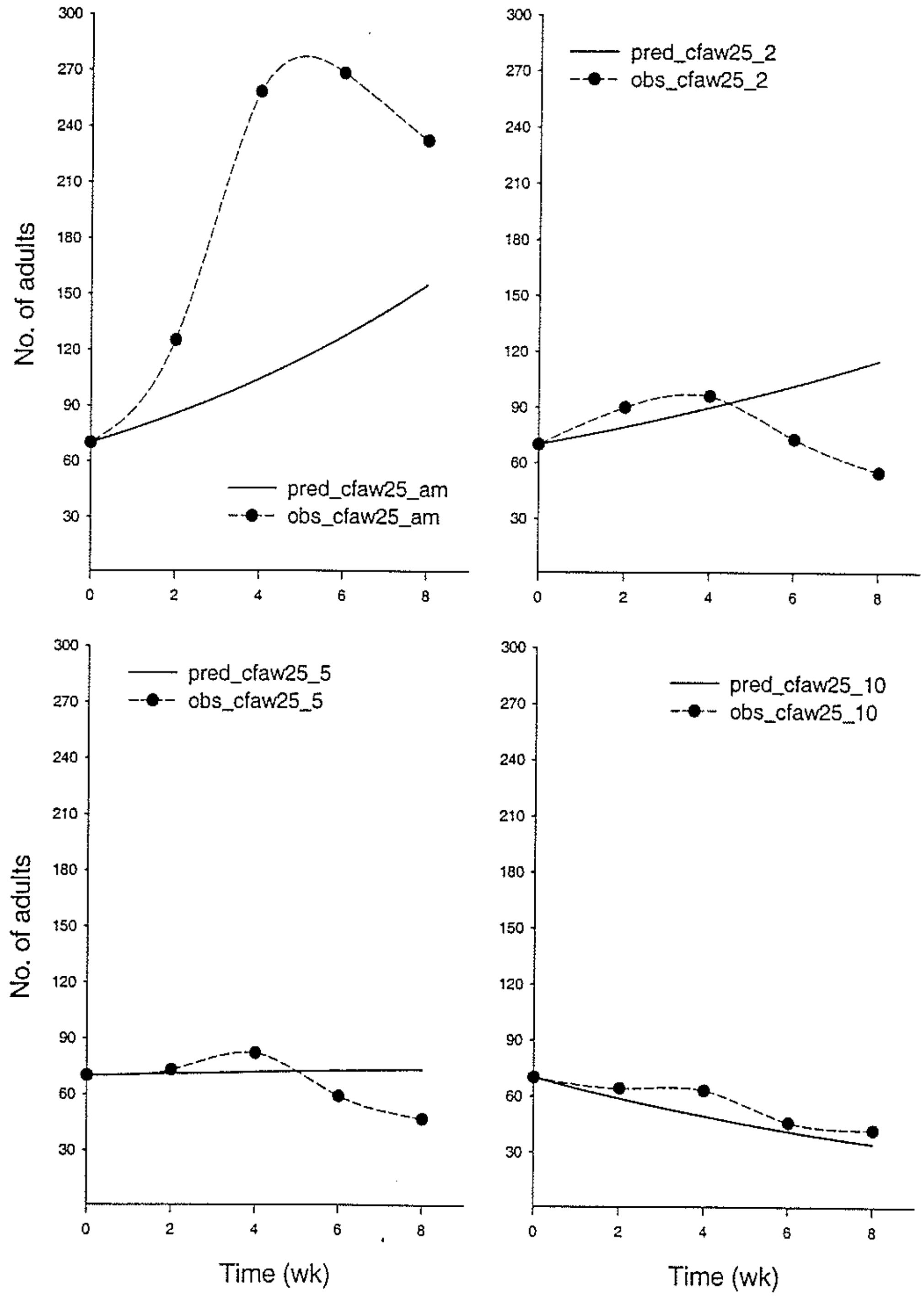

Fig. A50 Observed and predicted mean adult survival in single-species controls of *C. ferrugineus* in wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

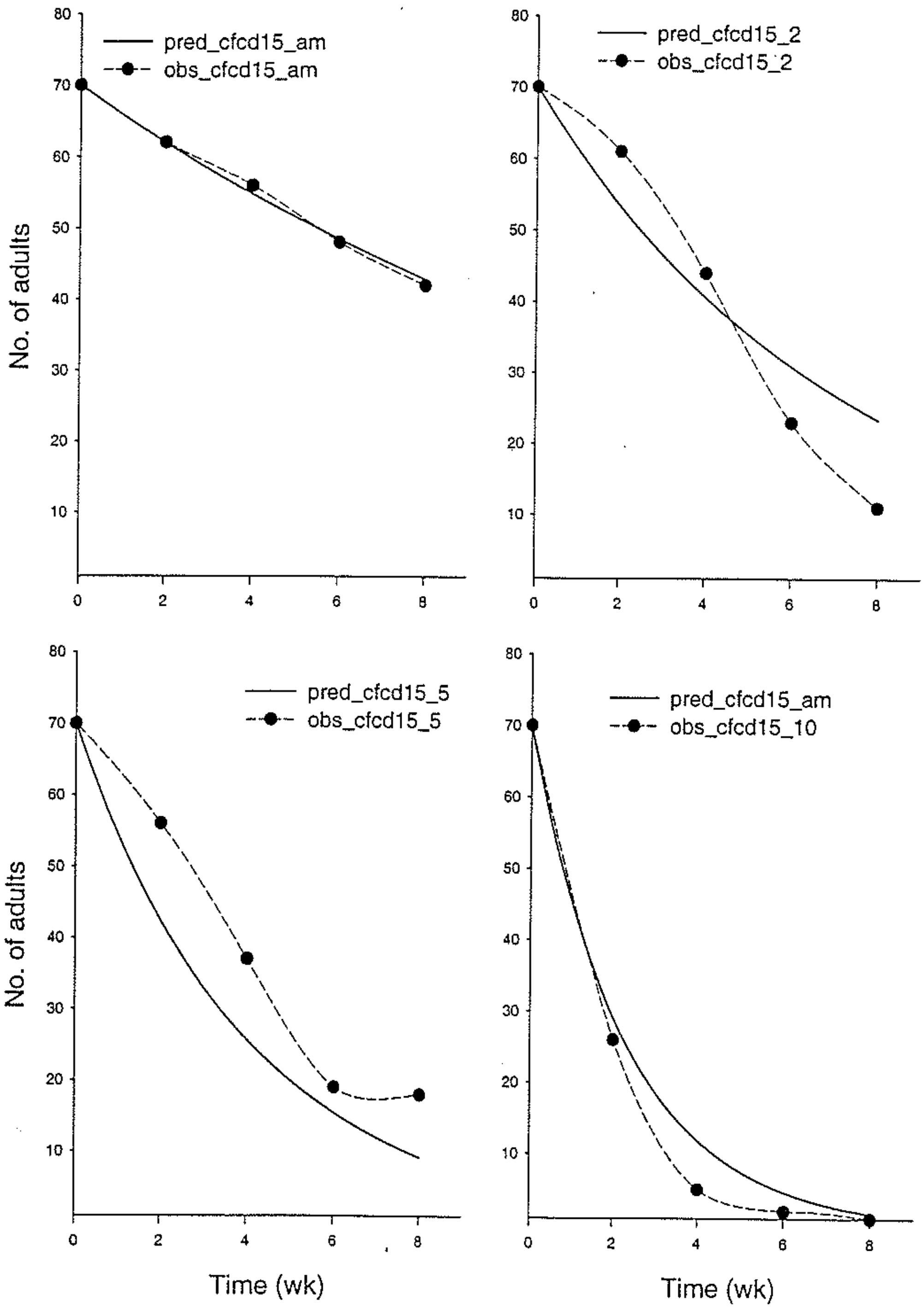

Fig. A51 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

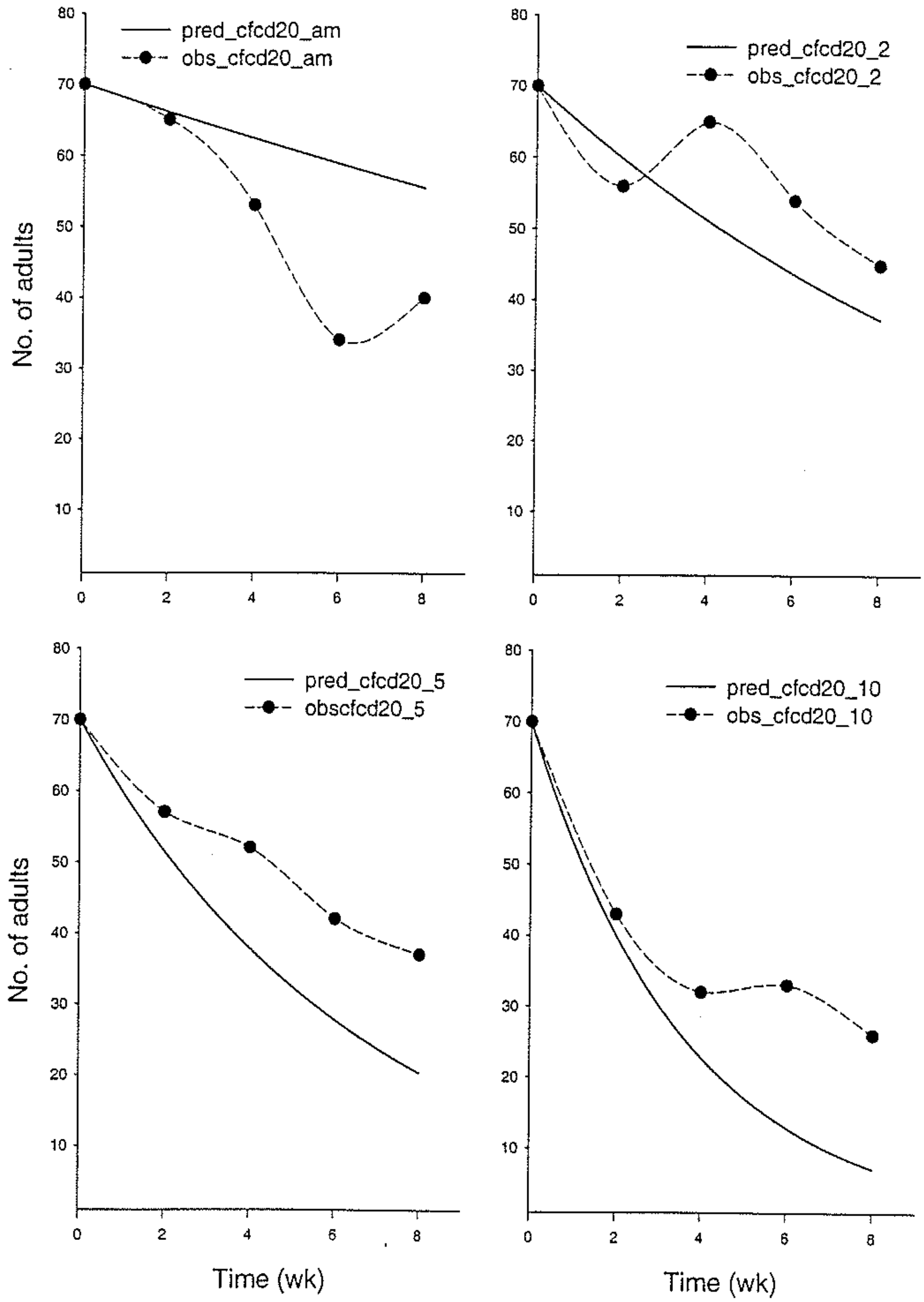

Fig. A52 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

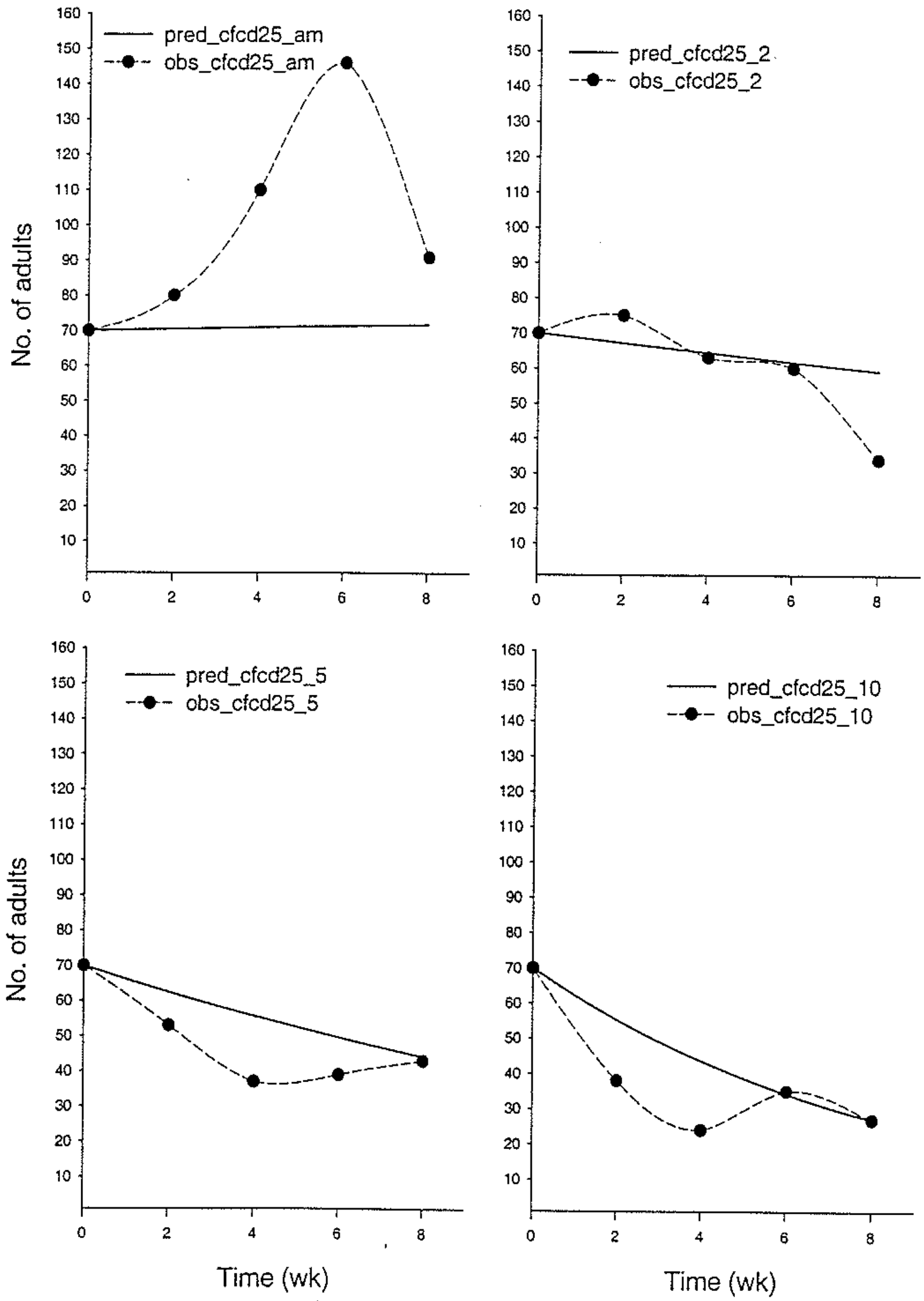

Fig. A53 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in dry (12% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

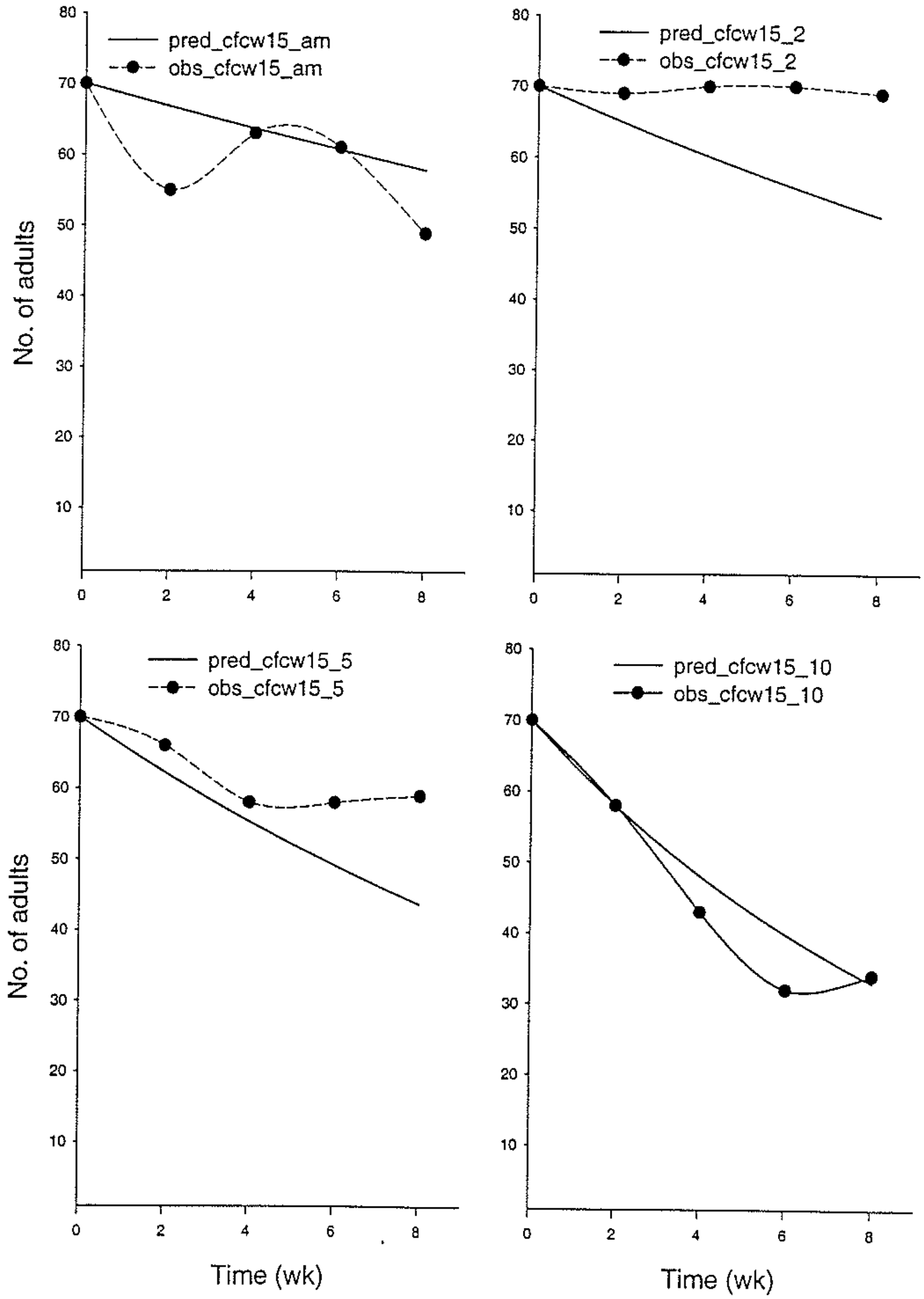

Fig. A54 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

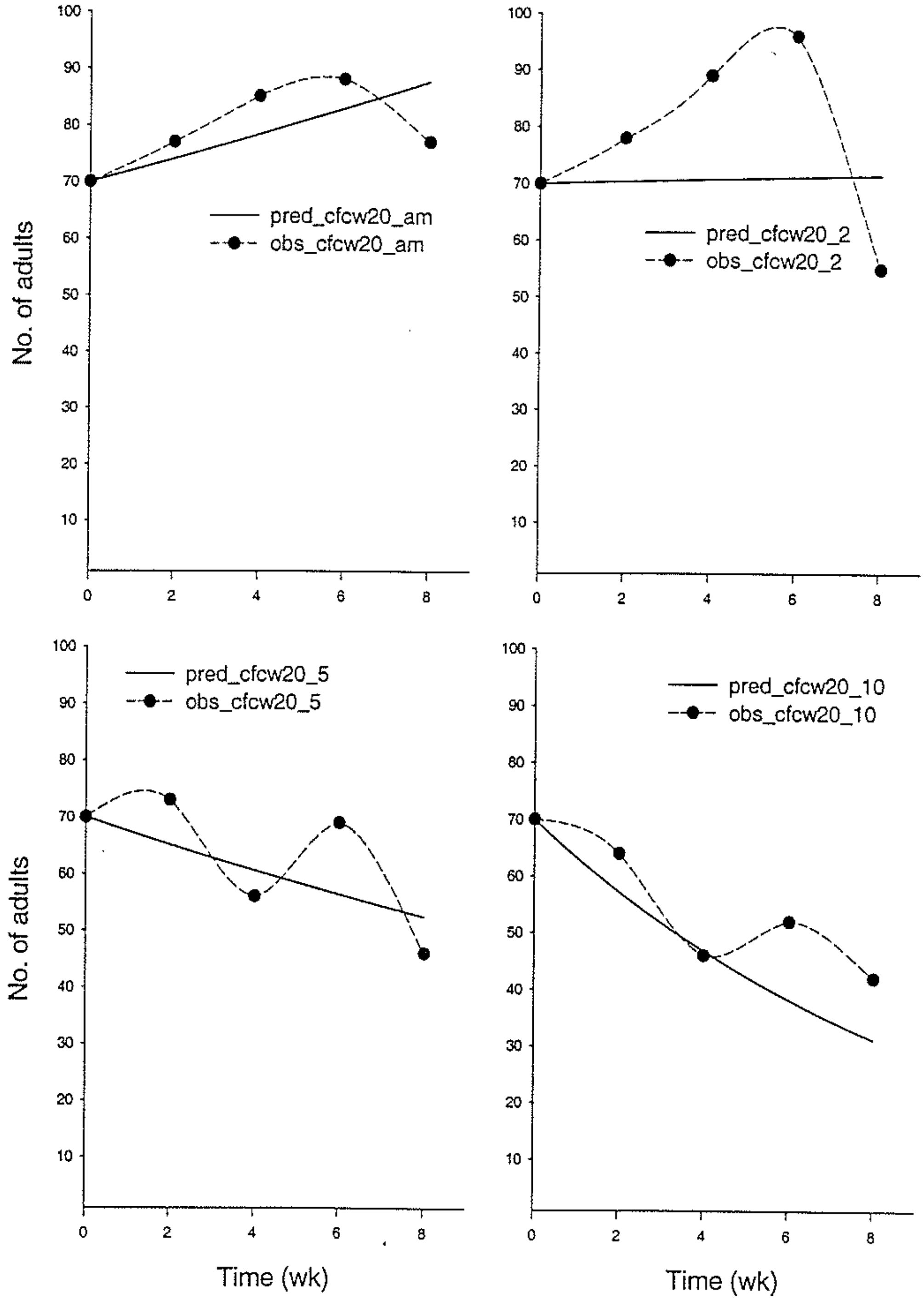

Fig. A55 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

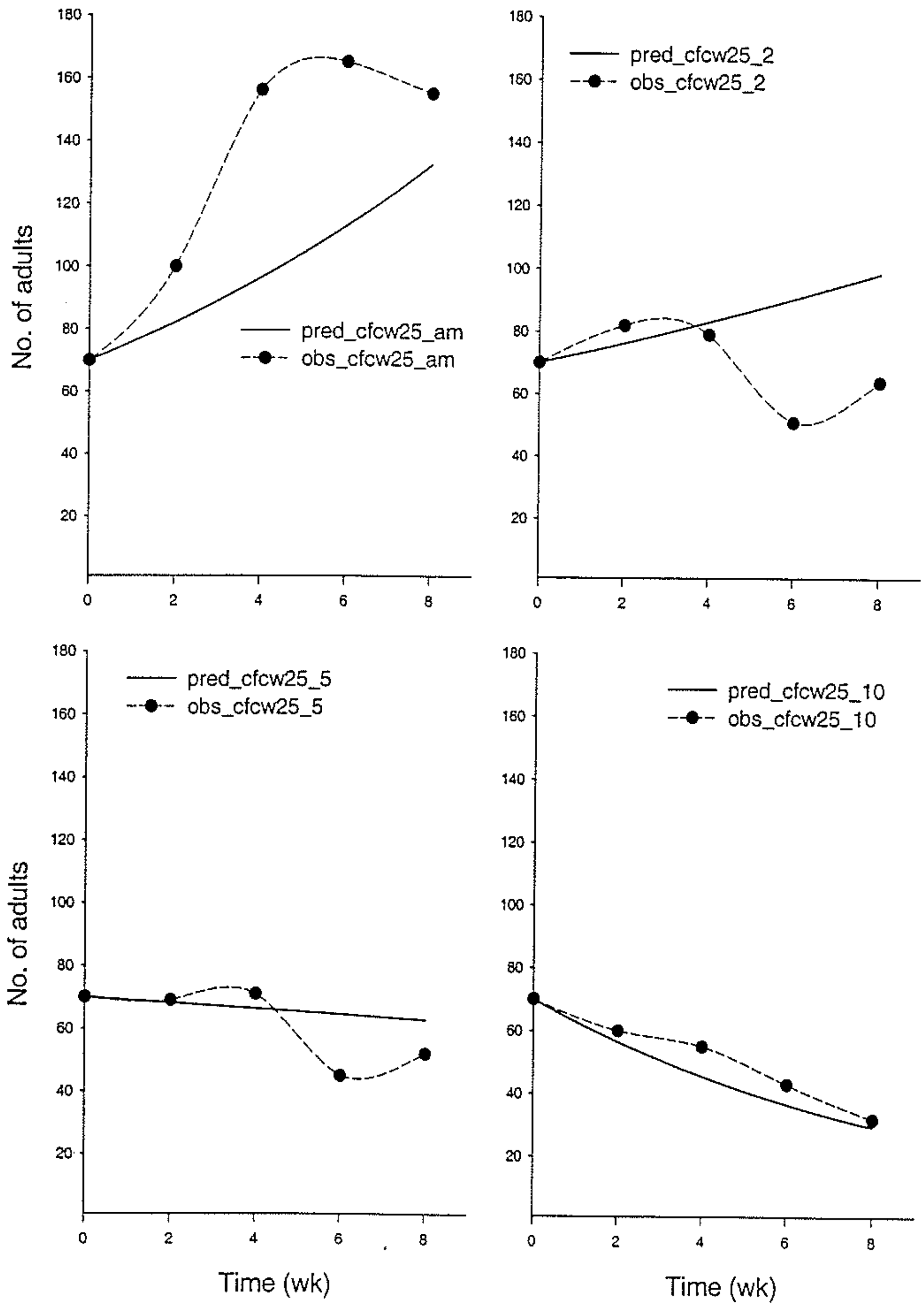

Fig. A56 Observed and predicted mean adult survival in mixed-species combination of *C. ferrugineus* in wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

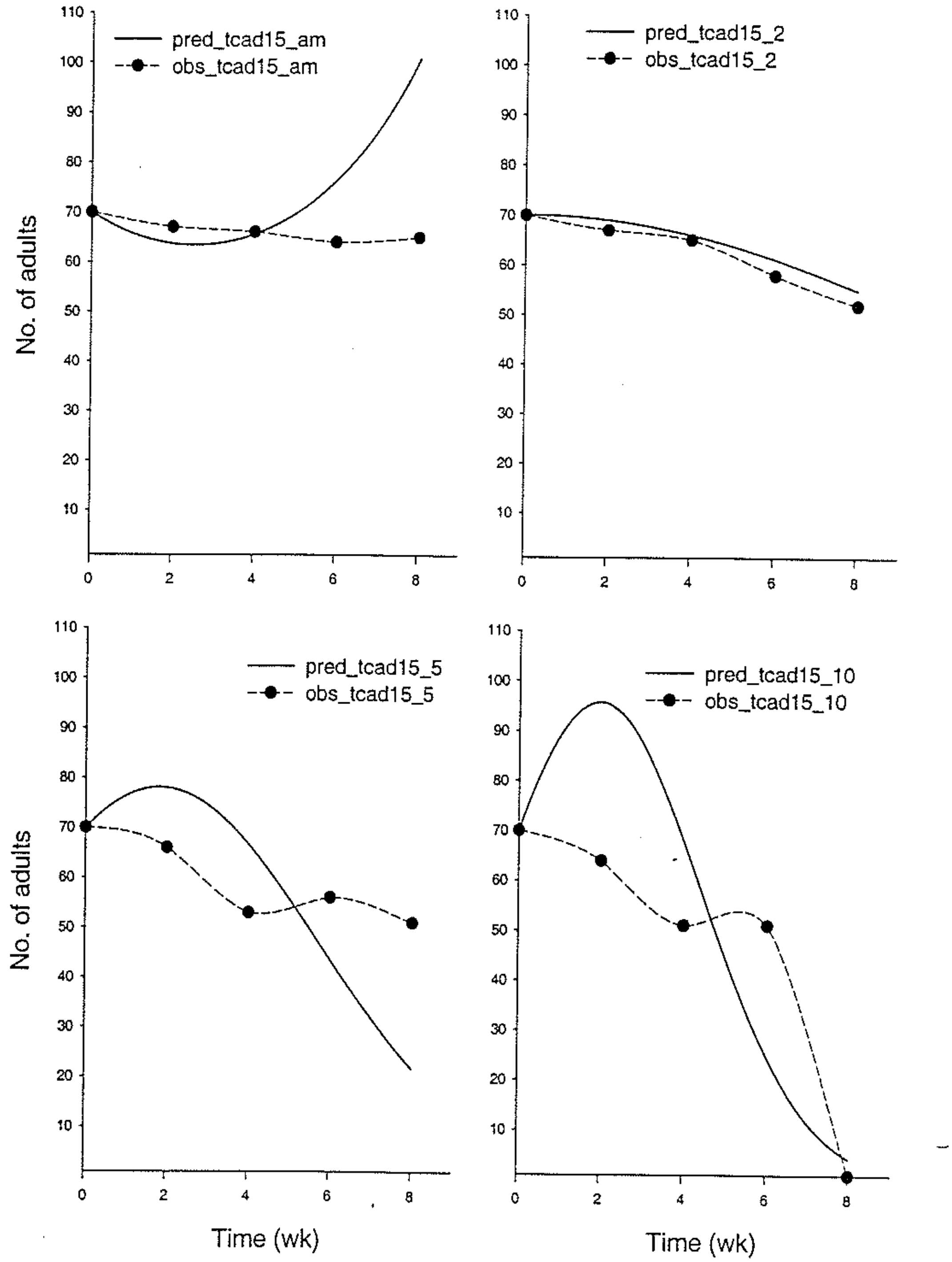

Fig. A57 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

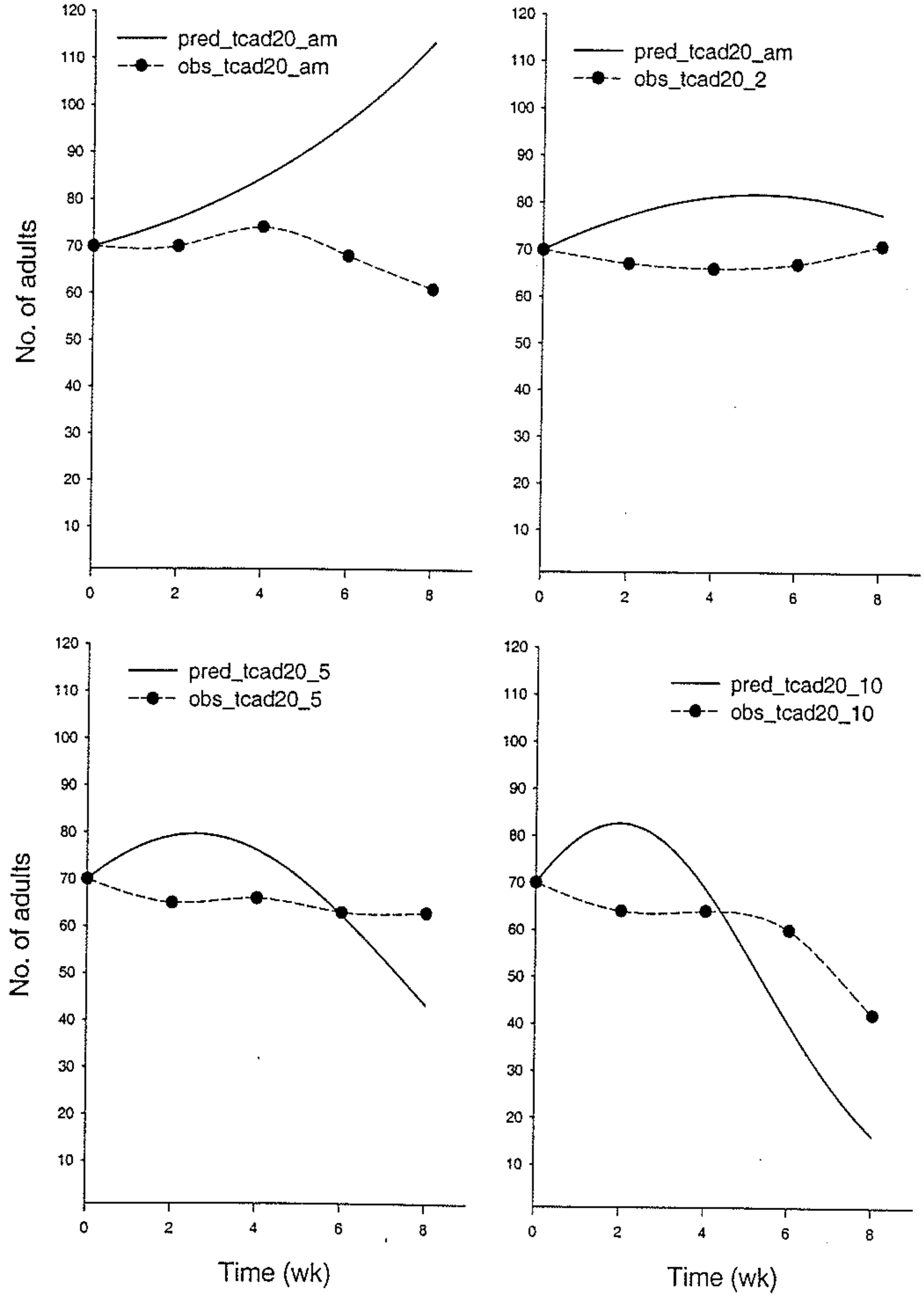

Fig. A58 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

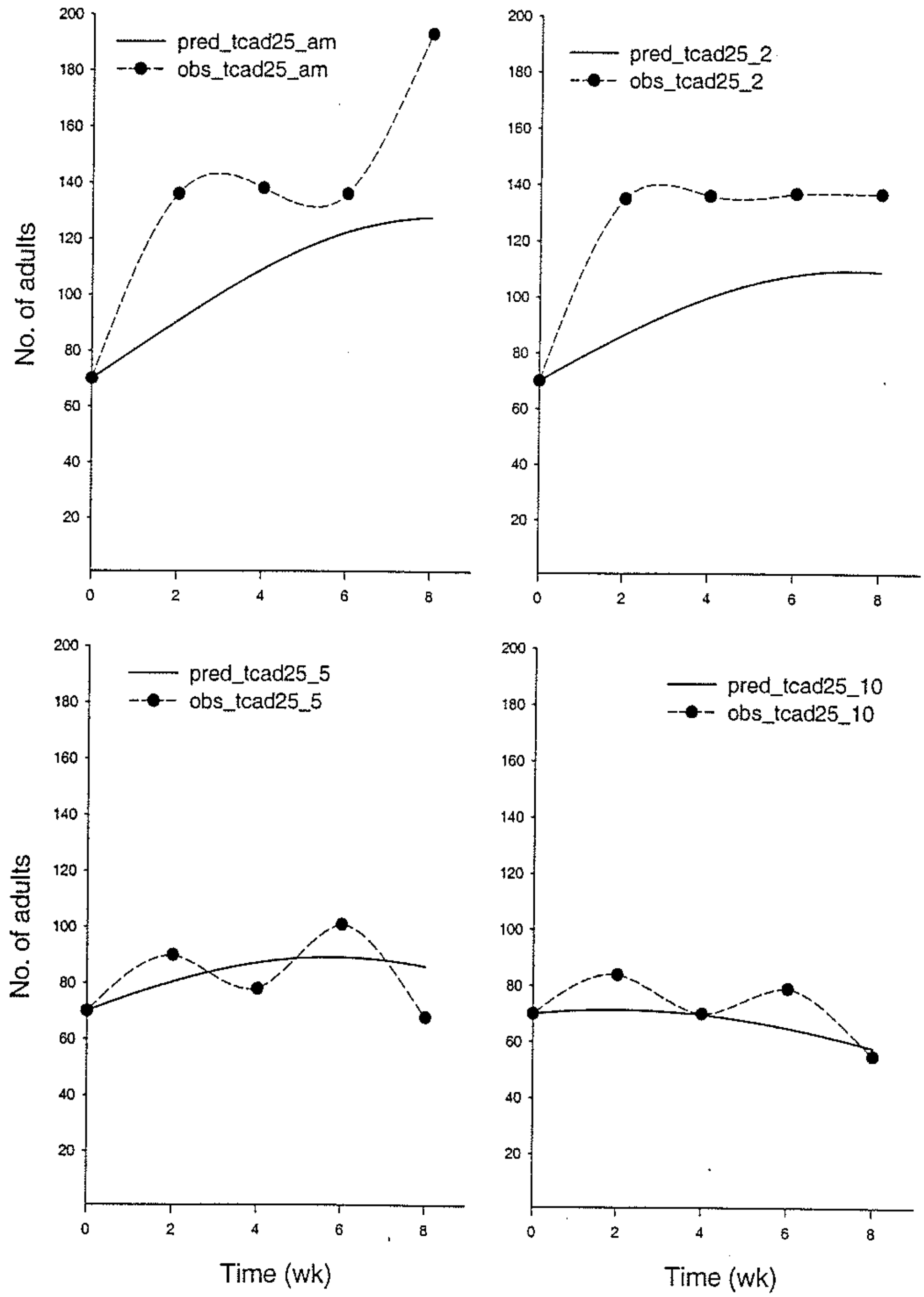

Fig. A59 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in dry (12% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

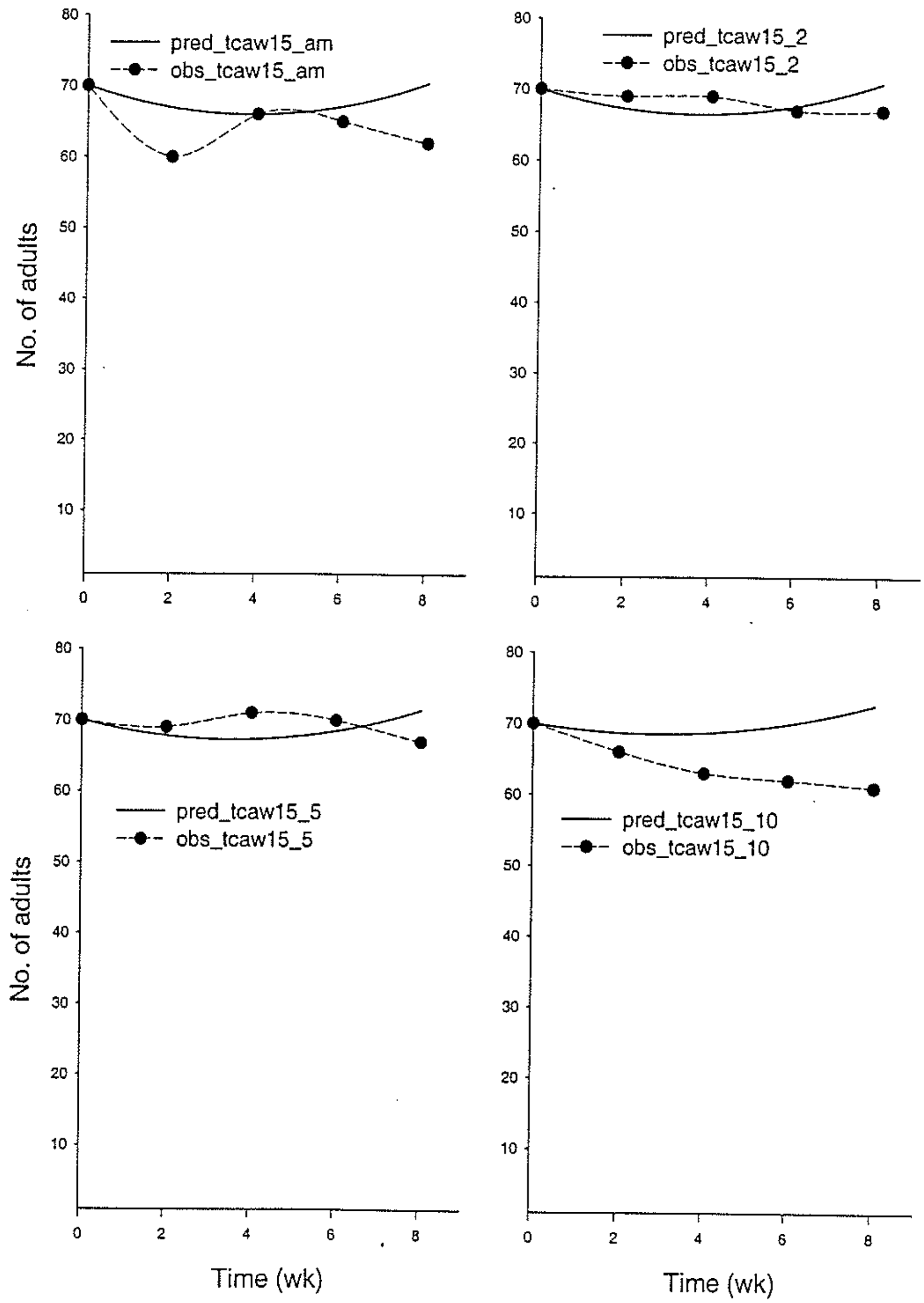

Fig. A60 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

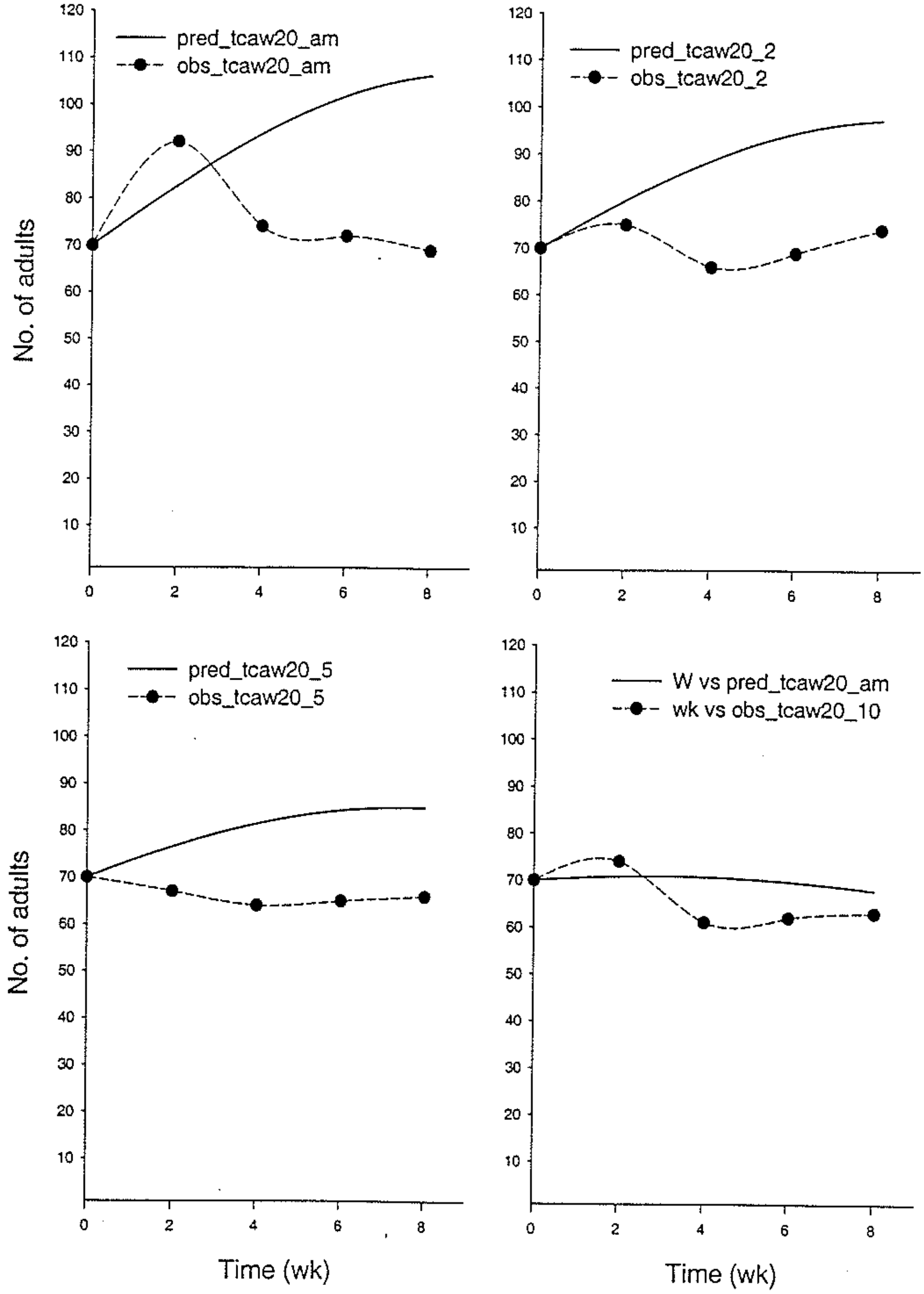

Fig. A61 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

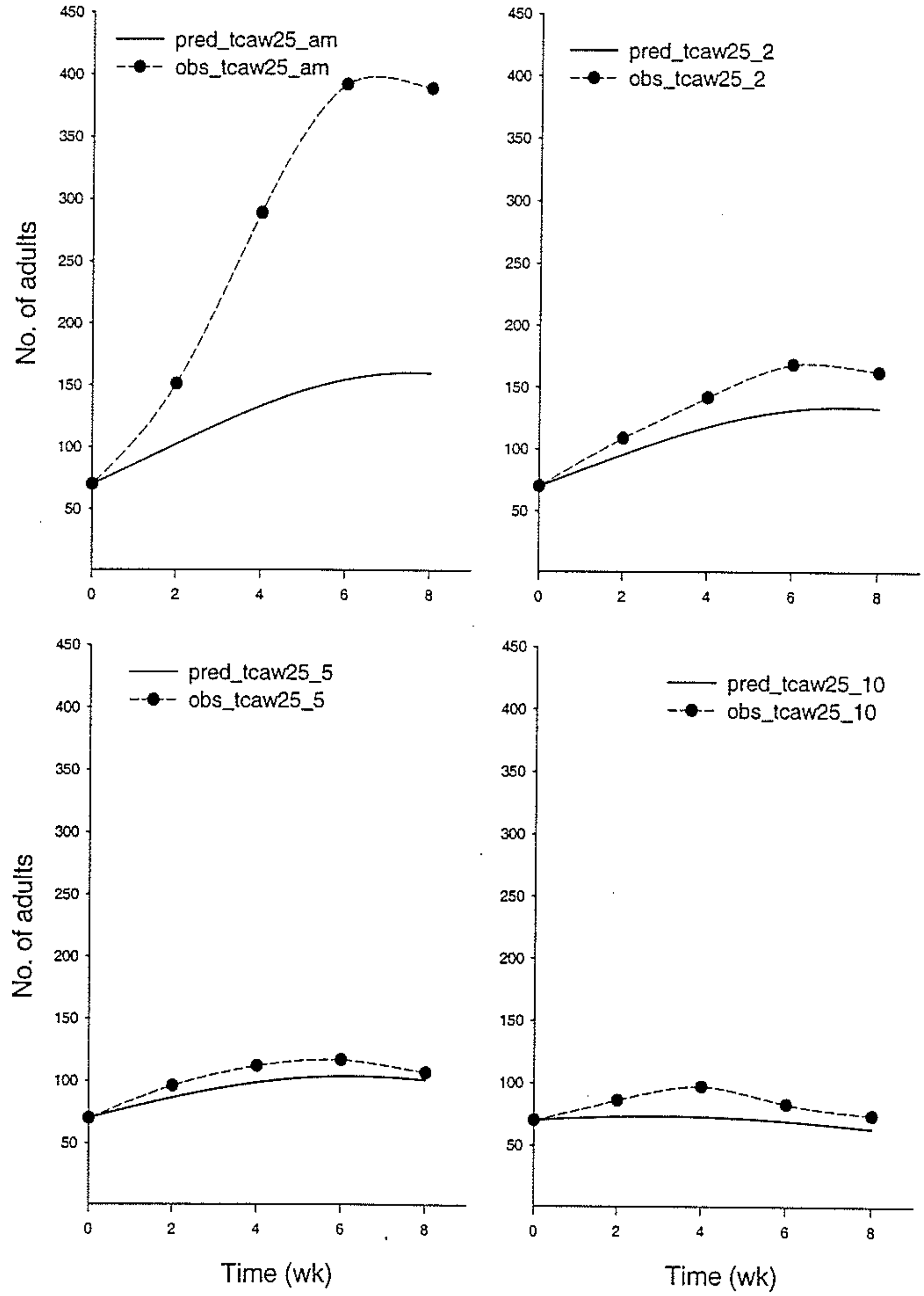

Fig. A62 Observed and predicted mean adult survival in single-species controls of *T. castaneum* in wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

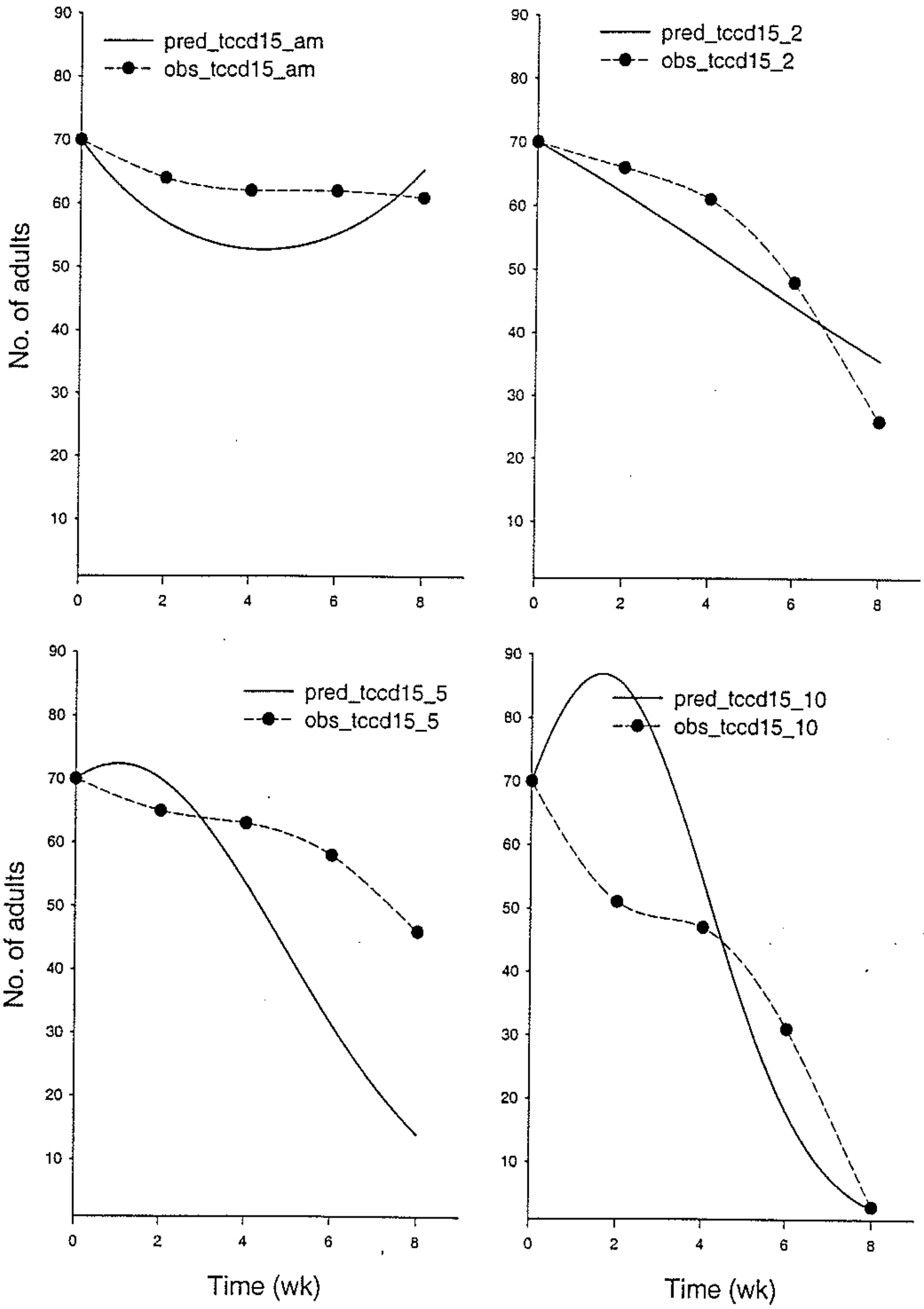

Fig. A63 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

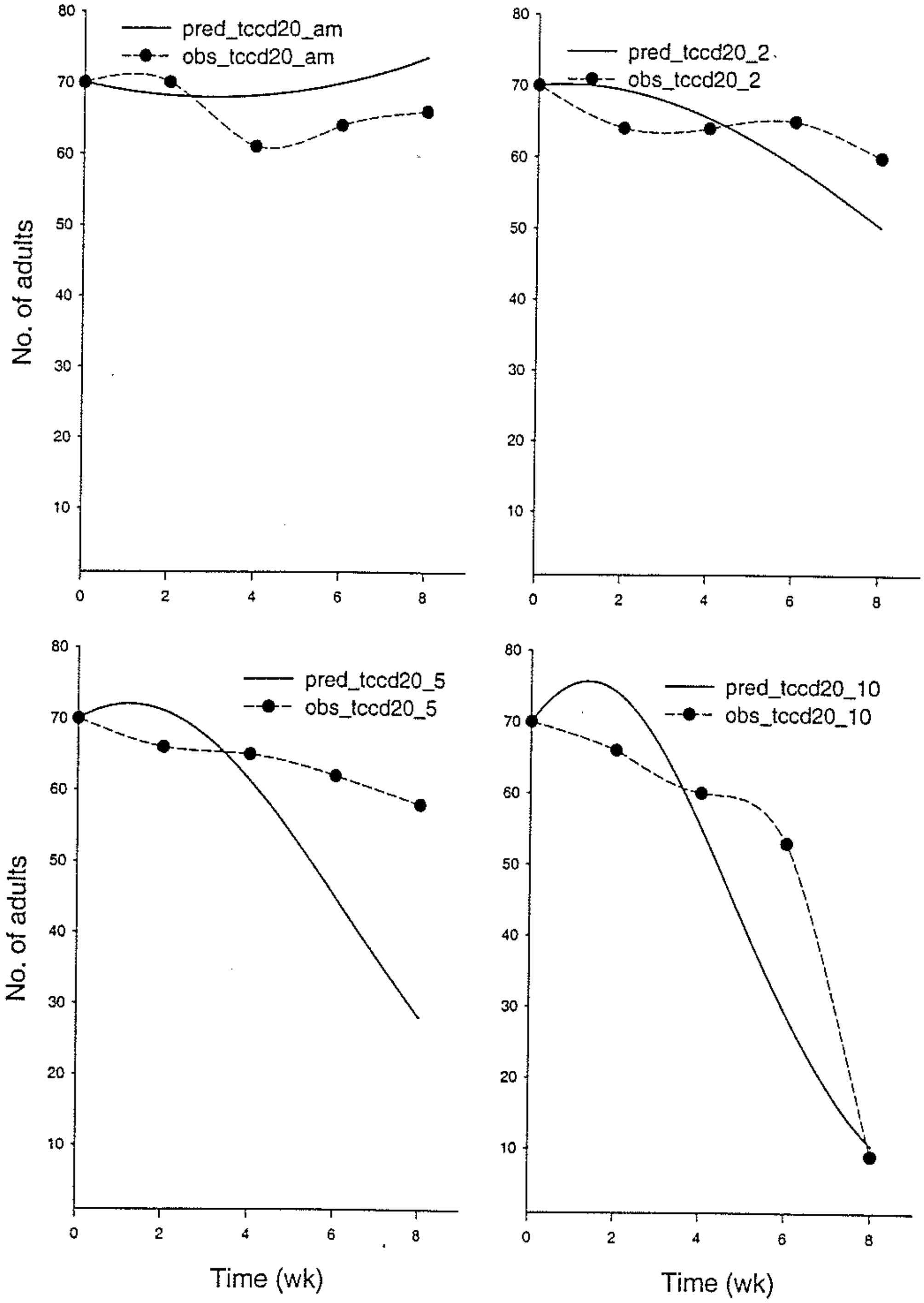

Fig. A64 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

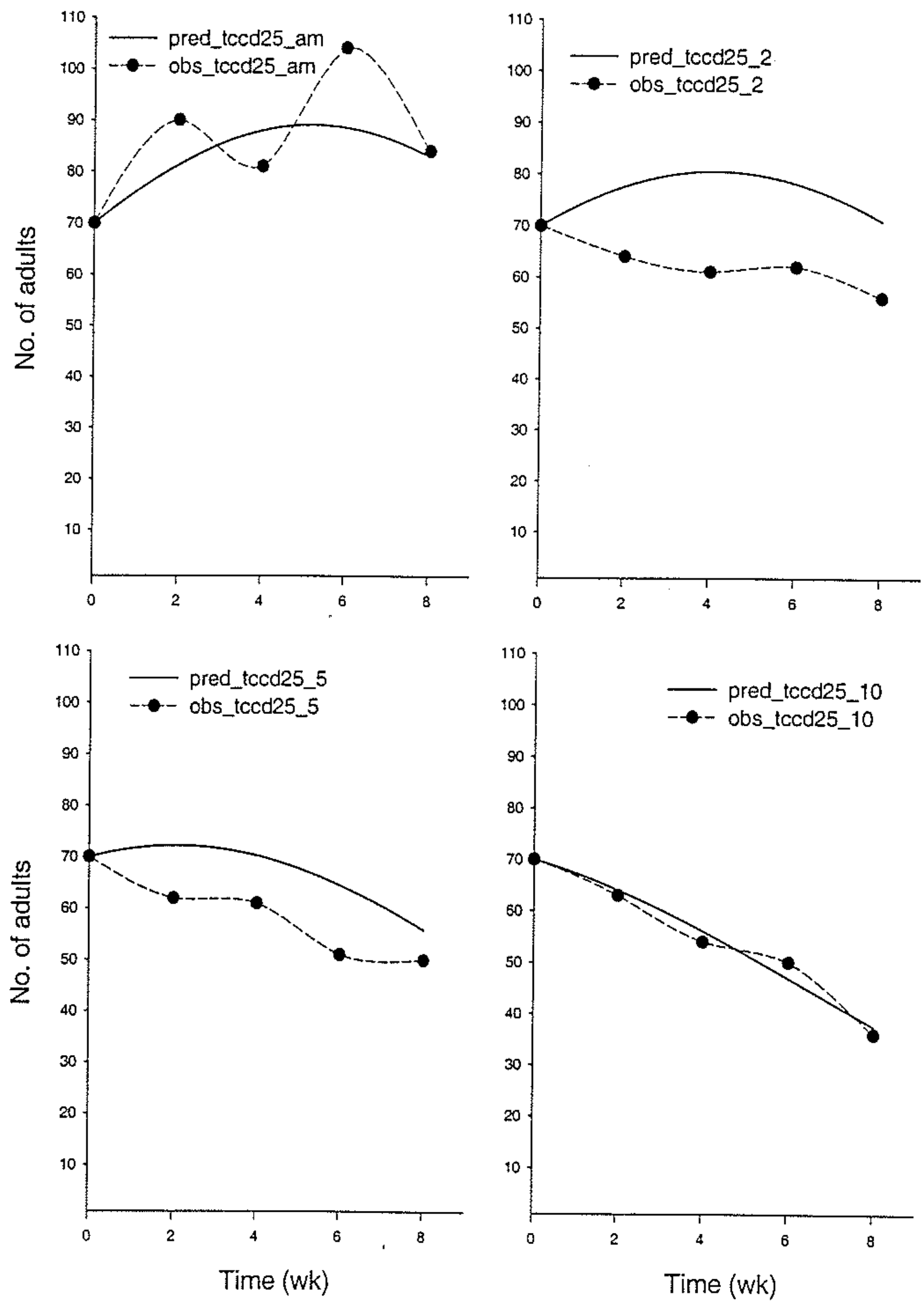

Fig. A65 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in dry (12% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2. A65

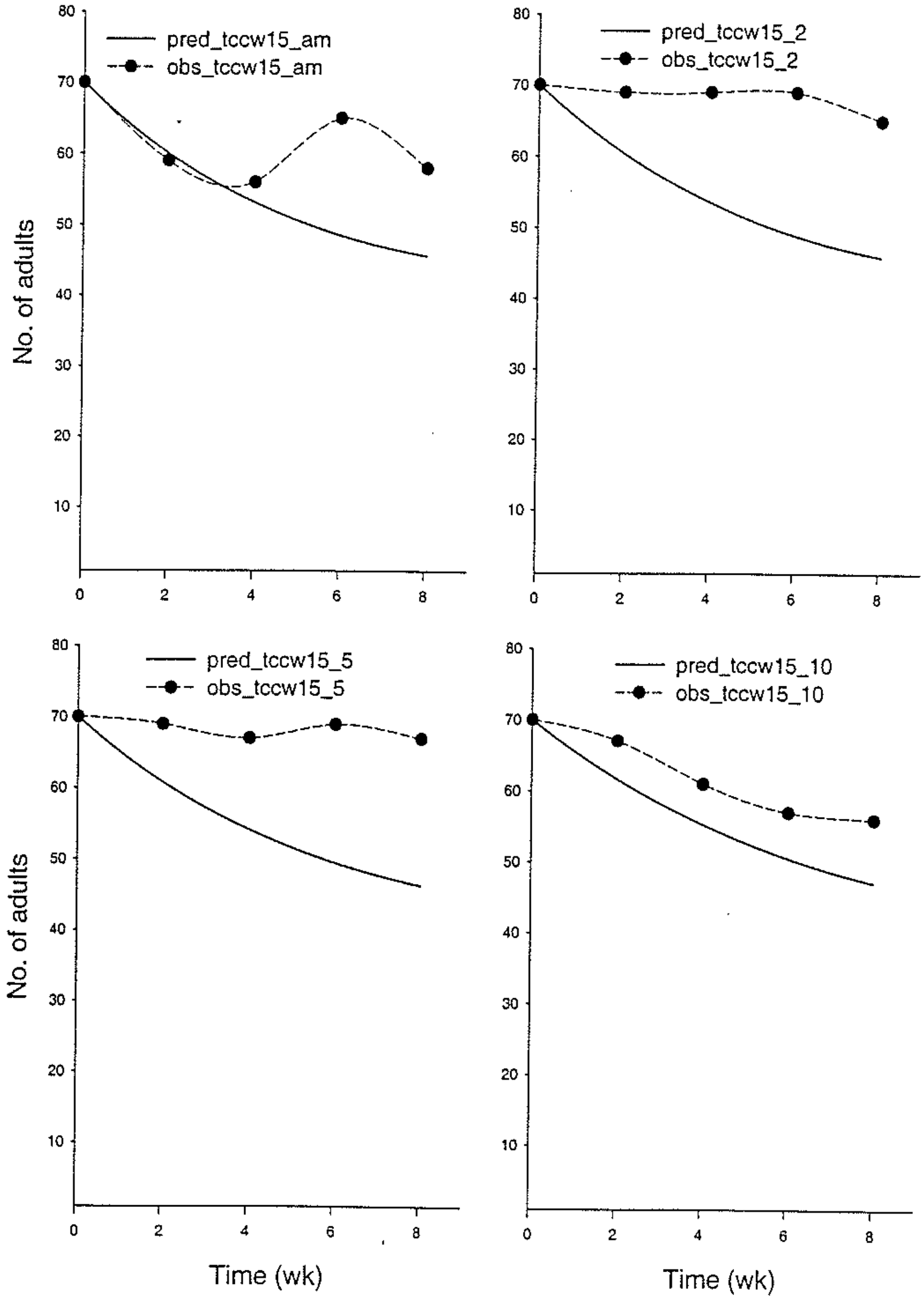

Fig. A66 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in wet (15% wb) grain at 15°C and ambient (am), 2, 5, and 10% levels of CO_2.

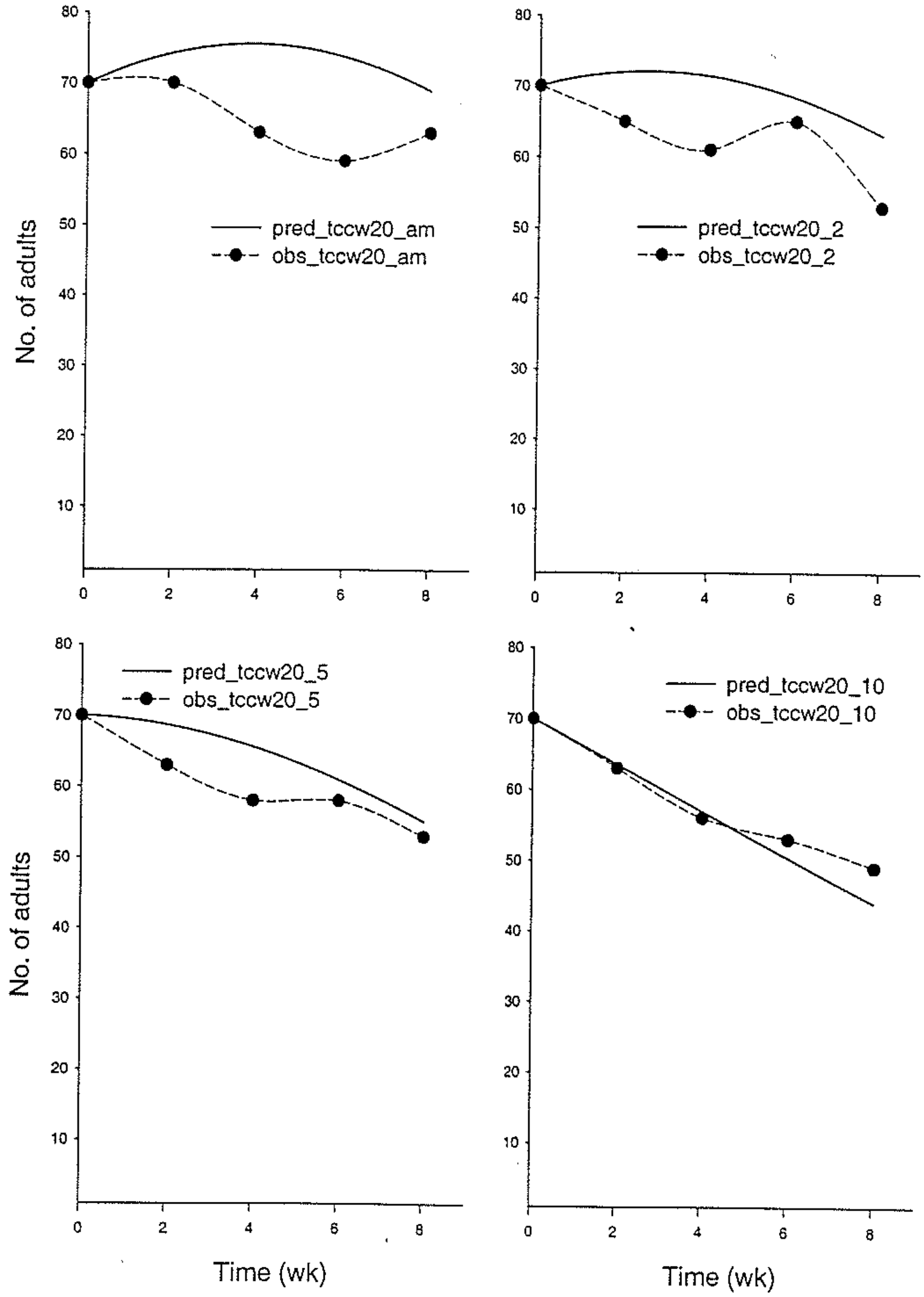

Fig. A67 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in wet (15% wb) grain at 20°C and ambient (am), 2, 5, and 10% levels of CO_2.

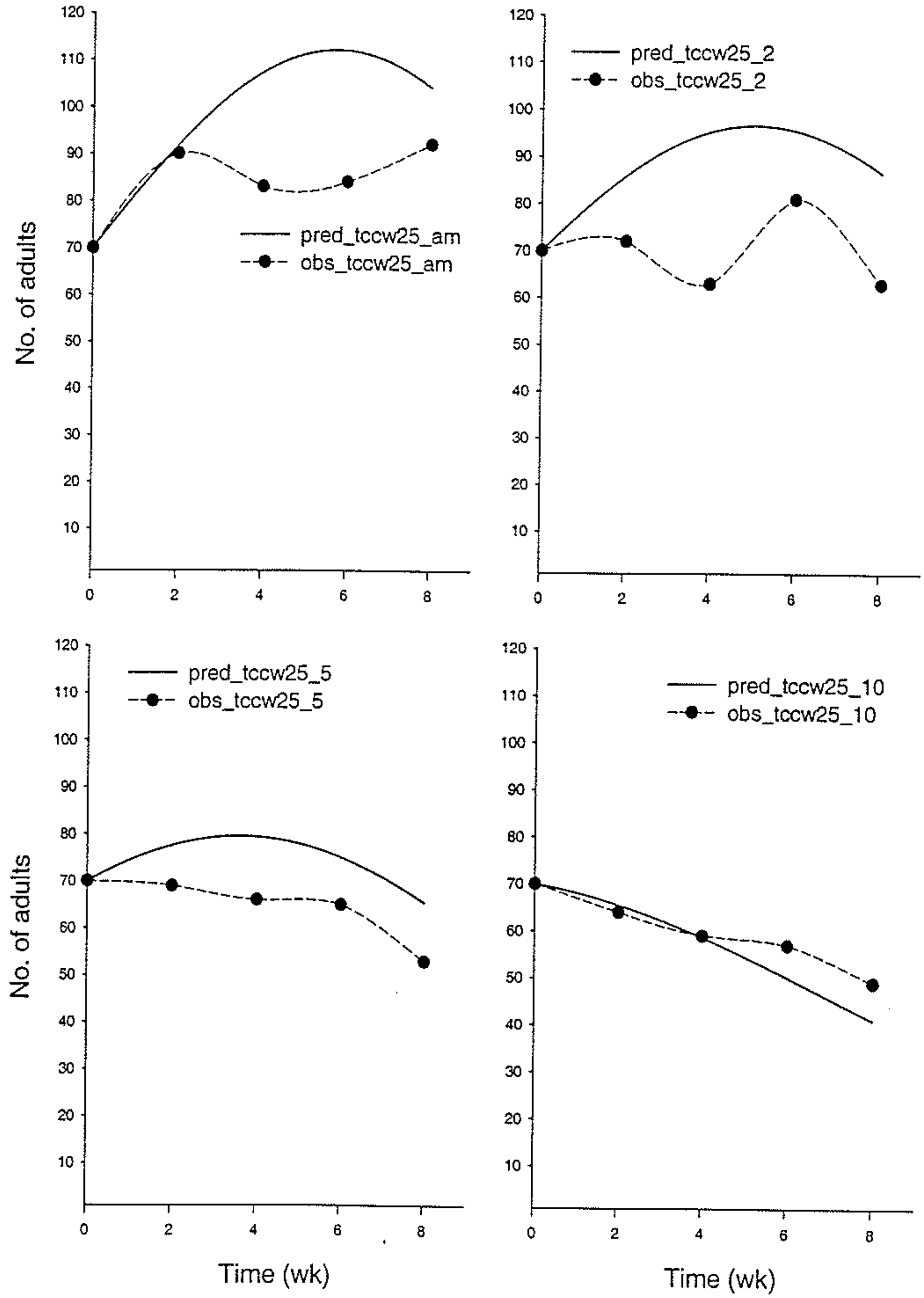

Fig. A68 Observed and predicted mean adult survival in mixed-species combination of *T. castaneum* in wet (15% wb) grain at 25°C and ambient (am), 2, 5, and 10% levels of CO_2.

APPENDIX B

Table B1 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and ambient CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-am-C-I	C	60	10	0	0	60		12.0
D-15-am-C-II	C	58	12	0	0	58	96	13.3
D-15-am-C-III	C	62	9	0	0	62		12.2
D-15-am-C-IV	C	60	10	0	0	60		12.2
D-15-am-T-I	T	68	2	0	0	68		12.2
D-15-am-T-II	T	66	4	0	0	66	94	12.1
D-15-am-T-III	T	69	1	0	0	69		11.9
D-15-am-T-IV	T	65	4	0	0	65		12.1
D-15-am-B-I	C	61	9	0	0	61		12.0
	T	64	6	0	0	64		
D-15-am-B-II	C	63	7	0	0	63		12.0
	T	62	9	0	0	62	94	
D-15-am-B-III	C	58	12	0	0	58		12.0
	T	66	5	0	0	66		
D-15-am-B-IV	C	66	5	0	0	66		12.3
	T	64	6	0	0	64		
W-15-am-C-I	C	61	8	0	0	61		14.8
W-15-am-C-II	C	58	8	0	0	58	94	15.1
W-15-am-C-III	C	60	3	0	0	60		14.9
W-15-am-C-IV	C	71	3	0	2	71		14.3
W-15-am-T-I	T	62	8	1	0	63		14.0
W-15-am-T-II	T	59	10	0	0	59	93	14.3
W-15-am-T-III	T	58	7	0	0	58		14.9
W-15-am-T-IV	T	61	5	0	0	61		14.9
W-15-am-B-I	C	55	17	0	0	55		17.4
	T	61	9	0	0	61		
W-15-am-B-II	C	58	12	0	2	58		14.1
	T	58	12	0	0	58	93	
W-15-am-B-III	C	55	15	0	0	55		14.1
	T	59	10	0	0	59		
W-15-am-B-IV	C	53	17	0	0	53		14.1
	T	57	13	0	0	57		

* The meaning of characters separated by hyphen in the code are: D or W represent dry and wet grain at 12 and 15% (wb), respectively; next two digits represent temperature in °C; next single or two digits represent percent CO_2 and 'am' in place of single or two digits represents ambient CO_2; next characters C, T, and B (also applicable to insect type column) represent insect species *C. ferrugineus*, *T. castaneum*, and both species together, respectively; and the last Roman numerals I, II, III, and IV represent the four replicates.

Table B2 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and ambient CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-am-C-I	C	57	13	0	0	57		11.8
D-15-am-C-II	C	56	14	0	0	56	94	11.9
D-15-am-C-III	C	62	8	0	0	62		12.3
D-15-am-C-IV	C	58	12	0	0	58		12.2
D-15-am-T-I	T	66	4	0	0	66		12.2
D-15-am-T-II	T	65	5	0	0	65	92	12.2
D-15-am-T-III	T	67	3	0	0	67		12.3
D-15-am-T-IV	T	66	4	0	0	66		12.3
D-15-am-B-I	C	58	12	0	0	58		11.8
	T	59	11	0	0	59		
D-15-am-B-II	C	54	16	0	0	54		12.2
	T	65	5	0	0	65	92	
D-15-am-B-III	C	51	20	0	0	51		12.3
	T	61	9	0	0	61		
D-15-am-B-IV	C	61	10	0	0	61		11.7
	T	63	8	0	0	63		
W-15-am-C-I	C	60	10	0	1	60		14.9
W-15-am-C-II	C	60	9	0	0	60	89	14.4
W-15-am-C-III	C	70	1	0	1	70		14.1
W-15-am-C-IV	C	57	11	0	0	57		14.9
W-15-am-T-I	T	67	3	0	1	67		15.2
W-15-am-T-II	T	63	7	0	0	63	91	15.0
W-15-am-T-III	T	68	2	0	0	68		14.2
W-15-am-T-IV	T	67	4	0	0	67		14.1
W-15-am-B-I	C	61	9	0	0	61		15.0
	T	57	12	0	0	57		
W-15-am-B-II	C	62	8	0	0	62		14.0
	T	58	12	0	0	58	91	
W-15-am-B-III	C	65	5	0	1	65		15.1
	T	53	17	0	0	53		
W-15-am-B-IV	C	62	8	0	1	62		14.8
	T	54	16	0	0	54		

* Refer to Table B1 for explanation of the code.

Table B3 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and ambient CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count: First count Live	First count Dead	Inc. count Live	Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-15-am-C-I	C	49	21	0	0	49		11.8
D-15-am-C-II	C	41	29	0	0	41	94	11.7
D-15-am-C-III	C	52	18	0	0	52		11.7
D-15-am-C-IV	C	38	32	0	0	38		12.0
D-15-am-T-I	T	66	4	0	0	66		12.2
D-15-am-T-II	T	62	8	0	0	62	92	11.9
D-15-am-T-III	T	61	9	0	0	61		12.0
D-15-am-T-IV	T	67	3	0	0	67		12.0
D-15-am-B-I	C	41	29	0	0	41		12.0
	T	58	12	0	0	58		
D-15-am-B-II	C	55	15	0	0	55		12.0
	T	66	4	0	0	66	92	
D-15-am-B-III	C	52	19	0	0	52		11.8
	T	61	8	0	0	61		
D-15-am-B-IV	C	44	26	0	0	44		11.9
	T	63	7	0	0	63		
W-15-am-C-I	C	50	18	0	0	50		14.3
W-15-am-C-II	C	67	2	0	0	67	90	13.8
W-15-am-C-III	C	50	23	0	0	50		14.1
W-15-am-C-IV	C	48	12	0	0	48		13.9
W-15-am-T-I	T	67	2	0	0	67		13.4
W-15-am-T-II	T	65	4	0	0	65	87	13.6
W-15-am-T-III	T	63	5	0	0	63		14.9
W-15-am-T-IV	T	64	4	0	0	64		14.0
W-15-am-B-I	C	58	12	0	0	58		13.7
	T	64	6	0	0	64		
W-15-am-B-II	C	63	7	0	0	63		13.7
	T	68	2	0	0	68	87	
W-15-am-B-III	C	65	5	0	0	65		13.6
	T	63	5	0	0	63		
W-15-am-B-IV	C	56	12	0	0	56		13.8
	T	65	8	0	0	65		

* Refer to Table B1 for explanation of the code.

Table B4 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and ambient CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-am-C-I	C	44	26	0	0	44		11.3
D-15-am-C-II	C	36	34	0	0	36	94	11.3
D-15-am-C-III	C	39	32	0	0	39		12.6
D-15-am-C-IV	C	49	22	0	0	49		12.4
D-15-am-T-I	T	65	5	0	0	65		11.4
D-15-am-T-II	T	66	4	0	0	66	92	12.3
D-15-am-T-III	T	64	6	0	0	64		12.2
D-15-am-T-IV	T	65	4	0	0	65		12.5
D-15-am-B-I	C	39	30	0	0	39		11.4
	T	59	11	0	0	59		
D-15-am-B-II	C	45	26	0	0	45		11.6
	T	63	7	0	0	63	91	
D-15-am-B-III	C	45	26	0	0	45		12.2
	T	64	6	0	0	64		
D-15-am-B-IV	C	39	31	0	0	39		12.4
	T	58	12	0	0	58		
W-15-am-C-I	C	57	11	0	0	57		14.6
W-15-am-C-II	C	48	24	0	0	48	77	14.5
W-15-am-C-III	C	59	9	0	0	59		15.4
W-15-am-C-IV	C	54	16	0	0	54		14.3
W-15-am-T-I	T	63	7	0	0	63		14.8
W-15-am-T-II	T	57	12	0	0	57	72	15.4
W-15-am-T-III	T	62	7	0	0	62		14.6
W-15-am-T-IV	T	64	4	0	0	64		15.0
W-15-am-B-I	C	44	25	0	0	44		14.5
	T	55	15	0	0	55		
W-15-am-B-II	C	51	16	0	0	51		14.6
	T	55	16	0	0	55	74	
W-15-am-B-III	C	52	21	0	0	52		14.4
	T	61	8	0	0	61		
W-15-am-B-IV	C	49	20	0	0	49		15.4
	T	62	8	0	0	62		

* Refer to Table B1 for explanation of the code.

Table B5 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 2% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-2-C-I*	C	56	14	0	0	56		11.5
D-15-2-C-II	C	58	11	0	0	58	97	11.7
D-15-2-C-III	C	59	11	0	0	59		11.7
D-15-2-C-IV	C	63	7	0	0	63		11.2
D-15-2-T-I	T	67	3	0	0	67		11.1
D-15-2-T-II	T	66	4	0	0	66	95	11.6
D-15-2-T-III	T	66	4	0	0	66		11.7
D-15-2-T-IV	T	69	1	0	0	69		11.7
D-15-2-B-I	C	60	11	0	0	60		11.1
	T	66	4	0	0	66		
D-15-2-B-II	C	56	14	0	0	56		11.4
	T	65	5	0	0	65	96	
D-15-2-B-III	C	62	8	0	0	62		11.8
	T	67	3	0	0	67		
D-15-2-B-IV	C	64	7	0	0	64		11.6
	T	67	3	0	0	67		
W-15-2-C-I	C	70	0	0	0	70		15.9
W-15-2-C-II	C	70	0	0	0	70	95	16.0
W-15-2-C-III	C	70	0	0	0	70		16.0
W-15-2-C-IV	C	70	0	1	0	71		16.1
W-15-2-T-I	T	68	2	1	0	69		16.0
W-15-2-T-II	T	67	3	0	0	67	94	16.2
W-15-2-T-III	T	70	0	0	0	70		16.1
W-15-2-T-IV	T	70	0	0	0	70		16.0
W-15-2-B-I	C	69	1	1	0	70		16.3
	T	70	0	0	0	70		
W-15-2-B-II	C	68	2	0	0	68		16.1
	T	69	0	0	0	69	93	
W-15-2-B-III	C	70	0	0	0	70		16.2
	T	69	1	0	0	69		
W-15-2-B-IV	C	69	1	0	0	69		16.1
	T	68	2	0	0	68		

* Refer to Table B1 for explanation of the code.

Table B6 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 2% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count: First count Live	First count Dead	Inc. count Live	Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-15-2-C-I*	C	45	25	0	0	45		11.5
D-15-2-C-II	C	43	27	0	0	43	95	11.3
D-15-2-C-III	C	49	22	0	0	49		11.6
D-15-2-C-IV	C	37	33	0	1	37		11.6
D-15-2-T-I	T	67	3	0	0	67		10.8
D-15-2-T-II	T	65	6	0	0	65	94	11.4
D-15-2-T-III	T	62	8	0	0	62		11.6
D-15-2-T-IV	T	64	5	0	0	64		11.7
D-15-2-B-I	C	29	42	0	0	29		10.8
	T	59	9	0	0	59		
D-15-2-B-II	C	48	23	0	0	48		11.3
	T	60	10	0	0	60	95	
D-15-2-B-III	C	42	29	0	0	64		11.6
	T	61	9	0	0	61		
D-15-2-B-IV	C	56	15	0	0	56		11.6
	T	62	8	0	0	62		
W-15-2-C-I	C	68	2	0	0	68		16.0
W-15-2-C-II	C	69	1	0	0	69	93	16.1
W-15-2-C-III	C	68	2	2	1	70		15.8
W-15-2-C-IV	C	69	1	0	0	69		16.1
W-15-2-T-I	T	69		0	0	69		16.1
W-15-2-T-II	T	69		0	0	69	91	16.2
W-15-2-T-III	T	68	2	0	0	68		16.2
W-15-2-T-IV	T	69	1	0	0	69		16.0
W-15-2-B-I	C	68	2	1	0	69		15.8
	T	70		0	0	70		
W-15-2-B-II	C	69	1	0	0	69		16.1
	T	69	1	0	0	69	91	
W-15-2-B-III	C	70		1	0	71		16.0
	T	69	1	0	0	69		
W-15-2-B-IV	C	70		0	0	70		16.2
	T	69	1	0	0	69		

* Refer to Table B1 for explanation of the code.

Table B7 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 2% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-2-C-I	C	39	31	0	0	39		11.3
D-15-2-C-II	C	31	38	0	0	31	95	11.3
D-15-2-C-III	C	41	29	0	0	41		11.6
D-15-2-C-IV	C	29	40	0	0	29		11.6
D-15-2-T-I	T	59	12	0	0	59		11.5
D-15-2-T-II	T	57	13	0	0	57	93	11.5
D-15-2-T-III	T	61	9	0	1	61		11.8
D-15-2-T-IV	T	55	15	0	1	55		11.8
D-15-2-B-I	C	25	45	0	0	25		10.8
	T	41	29	0	0	41		
D-15-2-B-II	C	27	43	0	0	27		11.2
	T	52	18	0	0	52	94	
D-15-2-B-III	C	27	43	0	0	55		11.4
	T	54	16	0	1	54		
D-15-2-B-IV	C	14	56	0		14		11.5
	T	44	26	0	1	44		
W-15-2-C-I	C	68	2	0	0	68		15.7
W-15-2-C-II	C	63	7	0	0	63	90	16.0
W-15-2-C-III	C	70	0	1	1	71		15.9
W-15-2-C-IV	C	69	1	1	0	70		16.0
W-15-2-T-I	T	67	3	0	1	67		16.0
W-15-2-T-II	T	69	1	0	0	69	90	16.1
W-15-2-T-III	T	66	4	0	0	66		16.0
W-15-2-T-IV	T	67	3	0	0	67		16.1
W-15-2-B-I	C	69	1	0	0	69		15.9
	T	69	1	0	0	69		
W-15-2-B-II	C	68	2	1	0	69		16.0
	T	69	1	0	0	69	90	
W-15-2-B-III	C	69	1	0	0	69		15.9
	T	69	1	0	0	69		
W-15-2-B-IV	C	70	0	1	0	71		16.1
	T	67	3	0	0	67		

* Refer to Table B1 for explanation of the code.

Table B8 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 2% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-2-C-I	C	36	34	1	1	37		11.3
D-15-2-C-II	C	28	42	0	0	28	95	11.4
D-15-2-C-III	C	32	37	0	2	32		11.5
D-15-2-C-IV	C	26	44	0	1	26		11.5
D-15-2-T-I	T	54	16	0	0	54		11.5
D-15-2-T-II	T	50	20	0	0	50	93	11.6
D-15-2-T-III	T	56	15	0	0	56		11.7
D-15-2-T-IV	T	47	23	0	0	47		11.6
D-15-2-B-I	C	2	68	0	1	2		11.1
	T	8	62	0	0	8		
D-15-2-B-II	C	7	63	0	1	7		11.4
	T	17	53	0	0	17	94	
D-15-2-B-III	C	12	58	0	0	47		11.5
	T	43	27	0	1	43		
D-15-2-B-IV	C	23	46	0	2	23		11.5
	T	37	33	0	0	37		
W-15-2-C-I	C	69	1	8	0	77		15.7
W-15-2-C-II	C	67	3	4	0	71	91	14.4
W-15-2-C-III	C	69	1	4	0	73		16.0
W-15-2-C-IV	C	66	4	2	0	68		15.8
W-15-2-T-I	T	67	3	0	0	67		15.8
W-15-2-T-II	T	68	2	0	0	68	88	16.0
W-15-2-T-III	T	65	5	1	0	66		16.1
W-15-2-T-IV	T	65	5	0	0	65		16.0
W-15-2-B-I	C	66	4	5	0	71		15.9
	T	61	9	0	0	61		
W-15-2-B-II	C	69	1	0	0	69		15.9
	T	65	5	0	0	65	88	
W-15-2-B-III	C	66	4	1	0	67		15.3
	T	67	3	0	0	67		
W-15-2-B-IV	C	68	2	0	0	68		15.2
	T	67	3	0	0	67		

* Refer to Table B1 for explanation of the code.

Table B9 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 5% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-5-C-I*	C	52	18	0	0	52		11.9
D-15-5-C-II	C	51	19	0	0	51	97	11.8
D-15-5-C-III	C	60	10	0	0	60		12.6
D-15-5-C-IV	C	57	13	0	0	57		12.1
D-15-5-T-I	T	66	4	0	0	66		12.2
D-15-5-T-II	T	64	6	0	0	64	95	11.8
D-15-5-T-III	T	66	4	0	0	66		12.3
D-15-5-T-IV	T	66	4	0	0	66		12.2
D-15-5-B-I	C	58	13	0	0	58		12.3
	T	69	1	0	0	69		
D-15-5-B-II	C	54	16	0	0	54		12.1
	T	62	8	0	0	62	96	
D-15-5-B-III	C	52	18	0	0	66		12.5
	T	64	6	0	0	64		
D-15-5-B-IV	C	60	11	1	0	61		12.4
	T	65	5	0	0	65		
W-15-5-C-I	C	65	5	1	0	66		14.8
W-15-5-C-II	C	65	5	0	1	65	94	14.9
W-15-5-C-III	C	65	5	0	0	65		15.1
W-15-5-C-IV	C	64	6	0	1	64		15.1
W-15-5-T-I	T	69	1	0	0	69		15.1
W-15-5-T-II	T	69	1	0	0	69	94	15.2
W-15-5-T-III	T	69	1	0	0	69		15.1
W-15-5-T-IV	T	69	1	0	0	69		15.3
W-15-5-B-I	C	67	3	0	1	67		14.7
	T	68	2	0	0	68		
W-15-5-B-II	C	65	5	0	0	65		14.7
	T	70	0	0	0	70	94	
W-15-5-B-III	C	67	3	0	2	67		16.4
	T	69	1	0	0	69		
W-15-5-B-IV	C	65	5	0	0	65		14.6
	T	68	2	0	0	68		

* Refer to Table B1 for explanation of the code.

Table B10 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 5% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-5-C-I	C	38	41	0	0	38		11.9
D-15-5-C-II	C	39	22	0	0	39	96	12.6
D-15-5-C-III	C	36	28	0	0	36		11.9
D-15-5-C-IV	C	41	19	0	0	41		12.5
D-15-5-T-I	T	59	11	0	0	59		12.0
D-15-5-T-II	T	47	23	0	0	47	94	11.9
D-15-5-T-III	T	51	19	1	0	52		12.3
D-15-5-T-IV	T	55	14	0	0	55		12.7
D-15-5-B-I	C	28	43	0	0	28		12.0
	T	57	13	0	0	57		
D-15-5-B-II	C	37	34	0	0	37		11.9
	T	66	5	0	0	66	95	
D-15-5-B-III	C	41	31	0	0	55		12.1
	T	63	9	0	0	63		
D-15-5-B-IV	C	43	32	0	0	43		12.8
	T	64	8	0	0	64		
W-15-5-C-I	C	64	6	1	0	65		14.8
W-15-5-C-II	C	58	14	2	0	60	93	15.0
W-15-5-C-III	C	52	17	1	0	53		15.0
W-15-5-C-IV	C	53	17	0	0	53		15.1
W-15-5-T-I	T	73	1	0	0	73		15.2
W-15-5-T-II	T	70	5	1	0	71	92	15.2
W-15-5-T-III	T	68	2	0	1	68		15.2
W-15-5-T-IV	T	71	1	0	0	71		15.1
W-15-5-B-I	C	60	11	0	0	60		14.5
	T	68	2	0	0	68		
W-15-5-B-II	C	60	10	0	0	60		14.5
	T	66	6	0	0	66	92	
W-15-5-B-III	C	55	15	1	0	56		14.6
	T	65	5	0	0	65		
W-15-5-B-IV	C	55	16	0	0	55		14.4
	T	67	3	0	0	67		

* Refer to Table B1 for explanation of the code.

Table B11 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 5% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count: First count Live	First count Dead	Inc. count Live	Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-15-5-C-I	C	26	44	0	0	26		11.5
D-15-5-C-II	C	32	37	0	0	32	96	11.9
D-15-5-C-III	C	33	37	1	0	34		12.2
D-15-5-C-IV	C	30	41	0	0	30		12.3
D-15-5-T-I	T	56	15	0	0	56		11.6
D-15-5-T-II	T	55	15	0	0	55	95	11.9
D-15-5-T-III	T	57	13	0	0	57		12.1
D-15-5-T-IV	T	56	14	0	0	56		12.2
D-15-5-B-I	C	15	62	0	0	15		11.1
	T	45	25	0	0	45		
D-15-5-B-II	C	17	54	0	0	17		11.7
	T	59	13	0	0	59	95	
D-15-5-B-III	C	37	36	0	0	56		11.9
	T	65	5	0	0	65		
D-15-5-B-IV	C	5		0	0	5		12.1
	T	64	7	0	0	64		
W-15-5-C-I	C	63	7	0	0	63		15.0
W-15-5-C-II	C	52	17	1	0	53	92	15.0
W-15-5-C-III	C	63	7	1	0	64		15.0
W-15-5-C-IV	C	58	13	1	0	59		15.0
W-15-5-T-I	T	68	4	0	0	68		15.2
W-15-5-T-II	T	70	2	0	0	70	91	15.2
W-15-5-T-III	T	70	3	0	1	70		15.1
W-15-5-T-IV	T	70	1	0	0	70		15.2
W-15-5-B-I	C	53	16	0	0	53		14.3
	T	70	1	0	0	70		
W-15-5-B-II	C	60	13	1	0	61		14.5
	T	65	5	0	0	65	91	
W-15-5-B-III	C	63	8	0	0	63		14.5
	T	70	1	0	0	70		
W-15-5-B-IV	C	54	15	1	0	55		14.5
	T	71		0	0	71		

* Refer to Table B1 for explanation of the code.

Table B12 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 5% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-5-C-I	C	36	34	0	0	36		11.6
D-15-5-C-II	C	27	43	0	0	27	96	11.9
D-15-5-C-III	C	34	36	0	0	34		11.9
D-15-5-C-IV	C	35	36	0	0	35		12.3
D-15-5-T-I	T	53	17	0	0	53		11.8
D-15-5-T-II	T	49	21	0	0	49	94	12.0
D-15-5-T-III	T	51	19	0	0	51		11.7
D-15-5-T-IV	T	51	20	0	1	51		12.3
D-15-5-B-I	C	3	70	0	0	3		11.3
	T	21	50	0	0	21		
D-15-5-B-II	C	17	56	0	0	17		11.7
	T	35	37	0	0	35	95	
D-15-5-B-III	C	26	44	0	0	51		11.9
	T	60	11	0	0	60		
D-15-5-B-IV	C	27	43	0	0	27		12.2
	T	66	7	0	0	66		
W-15-5-C-I	C	62	8	3	0	65		14.8
W-15-5-C-II	C	59	10	1	0	60	92	15.0
W-15-5-C-III	C	62	8	2	0	64		15.0
W-15-5-C-IV	C	63	7	2	0	65		15.1
W-15-5-T-I	T	67	4	0	0	67		15.0
W-15-5-T-II	T	68	3	0	0	68	89	15.1
W-15-5-T-III	T	65	5	0	0	65		15.1
W-15-5-T-IV	T	67	4	0	0	67		16.0
W-15-5-B-I	C	54	16	1	0	55		14.3
	T	64	5	0	0	64		
W-15-5-B-II	C	54	16	0	0	54		14.4
	T	67	3	0	0	67	90	
W-15-5-B-III	C	59	11	0	0	59		14.3
	T	70	0	0	0	70		
W-15-5-B-IV	C	65	5	2	0	67		14.6
	T	67	3	0	0	67		

* Refer to Table B1 for explanation of the code.

Table B13 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 10% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-10-C-I	C	28	42	0	1	28		11.2
D-15-10-C-II	C	29	42	0	0	29	96	11.9
D-15-10-C-III	C	23	47	0	3	23		12.1
D-15-10-C-IV	C	23	50	0	0	23		12.1
D-15-10-T-I	T	56	14	0	0	56		10.1
D-15-10-T-II	T	71	2	0	0	71	96	11.5
D-15-10-T-III	T	67	5	0	0	67		12.1
D-15-10-T-IV	T	59	11	3	0	62		12.1
D-15-10-B-I	C	15	55	0	2	15		10.8
	T	57	11	0	0	57		
D-15-10-B-II	C	46	28	0	3	46		11.9
	T	60	8	0	0	60	96	
D-15-10-B-III	C	23	44	0	1	23		12.7
	T	64	6	0	0	64		
D-15-10-B-IV	C	20	48	0	0	20		11.9
	T	24	14	0	0	24		
W-15-10-C-I	C	58	13	0	0	58		15.1
W-15-10-C-II	C	54	14	0	0	54	94	14.5
W-15-10-C-III	C	48	12	1	0	49		14.4
W-15-10-C-IV	C	52	18	0	0	52		14.4
W-15-10-T-I	T	69	2	0	0	69		14.7
W-15-10-T-II	T	67	3	6	0	73	94	14.6
W-15-10-T-III	T	63	7	1	0	64		14.5
W-15-10-T-IV	T	56	14	1	0	57		14.6
W-15-10-B-I	C	57	13	0	2	57		14.9
	T	65	4	0	0	65		
W-15-10-B-II	C	64	10	0	1	64		14.8
	T	64	5	0	0	64	94	
W-15-10-B-III	C	57	15	0	0	57		14.5
	T	71	0	0	0	71		
W-15-10-B-IV	C	53	18	0	3	53		14.6
	T	68	4	0	0	68		

* Refer to Table B1 for explanation of the code.

Table B14 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 10% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-10-C-I	C	9	61	0	1	9		11.2
D-15-10-C-II	C	7	63	0	0	7	96	12.0
D-15-10-C-III	C	16	55	0	2	16		12.1
D-15-10-C-IV	C	8	62	0	0	8		12.4
D-15-10-T-I	T	40	29	1	0	41		11.1
D-15-10-T-II	T	51	18	0	1	51	95	11.9
D-15-10-T-III	T	55	14	0	0	55		12.0
D-15-10-T-IV	T	55	15	0	0	55		11.8
D-15-10-B-I	C	4	66	0	0	4		11.0
	T	41	29	0	0	41		
D-15-10-B-II	C	4	66	0	0	4		11.7
	T	46	25	0	0	46	96	
D-15-10-B-III	C	4	65	0	0	4		12.1
	T	50	21	0	0	50		
D-15-10-B-IV	C	6	64	0	0	6		12.2
	T	49	21	1	0	50		
W-15-10-C-I	C	56	15	0	1	56		14.6
W-15-10-C-II	C	55	18	1	1	56	93	14.5
W-15-10-C-III	C	59	11	0	1	59		15.4
W-15-10-C-IV	C	60	11	0	0	60		14.3
W-15-10-T-I	T	64	6	0	0	64		14.8
W-15-10-T-II	T	67	6	0	0	67	92	15.4
W-15-10-T-III	T	62	8	0	0	62		14.6
W-15-10-T-IV	T	60	10	0	2	60		15.0
W-15-10-B-I	C	47	27	0	1	47		14.5
	T	63	7	0	0	63		
W-15-10-B-II	C	39	31	0	0	39		14.6
	T	58	13	1	2	59	92	
W-15-10-B-III	C	44	25	0	0	44		14.4
	T	64	5	0	0	64		
W-15-10-B-IV	C	43	25	0	1	43		15.4
	T	59	11	0	1	59		

* Refer to Table B1 for explanation of the code.

Table B15 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 10% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-15-10-C-I	C	0	70	0	0	0		10.9
D-15-10-C-II	C	4	65	0	0	4	96	11.6
D-15-10-C-III	C	6	64	0	0	6		11.9
D-15-10-C-IV	C	8	62	0	0	8		12.2
D-15-10-T-I	T	62	7	0	0	62		11.4
D-15-10-T-II	T	48	21	0	0	48	95	11.7
D-15-10-T-III	T	43	25	0	0	43		11.8
D-15-10-T-IV	T	51	19	0	0	51		12.2
D-15-10-B-I	C	1	67	0	0	1		11.5
	T	12	56	0	0	12		
D-15-10-B-II	C	2	66	0	0	2		11.9
	T	32	36	0	0	32	95	
D-15-10-B-III	C	1	69	0	0	1		11.8
	T	42	29	0	0	42		
D-15-10-B-IV	C	3	65	0	0	3		12.2
	T	39	33	0	0	39		
W-15-10-C-I	C	35	34	0	0	35		14.3
W-15-10-C-II	C	29	40	0	0	29	92	14.3
W-15-10-C-III	C	29	41	0	0	29		14.2
W-15-10-C-IV	C	37	33	0	0	37		14.0
W-15-10-T-I	T	66	5	0	0	66		14.2
W-15-10-T-II	T	63	7	0	0	63	90	14.2
W-15-10-T-III	T	59	8	0	0	59		14.0
W-15-10-T-IV	T	58	13	0	0	58		14.1
W-15-10-B-I	C	30	41	0	0	30		14.3
	T	56	12	0	0	56		
W-15-10-B-II	C	44	27	0	0	44		14.2
	T	62	10	0	0	62	92	
W-15-10-B-III	C	26	44	0	0	26		14.1
	T	50	20	0	0	50		
W-15-10-B-IV	C	28	40	0	0	28		14.0
	T	61	8	0	0	61		

* Refer to Table B1 for explanation of the code.

Table B16 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 15°C and 10% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count: First count Live	Adult Count: First count Dead	Adult Count: Inc. count Live	Adult Count: Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-15-10-C-I	C	0	67	0	0	0		11.3
D-15-10-C-II	C	3	65	0	0	3	96	11.3
D-15-10-C-III	C	1	68	0	0	1		12.6
D-15-10-C-IV	C	2	67	0	0	2		12.4
D-15-10-T-I	T	2	68	0	0	2		11.4
D-15-10-T-II	T	0	70	0	0	0	95	12.3
D-15-10-T-III	T	0	70	0	0	0		12.2
D-15-10-T-IV	T	3	67	0	0	3		12.5
D-15-10-B-I	C	0	70	0	0	0		11.4
	T	0	69	0	0	0		
D-15-10-B-II	C	0	70	0	0	0		11.6
	T	0	70	0	0	0	95	
D-15-10-B-III	C	2	68	0	0	2		12.2
	T	2	68	0	0	2		
D-15-10-B-IV	C	2	67	0	0	2		12.4
	T	11	57	0	0	11		
W-15-10-C-I	C	33	36	0	0	33		14.6
W-15-10-C-II	C	32	40	0	0	32	92	14.5
W-15-10-C-III	C	26	46	0	0	26		15.4
W-15-10-C-IV	C	33	37	0	0	33		14.3
W-15-10-T-I	T	58	13	0	0	58		14.8
W-15-10-T-II	T	65	5	0	0	65	89	15.4
W-15-10-T-III	T	62	10	0	0	62		14.6
W-15-10-T-IV	T	58	14	0	0	58		15.0
W-15-10-B-I	C	39	33	0	0	39		14.5
	T	54	14	0	0	54		
W-15-10-B-II	C	44	30	0	0	44		14.6
	T	62	6	0	0	62	90	
W-15-10-B-III	C	25	44	0	0	25		14.4
	T	64	6	0	0	64		
W-15-10-B-IV	C	29	40	0	0	29		15.4
	T	45	27	0	0	45		

* Refer to Table B1 for explanation of the code.

Table B17 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and ambient CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count: First count Live	First count Dead	Inc. count Live	Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-20-am-C-I	C	69	2	6	0	75		11.4
D-20-am-C-II	C	71	1	4	0	75	94	11.4
D-20-am-C-III	C	65	4	3	0	68		11.3
D-20-am-C-IV	C	68	2	3	0	71		11.3
D-20-am-T-I	T	60	9	15	2	75		11.4
D-20-am-T-II	T	67	3	3	1	70	93	11.5
D-20-am-T-III	T	66	4	12	1	78		11.6
D-20-am-T-IV	T	55	14	1	1	56		11.7
D-20-am-B-I	C	70	1	3	1	73		11.1
	T	69	1	3	0	72		
D-20-am-B-II	C	68	2	1	0	69		11.2
	T	70	0	4	0	74	93	
D-20-am-B-III	C	55	15	0	0	55		11.0
	T	66	4	0	0	66		
D-20-am-B-IV	C	64	7	0	2	64		11.4
	T	68	2	0	0	68		
W-20-am-C-I	C	71	0	10	0	81		14.5
W-20-am-C-II	C	71	0	10	1	81	92	15.0
W-20-am-C-III	C	70	0	7	1	77		15.2
W-20-am-C-IV	C	71	0	8	0	79		15.2
W-20-am-T-I	T	68	2	14	0	82		14.4
W-20-am-T-II	T	66	2	28	1	94	93	15.3
W-20-am-T-III	T	67	3	20	0	87		15.2
W-20-am-T-IV	T	71	0	32	1	103		15.2
W-20-am-B-I	C	66	4	7	0	73		14.0
	T	61	9	8	1	69		
W-20-am-B-II	C	71	0	9	1	80		14.8
	T	60	11	10	2	70	91	
W-20-am-B-III	C	67	2	6	0	73		15.2
	T	63	7	8	1	71		
W-20-am-B-IV	C	68	2	14	0	82		15.1
	T	62	8	7	0	69		

* Refer to Table B1 for explanation of the code.

Table B18 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and ambient CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count First count Live	Adult Count First count Dead	Adult Count Inc. count Live	Adult Count Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-20-am-C-I	C	62	8	7	0	69		11.0
D-20-am-C-II	C	65	5	8	2	73	92	11.3
D-20-am-C-III	C	67	2	4	1	71		11.4
D-20-am-C-IV	C	55	14	6	0	61		11.3
D-20-am-T-I	T	63	7	8	0	71		11.5
D-20-am-T-II	T	55	15	19	1	74	92	11.4
D-20-am-T-III	T	68	1	9	0	77		11.3
D-20-am-T-IV	T	63	7	10	1	73		11.9
D-20-am-B-I	C	50	19	0	3	50		11.4
	T	65	5	0	0	65		
D-20-am-B-II	C	53	18	1	2	54		11.7
	T	62	8	0	0	62	91	
D-20-am-B-III	C	49	21	0	2	49		11.6
	T	52	19	0	0	52		
D-20-am-B-IV	C	58	12	1	1	59		11.4
	T	64	7	0	0	64		
W-20-am-C-I	C	72	0	43	1	115		14.1
W-20-am-C-II	C	71	0	33	0	104	91	14.5
W-20-am-C-III	C	69	1	37	0	106		14.8
W-20-am-C-IV	C	72	0	39	0	111		14.8
W-20-am-T-I	T	66	4	2	0	68		14.1
W-20-am-T-II	T	68	2	8	1	76	86	14.5
W-20-am-T-III	T	69	1	6	0	75		14.7
W-20-am-T-IV	T	65	5	12	0	77		14.9
W-20-am-B-I	C	70	0	18	0	88		14.2
	T	61	9	1	0	62		
W-20-am-B-II	C	70	0	5	1	75		14.6
	T	60	10	0	0	60	85	
W-20-am-B-III	C	68	1	22	2	90		14.8
	T	60	10	2	1	62		
W-20-am-B-IV	C	69	1	17	0	86		14.9
	T	62	9	7	0	69		

* Refer to Table B1 for explanation of the code.

Table B19 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and ambient Co2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-am-C-I	C	62	8	6	0	68		11.3
D-20-am-C-II	C	66	5	8	1	74	90	12.3
D-20-am-C-III	C	60	10	5	0	65		12.4
D-20-am-C-IV	C	60	10	5	0	65		11.7
D-20-am-T-I	T	68	2	2	0	70		12.1
D-20-am-T-II	T	62	8	0	1	62	89	11.2
D-20-am-T-III	T	67	3	2	0	69		11.4
D-20-am-T-IV	T	67	4	4	0	71		11.6
D-20-am-B-I	C	35	36	0	1	35		12.5
	T	60	9	0	0	60		
D-20-am-B-II	C	37	32	0	1	37		11.8
	T	65	5	0	0	65	87	
D-20-am-B-III	C	31	38	0	1	31		11.7
	T	63	8	0	1	63		
D-20-am-B-IV	C	32	38	0	2	32		11.7
	T	66	5	0	0	66		
W-20-am-C-I	C	70	1	9	2	79		14.1
W-20-am-C-II	C	73	0	22	0	95	87	14.5
W-20-am-C-III	C	70	1	50	0	120		14.7
W-20-am-C-IV	C	72	2	48	1	120		14.5
W-20-am-T-I	T	66	4	0	1	66		14.5
W-20-am-T-II	T	68	2	6	0	74	82	14.7
W-20-am-T-III	T	69	2	3	1	72		15.0
W-20-am-T-IV	T	68	2	7	0	75		15.0
W-20-am-B-I	C	62	8	26	7	88		13.6
	T	60	11	0	0	60		
W-20-am-B-II	C	66	3	16	1	82		14.4
	T	57	13	0	0	57	85	
W-20-am-B-III	C	69	2	17	2	86		14.5
	T	59	11.	0	2	59		
W-20-am-B-IV	C	69	2	26	5	95		14.6
	T	58	12	0	0	58		

* Refer to Table B1 for explanation of the code.

Table B20 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and ambient CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-am-C-I	C	45	24	7	2	52		11.1
D-20-am-C-II	C	56	14	5	1	61	91	12.9
D-20-am-C-III	C	58	13	6	1	64		11.6
D-20-am-C-IV	C	58	11	2	2	60		11.0
D-20-am-T-I	T	67	4	0	0	67		11.5
D-20-am-T-II	T	44	26	1	0	45	88	11.2
D-20-am-T-III	T	63	8	0	0	63		11.2
D-20-am-T-IV	T	66	4	1	0	67		11.2
D-20-am-B-I	C	44	27	0	2	44		11.1
	T	67	3	0	0	67		
D-20-am-B-II	C	43	28	0	1	43		11.1
	T	67	3	0	0	67	88	
D-20-am-B-III	C	35	34	0	0	35		11.5
	T	67	3	0	0	67		
D-20-am-B-IV	C	36	34	0	1	36		11.1
	T	61	9	0	0	61		
W-20-am-C-I	C	69	4	9	1	78		15.0
W-20-am-C-II	C	70	4	10	0	80	84	14.2
W-20-am-C-III	C	72	2	11	0	83		14.7
W-20-am-C-IV	C	67	3	6	2	73		15.0
W-20-am-T-I	T	66	2	0	0	66		15.0
W-20-am-T-II	T	67	5	0	0	67	81	15.3
W-20-am-T-III	T	71	1	0	0	71		14.4
W-20-am-T-IV	T	67	2	3	0	70		14.3
W-20-am-B-I	C	65	4	4	1	69		14.9
	T	64	7	0	0	64		
W-20-am-B-II	C	69	1	24	1	93		15.2
	T	62	7	0	0	62	83	
W-20-am-B-III	C	58	12	2	0	60		14.5
	T	60	10.	0	0	60		
W-20-am-B-IV	C	69	2	15	1	84		14.3
	T	65	4	0	0	65		

* Refer to Table B1 for explanation of the code.

Table B21 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 2% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-2-C-I	C	56	14	1	0	57		11.8
D-20-2-C-II	C	55	15	2	0	57	94	12.1
D-20-2-C-III	C	58	12	2	1	60		12.0
D-20-2-C-IV	C	59	11	0	0	59		12.0
D-20-2-T-I	T	63	7	2	1	65		12.2
D-20-2-T-II	T	65	5	5	0	70	94	12.0
D-20-2-T-III	T	67	3	3	0	70		12.3
D-20-2-T-IV	T	62	8	2	0	64		11.9
D-20-2-B-I	C	53	17	0	1	53		11.6
	T	62	8	0	0	62		
D-20-2-B-II	C	51	19	0	2	51		12.3
	T	66	4	0	0	66	95	
D-20-2-B-III	C	56	14	1	0	57		12.0
	T	64	6	0	0	64		
D-20-2-B-IV	C	59	11	2	2	61		12.0
	T	62	8	0	0	62		
W-20-2-C-I	C	67	3	9	1	76		15.9
W-20-2-C-II	C	63	7	15	2	78	94	16.4
W-20-2-C-III	C	66	4	11	0	77		16.6
W-20-2-C-IV	C	67	3	13	1	80		16.6
W-20-2-T-I	T	69	1	10	3	79		16.0
W-20-2-T-II	T	66	4	4	1	70	94	16.6
W-20-2-T-III	T	66	4	6	0	72		16.8
W-20-2-T-IV	T	70	0	10	1	80		16.9
W-20-2-B-I	C	63	6	9	1	72		15.7
	T	63	7	1	0	64		
W-20-2-B-II	C	68	2	16	1	84		16.2
	T	65	5	2	0	67	91	
W-20-2-B-III	C	69	1	9	1	78		16.3
	T	66	4	0	0	66		
W-20-2-B-IV	C	70	0	9	0	79		16.3
	T	62	8	0	0	62		

* Refer to Table B1 for explanation of the code.

Table B22 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 2% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-2-C-I	C	50	20	2	0	52		11.4
D-20-2-C-II	C	54	16	1	0	55	93	11.8
D-20-2-C-III	C	54	16	0	0	54		12.1
D-20-2-C-IV	C	56	14	1	0	57		12.1
D-20-2-T-I	T	61	9	3	1	64		11.4
D-20-2-T-II	T	62	8	2	1	64	94	12.0
D-20-2-T-III	T	64	6	2	3	66		11.8
D-20-2-T-IV	T	68	2	2	0	70		12.0
D-20-2-B-I	C	56	13	1	0	57		11.6
	T	64	6	0	0	64		
D-20-2-B-II	C	55	15	10	1	65		11.9
	T	66	4	1	0	67	93	
D-20-2-B-III	C	56	14	12	0	68		12.0
	T	68	2	0	0	68		
D-20-2-B-IV	C	51	18	18	3	69		12.0
	T	58	11	0	0	58		
W-20-2-C-I	C	57	13	51	2	108		15.8
W-20-2-C-II	C	55	15	33	1	88	93	16.3
W-20-2-C-III	C	52	17	46	3	98		16.6
W-20-2-C-IV	C	58	12	38	1	96		16.5
W-20-2-T-I	T	66	4	0	1	66		16.2
W-20-2-T-II	T	67	3	2	0	69	91	16.6
W-20-2-T-III	T	67	3	0	0	67		16.8
W-20-2-T-IV	T	61	9	1	2	62		16.8
W-20-2-B-I	C	52	18	39	1	91		15.5
	T	64	6	0	0	64		
W-20-2-B-II	C	50	19	27	2	77		15.9
	T	58	11	0	0	58	87	
W-20-2-B-III	C	59	11	31	0	90		16.0
	T	62	8	0	0	62		
W-20-2-B-IV	C	61	9	35	0	96		16.1
	T	60	10	0	0	60		

* Refer to Table B1 for explanation of the code.

Table B23 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 2% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-2-C-I	C	39	30	2	0	41		11.9
D-20-2-C-II	C	41	29	3	1	44	92	12.0
D-20-2-C-III	C	52	18	5	1	57		12.1
D-20-2-C-IV	C	41	31	6	0	47		11.9
D-20-2-T-I	T	64	6	1	0	65		12.0
D-20-2-T-II	T	69	1	3	0	72	92	12.2
D-20-2-T-III	T	63	7	2	3	65		12.4
D-20-2-T-IV	T	62	8	2	0	64		12.2
D-20-2-B-I	C	47	24	3	0	50		11.7
	T	67	3	0	0	67		
D-20-2-B-II	C	49	22	4	0	53		11.9
	T	67	2	1	0	68	92	
D-20-2-B-III	C	52	18	4	0	56		11.7
	T	64	6	0	0	64		
D-20-2-B-IV	C	46	24	10	1	56		12.1
	T	60	10	0	0	60		
W-20-2-C-I	C	51	19	27	2	78		15.2
W-20-2-C-II	C	62	7	19	0	81	89	14.9
W-20-2-C-III	C	47	21	21	1	68		15.2
W-20-2-C-IV	C	55	17	25	1	80		15.3
W-20-2-T-I	T	68	2	0	3	68		14.9
W-20-2-T-II	T	66	5	6	1	72	86	14.9
W-20-2-T-III	T	60	10	3	1	63		15.6
W-20-2-T-IV	T	64	6	8	1	72		15.1
W-20-2-B-I	C	54	16	11	3	65		15.5
	T	65	4	0	0	65		
W-20-2-B-II	C	60	10	72	0	132		15.8
	T	63	8	0	0	63	88	
W-20-2-B-III	C	55	14	53	2	108		15.0
	T	64	6	0	0	64		
W-20-2-B-IV	C	53	18	24	1	77		15.5
	T	65	5	1	1	66		

* Refer to Table B1 for explanation of the code.

Table B24 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 2% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-2-C-I	C	43	28	1	0	44		11.9
D-20-2-C-II	C	42	27	2	0	44	92	12.2
D-20-2-C-III	C	50	19	4	0	54		12.1
D-20-2-C-IV	C	22	58	5	0	27		12.0
D-20-2-T-I	T	63	7	4	1	67		12.1
D-20-2-T-II	T	64	6	9	0	73	90	11.9
D-20-2-T-III	T	65	5	4	1	69		12.2
D-20-2-T-IV	T	65	6	8	1	73		12.6
D-20-2-B-I	C	34	38	0	0	34		12.0
	T	63	8	0	0	63		
D-20-2-B-II	C	50	21	6	0	56		12.0
	T	58	12	0	0	58	91	
D-20-2-B-III	C	42	29	3	0	45		11.8
	T	59	12	0	0	59		
D-20-2-B-IV	C	39	31	5	3	44		12.2
	T	60	10	0	0	60		
W-20-2-C-I	C	45	25	7	0	52		16.0
W-20-2-C-II	C	51	19	9	1	60	88	16.3
W-20-2-C-III	C	47	24	5	0	52		16.3
W-20-2-C-IV	C	41	28	7	1	48		16.2
W-20-2-T-I	T	65	5	5		70		16.5
W-20-2-T-II	T	62	8	25	3	87	85	16.8
W-20-2-T-III	T	64	6	3		67		16.9
W-20-2-T-IV	T	64	6	6		70		16.9
W-20-2-B-I	C	53	17	7	2	60		15.8
	T	55	15	0		55		
W-20-2-B-II	C	50	20	3		53		16.1
	T	51	19	2		53	86	
W-20-2-B-III	C	52	18	6		58		16.3
	T	49	21	0		49		
W-20-2-B-IV	C	45	25	4		49		16.6
	T	56	13	0		56		

* Refer to Table B1 for explanation of the code.

Table B25 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 5% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-5-C-I	C	61	9	0	0	61		11.0
D-20-5-C-II	C	54	15	0	0	54	96	11.7
D-20-5-C-III	C	52	18	0	0	52		12.1
D-20-5-C-IV	C	58	12	1	0	59		12.1
D-20-5-T-I	T	64	6	0	0	64		10.2
D-20-5-T-II	T	65	5	0	0	65	95	11.4
D-20-5-T-III	T	64	6	2	0	66		12.1
D-20-5-T-IV	T	63	8	2	0	65		12.4
D-20-5-B-I	C	52	17	1	0	53		9.8
	T	64	6	0	0	64		
D-20-5-B-II	C	48	22	3	0	51		11.1
	T	62	8	0	0	62	95	
D-20-5-B-III	C	62	8	1	0	63		11.8
	T	69	1	0	0	69		
D-20-5-B-IV	C	61	9	0	0	61		12.1
	T	69	1	0	0	69		
W-20-5-C-I	C	64	6	7	0	71		15.0
W-20-5-C-II	C	67	3	3	0	70	96	15.3
W-20-5-C-III	C	61	9	6	0	67		15.7
W-20-5-C-IV	C	64	6	4	0	68		15.6
W-20-5-T-I	T	66	4	2	0	68		15.2
W-20-5-T-II	T	62	7	4	0	66	94	15.4
W-20-5-T-III	T	63	7	3	0	66		15.7
W-20-5-T-IV	T	64	6	3	0	67		15.6
W-20-5-B-I	C	66	4	7	0	73		15.0
	T	64	6	1	0	65		
W-20-5-B-II	C	68	2	6	0	74		15.3
	T	60	11	0	0	60	92	
W-20-5-B-III	C	65	6	7	0	72		15.4
	T	61	9	0	0	61		
W-20-5-B-IV	C	68	2	5	0	73		15.4
	T	66	5	0	0	66		

* Refer to Table B1 for explanation of the code.

Table B26 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 5% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-5-C-I	C	48	21	0	0	48		10.6
D-20-5-C-II	C	42	28	0	0	42	95	11.7
D-20-5-C-III	C	44	25	1	0	45		12.2
D-20-5-C-IV	C	48	22	3	0	51		12.5
D-20-5-T-I	T	64	7	0	0	64		10.1
D-20-5-T-II	T	66	5	0	0	66	95	11.2
D-20-5-T-III	T	67	4	0	0	67		11.9
D-20-5-T-IV	T	63	8	4	0	67		12.2
D-20-5-B-I	C	43	27	5	1	48		10.8
	T	65	4	0	0	65		
-20-5-B-II	C	52	18	0	0	52		11.8
	T	61	8	1	0	62	96	
D-20-5-B-III	C	54	16	5	0	59		12.2
	T	68	2	0	0	68		
D-20-5-B-IV	C	41	28	8	0	49		12.4
	T	64	6	0	0	64		
W-20-5-C-I	C	57	13	13	0	70		15.1
W-20-5-C-II	C	51	19	7	0	58	95	14.5
W-20-5-C-III	C	56	15	11	0	67		14.2
W-20-5-C-IV	C	52	18	9	0	61		15.7
W-20-5-T-I	T	65	5	0	0	65		15.3
W-20-5-T-II	T	61	9	1	0	62	93	15.5
W-20-5-T-III	T	64	6	0	0	64		15.6
W-20-5-T-IV	T	63	7	3	0	66		15.6
W-20-5-B-I	C	53	17	4	1	57		15.3
	T	57	14	0	0	57		
W-20-5-B-II	C	49	20	5	0	54		15.4
	T	58	13	0	0	58	90	
W-20-5-B-III	C	50	20	6	0	56		15.5
	T	61	9	0	0	61		
W-20-5-B-IV	C	53	17	2	1	55		15.5
	T	55	14	0	0	55		

* Refer to Table B1 for explanation of the code.

Table B27 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 5% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-5-C-I	C	41	29	1	0	42		11.1
D-20-5-C-II	C	42	28	2	0	44	94	11.8
D-20-5-C-III	C	45	24	0	0	45		12.2
D-20-5-C-IV	C	36	33	1	0	37		12.3
D-20-5-T-I	T	62	9	0	0	62		10.6
D-20-5-T-II	T	63	7	0	0	63	94	11.4
D-20-5-T-III	T	65	6	0	0	65		11.9
D-20-5-T-IV	T	61	10	0	0	61		12.2
D-20-5-B-I	C	39	30	1	0	40		10.9
	T	60	10	0	0	60		
D-20-5-B-II	C	46	24	1	0	47		11.7
	T	59	11	0	0	59	94	
D-20-5-B-III	C	44	27	0	0	44		12.2
	T	63	8	0	0	63		
D-20-5-B-IV	C	37	33	0	0	37		12.3
	T	67	3	0	0	67		
W-20-5-C-I	C	56	14	16	2	72		15.1
W-20-5-C-II	C	46	23	6	1	52	93	15.3
W-20-5-C-III	C	49	21	12	2	61		15.4
W-20-5-C-IV	C	53	18	10	1	63		15.6
W-20-5-T-I	T	66	4	0	0	66		15.3
W-20-5-T-II	T	65	5	0	0	65	88	15.5
W-20-5-T-III	T	67	3	0	0	67		15.6
W-20-5-T-IV	T	63	7	0	0	63		15.6
W-20-5-B-I	C	61	9	11	3	72		15.3
	T	58	12	0	0	58		
W-20-5-B-II	C	54	16	16	5	70		15.4
	T	57	13	0	0	57	88	
W-20-5-B-III	C	56	15	8	2	64		15.6
	T	57	14.	0	0	57		
W-20-5-B-IV	C	58	13	13	2	71		15.4
	T	59	11	0	0	59		

* Refer to Table B1 for explanation of the code.

Table B28 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 5% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-5-C-I	C	31	39	1	0	32		10.9
D-20-5-C-II	C	36	35	2	0	38	94	11.7
D-20-5-C-III	C	46	34	3	0	49		12.1
D-20-5-C-IV	C	32	38	2	0	34		12.3
D-20-5-T-I	T	65	6	0	0	65		11.2
D-20-5-T-II	T	61	10	0	0	61	92	12.0
D-20-5-T-III	T	64	6	0	0	64		12.1
D-20-5-T-IV	T	63	7	0	0	63		12.5
D-20-5-B-I	C	32	38	0	0	32		11.3
	T	51	19	0	0	51		
D-20-5-B-II	C	31	39	0	0	31		11.9
	T	53	17	0	0	53	93	
D-20-5-B-III	C	39	32	2	0	41		12.3
	T	63	7	0	0	63		
D-20-5-B-IV	C	41	29	4	0	45		12.4
	T	65	5	0	0	65		
W-20-5-C-I	C	41	29	5	0	46		15.7
W-20-5-C-II	C	43	27	7	1	50	90	15.6
W-20-5-C-III	C	47	22	4	1	51		12.2
W-20-5-C-IV	C	38	32	8	0	46		15.8
W-20-5-T-I	T	66	4	0	0	66		15.8
W-20-5-T-II	T	66	4	0	1	66	86	15.8
W-20-5-T-III	T	65	5	0	0	65		15.5
W-20-5-T-IV	T	66	4	0	0	66		15.9
W-20-5-B-I	C	45	24	5	1	50		15.6
	T	52	19	0	0	52		
W-20-5-B-II	C	41	29	1	3	42		15.7
	T	54	16	0	0	54	87	-
W-20-5-B-III	C	42	28	4	0	46		15.8
	T	53	17.	0	0	53		
W-20-5-B-IV	C	43	27	3	0	46		15.8
	T	54	16	0	0	54		

* Refer to Table B1 for explanation of the code.

Table B29 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 10% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-10-C-I	C	42	27	0	1	42		10.3
D-20-10-C-II	C	46	23	0	1	46	96	11.5
D-20-10-C-III	C	51	19	0	2	51		11.5
D-20-10-C-IV	C	46	24	0	0	46		11.2
D-20-10-T-I	T	63	7	1	0	64		10.4
D-20-10-T-II	T	62	8	3	4	65	95	11.3
D-20-10-T-III	T	64	6	2	0	66		11.5
D-20-10-T-IV	T	60	11	2	0	62		11.9
D-20-10-B-I	C	26	45	2	5	28		10.1
	T	64	5	0	0	64		
D-20-10-B-II	C	52	18	1	4	53		11.0
	T	63	7	0	0	63	95	
D-20-10-B-III	C	52	17	2	0	54		11.4
	T	67	3	0	0	67		
D-20-10-B-IV	C	35	35	0	1	35		11.6
	T	69	1	0	0	69		
W-20-10-C-I	C	57	13	0	0	57		14.6
W-20-10-C-II	C	59	11	0	0	59	94	14.3
W-20-10-C-III	C	64	6	2	0	66		14.9
W-20-10-C-IV	C	63	8	6	0	69		15.0
W-20-10-T-I	T	72	1	9	0	81		14.6
W-20-10-T-II	T	63	7	2	0	65	91	15.4
W-20-10-T-III	T	69	2	4	1	73		15.2
W-20-10-T-IV	T	67	4	11	1	78		15.2
W-20-10-B-I	C	59	11	3	0	62		14.6
	T	63	7	0	0	63		
W-20-10-B-II	C	56	15	7	0	63		15.7
	T	62	9	0	0	62	93	
W-20-10-B-III	C	62	9	1	2	63		14.7
	T	62	8	1	0	63		
W-20-10-B-IV	C	68	2	0	1	68		14.9
	T	62	8	2	0	64		

* Refer to Table B1 for explanation of the code.

Table B30 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 10% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-10-C-I	C	34	36	0	0	34		11.3
D-20-10-C-II	C	33	38	0	2	33	95	11.7
D-20-10-C-III	C	36	33	1	1	37		11.5
D-20-10-C-IV	C	44	26	0	0	44		11.5
D-20-10-T-I	T	64	6	0	0	64		11.0
D-20-10-T-II	T	66	4	0	0	66	95	11.0
D-20-10-T-III	T	62	8	0	0	62		11.4
D-20-10-T-IV	T	65	5	0	1	65		11.5
D-20-10-B-I	C	31	39	0	7	31		11.4
	T	59	11	0	0	59		
D-20-10-B-II	C	26	44	0	5	26		11.2
	T	61	9	0	0	61	94	
D-20-10-B-III	C	28	41	0	5	28		11.3
	T	62	8	0	0	62		
D-20-10-B-IV	C	43	27	0	3	43		11.1
	T	58	13	0	0	58		
W-20-10-C-I	C	52	19	1	0	53		14.2
W-20-10-C-II	C	48	21	0	0	48	94	14.6
W-20-10-C-III	C	51	19	1	1	52		14.7
W-20-10-C-IV	C	50	21	0	0	50		14.8
W-20-10-T-I	T	60	10	0	0	60		14.4
W-20-10-T-II	T	62	8	0	0	62	89	14.9
W-20-10-T-III	T	61	9	0	0	61		15.0
W-20-10-T-IV	T	60	10	0	1	60		15.2
W-20-10-B-I	C	43	26	0	2	43		14.2
	T	55	16	0	2	55		
W-20-10-B-II	C	40	30	0	2	40		15.0
	T	56	14	0	0	56	91	
W-20-10-B-III	C	48	22	0	2	48		14.8
	T	55	16	0	1	55		
W-20-10-B-IV	C	54	17	0	1	54		14.6
	T	57	13	0	0	57		

* Refer to Table B1 for explanation of the code.

Table B31 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 10% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-10-C-I	C	8	61	0	6	8		10.9
D-20-10-C-II	C	9	62	0	3	9	95	10.6
D-20-10-C-III	C	34	36	0	0	34		10.9
D-20-10-C-IV	C	36	32	0	2	36		10.7
D-20-10-T-I	T	62	9	0	0	62		10.7
D-20-10-T-II	T	58	12	0	0	58	93	10.9
D-20-10-T-III	T	57	14	0	0	57		10.9
D-20-10-T-IV	T	63	7	0	0	63		10.9
D-20-10-B-I	C	37	33	0	4	37		10.7
	T	57	13	0	0	57		
D-20-10-B-II	C	29	41	0	4	29		11.5
	T	49	21	0	0	49	94	
D-20-10-B-III	C	21	49	0	8	21		10.9
	T	56	15	0	0	56		
D-20-10-B-IV	C	44	25	0	3	44		10.6
	T	50	21	0	0	50		
W-20-10-C-I	C	45	26	1	0	46		14.0
W-20-10-C-II	C	43	27	0	1	43	92	14.0
W-20-10-C-III	C	50	21	0	2	50		14.3
W-20-10-C-IV	C	51	19	0	1	51		14.0
W-20-10-T-I	T	47	22	0	3	47		13.7
W-20-10-T-II	T	66	5	0	0	66	88	14.1
W-20-10-T-III	T	62	7	0	1	62		14.4
W-20-10-T-IV	T	72	0	0	0	72		14.5
W-20-10-B-I	C	50	19	1	1	51		13.6
	T	56	13	0	3	56		
W-20-10-B-II	C	49	22	1	1	50		14.4
	T	50	21	0	0	50	90	
W-20-10-B-III	C	52	18	1	1	53		14.2
	T	56	14	0	3	56		
W-20-10-B-IV	C	53	17	0	1	53		14.2
	T	51	20	0	0	51		

* Refer to Table B1 for explanation of the code.

Table B32 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 20°C and 10% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-20-10-C-I	C	14	56	0	2	14		9.5
D-20-10-C-II	C	12	58	0	3	12	95	10.2
D-20-10-C-III	C	22	45	0	2	22		10.5
D-20-10-C-IV	C	23	45	0	0	23		10.4
D-20-10-T-I	T	48	23	0	0	48		10.4
D-20-10-T-II	T	46	24	0	1	46	94	10.7
D-20-10-T-III	T	41	29	0	0	41		11.0
D-20-10-T-IV	T	31	39	0	0	31		11.5
D-20-10-B-I	C	29	41	0	0	29		9.8
	T	0	69	0	0	0		
D-20-10-B-II	C	23	48	0	2	23		10.1
	T	3	67	0	0	3	93	
D-20-10-B-III	C	21	49	0	0	21		10.4
	T	16	55	0	0	16		
D-20-10-B-IV	C	30	40	0	0	30		10.4
	T	15	54	0	0	15		
W-20-10-C-I	C	37	33	0	0	37		13.7
W-20-10-C-II	C	38	32	0	1	38	92	14.1
W-20-10-C-III	C	40	31	0	0	40		14.4
W-20-10-C-IV	C	42	29	0	2	42		14.3
W-20-10-T-I	T	66	4	0	0	66		13.9
W-20-10-T-II	T	68	3	0	0	68	87	14.2
W-20-10-T-III	T	51	20	0	2	51		14.4
W-20-10-T-IV	T	67	4	0	0	67		14.5
W-20-10-B-I	C	39	32	0	1	39		13.9
	T	48	13	0	0	48		
W-20-10-B-II	C	44	25	0	3	44		14.0
	T	51	20	0	4	51	88	
W-20-10-B-III	C	44	26	1	1	45		14.4
	T	54	16.	0	1	54		
W-20-10-B-IV	C	40	31	0	0	40		14.2
	T	43	26	0	0	43		

* Refer to Table B1 for explanation of the code.

Table B33 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and ambient CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-am-C-I	C	66	4	17	1	83		11.6
D-25-am-C-II	C	67	3	20	0	87	95	11.7
D-25-am-C-III	C	68	2	23	0	91		11.9
D-25-am-C-IV	C	68	2	18	0	86		11.8
D-25-am-T-I	T	69	1	67	0	136		11.5
D-25-am-T-II	T	70	0	69	0	139	91	11.6
D-25-am-T-III	T	68	2	65	0	133		11.8
D-25-am-T-IV	T	70	0	67	0	137		11.6
D-25-am-B-I	C	70	0	7	2	77		11.3
	T	64	6	14	0	78		
D-25-am-B-II	C	66	4	19	1	85		11.9
	T	69	1	22	0	91	92	
D-25-am-B-III	C	65	5	13	1	78		11.8
	T	70	0	27	0	97		
D-25-am-B-IV	C	63	7	17	0	80		11.7
	T	69	1	23	0	92		
W-25-am-C-I	C	70	0	59	1	129		14.1
W-25-am-C-II	C	68	2	53	0	121	89	14.3
W-25-am-C-III	C	69	1	61	1	130		15.4
W-25-am-C-IV	C	69	1	52	1	121		14.4
W-25-am-T-I	T	67	3	89	1	156		15.2
W-25-am-T-II	T	70	0	74	0	144	88	14.7
W-25-am-T-III	T	69	1	87	2	156		14.4
W-25-am-T-IV	T	69	1	77	1	146		14.7
W-25-am-B-I	C	69	1	35	1	104		14.6
	T	70	1	21	0	91		
W-25-am-B-II	C	67	3	29	0	96		14.6
	T	71	1	17	1	88	88	
W-25-am-B-III	C	68	2	33	1	101		14.8
	T	72	0	23	0	95		
W-25-am-B-IV	C	68	2	32	0	100		15.0
	T	70	0	16	1	86		

* Refer to Table B1 for explanation of the code.

Table B34 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and ambient CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-am-C-I	C	66	4	42	0	108		11.6
D-25-am-C-II	C	64	6	77	0	141	95	11.8
D-25-am-C-III	C	62	7	64	4	126		11.8
D-25-am-C-IV	C	68	2	52	0	120		11.9
D-25-am-T-I	T	65	2	76	1	141		11.5
D-25-am-T-II	T	67	3	65	2	132	86	11.8
D-25-am-T-III	T	70	0	82	4	152		11.8
D-25-am-T-IV	T	68	2	57	2	125		11.9
D-25-am-B-I	C	64	6	29	1	93		11.7
	T	65	5	13	0	78		
D-25-am-B-II	C	64	6	48	0	112		11.8
	T	70	0	11	1	81	89	
D-25-am-B-III	C	65	5	44	0	109		11.8
	T	68	2	13	0	81		
D-25-am-B-IV	C	67	3	57	0	124		11.9
	T	69	1	16	1	85		
W-25-am-C-I	C	71	0	210	5	281		14.8
W-25-am-C-II	C	70	0	166	7	236	81	14.6
W-25-am-C-III	C	70	0	191	2	261		14.8
W-25-am-C-IV	C	70	0	185	2	255		15.0
W-25-am-T-I	T	67	2	257	3	324		15.0
W-25-am-T-II	T	68	2	186	1	254	80	15.2
W-25-am-T-III	T	68	2	231	2	299		15.1
W-25-am-T-IV	T	69	1	211	1	280		15.3
W-25-am-B-I	C	69	1	96	1	165		14.2
	T	68	2	11	0	79		
W-25-am-B-II	C	69	1	78	0	147		14.7
	T	70	2	17	0	87	79	
W-25-am-B-III	C	68	2	81	1	149		14.9
	T	68	2	16	1	84		
W-25-am-B-IV	C	69	1	93	2	162		14.8
	T	70	0	12	0	82		

* Refer to Table B1 for explanation of the code.

Table B35 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and ambient CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-am-C-I	C	64	6	41	1	105		11.2
D-25-am-C-II	C	74	1	22	8	96	90	11.4
D-25-am-C-III	C	59	15	65	8	124		11.5
D-25-am-C-IV	C	54	16	48	9	102		11.7
D-25-am-T-I	T	78	3	66	2	144		11.8
D-25-am-T-II	T	81	3	53	2	134	83	11.8
D-25-am-T-III	T	72	5	71	4	143		11.6
D-25-am-T-IV	T	72	4	51	3	123		11.7
D-25-am-B-I	C	61	9	68	1	129		11.6
	T	67	3	18	0	85		
D-25-am-B-II	C	66	5	103	0	169		11.9
	T	69	1	28	1	97	87	
D-25-am-B-III	C	69	1	83	0	152		12.0
	T	70	0	40	0	110		
D-25-am-B-IV	C	66	4	66	1	132		12.0
	T	66	4	58	0	124		
W-25-am-C-I	C	74	0	213	2	287		15.2
W-25-am-C-II	C	70	0	180	1	250	76	14.6
W-25-am-C-III	C	73	0	191	1	264		14.5
W-25-am-C-IV	C	71	0	201	1	272		14.5
W-25-am-T-I	T	85	1	341	2	426		15.3
W-25-am-T-II	T	77	0	282	1	359	74	14.1
W-25-am-T-III	T	78	0	305	3	383		14.5
W-25-am-T-IV	T	84	1	317	1	401		14.7
W-25-am-B-I	C	68	2	107	1	175		14.7
	T	73	0	13	0	86		
W-25-am-B-II	C	69	1	84	1	153		14.4
	T	74	0	9	0	83	76	
W-25-am-B-III	C	69	1	89	0	158		15.4
	T	73	0	7	0	80		
W-25-am-B-IV	C	69	1	103	1	172		14.5
	T	72	0	15	0	87		

* Refer to Table B1 for explanation of the code.

Table B36 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and ambient CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count: First count Live	Adult Count: First count Dead	Adult Count: Inc. count Live	Adult Count: Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-25-am-C-I	C	60	9	26	0	86		11.6
D-25-am-C-II	C	67	3	43	2	110	87	12.5
D-25-am-C-III	C	66	4	57	4	123		11.6
D-25-am-C-IV	C	71	2	71	1	142		12.1
D-25-am-T-I	T	145	13	45	9	190		12.0
D-25-am-T-II	T	131	11	25	2	156	82	11.5
D-25-am-T-III	T	126	9	104	5	230		11.0
D-25-am-T-IV	T	122	7	75	1	197		12.8
D-25-am-B-I	C	59	10	10	2	69		12.2
	T	68	4	41	18	109		
D-25-am-B-II	C	56	14	34	4	90		12.0
	T	60	10	9	11	69	84	
D-25-am-B-III	C	63	8	23	2	86		11.3
	T	60	9	9	14	69		
D-25-am-B-IV	C	58	11	61	1	119		12.0
	T	66	5	21	1	87		
W-25-am-C-I	C	85	0	162	1	247		15.7
W-25-am-C-II	C	82	0	137	0	219	77	14.4
W-25-am-C-III	C	81	0	129	1	210		16.0
W-25-am-C-IV	C	84	0	167	2	251		15.8
W-25-am-T-I	T	164	1	247	3	411		15.8
W-25-am-T-II	T	151	0	216	1	367	72	16.0
W-25-am-T-III	T	173	2	223	0	396		16.1
W-25-am-T-IV	T	141	0	239	2	380		16.0
W-25-am-B-I	C	75	0	83	1	158		15.9
	T	91	2	7	0	98		
W-25-am-B-II	C	77	0	74	0	151		15.9
	T	83	1	3	0	86	74	
W-25-am-B-III	C	79	0	71	0	150		15.3
	T	86	1	4	0	90		
W-25-am-B-IV	C	73	0	87	2	160		15.2
	T	88	0	6	0	94		

* Refer to Table B1 for explanation of the code.

Table B37 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 2% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-2-C-I	C	41	29	4	1	45		11.1
D-25-2-C-II	C	50	20	19	4	69	96.8	10.8
D-25-2-C-III	C	48	22	12	4	60		11.0
D-25-2-C-IV	C	44	26	23	1	67		11.6
D-25-2-T-I	T	69	1	64	1	133		12.5
D-25-2-T-II	T	62	8	75	0	137	94	11.6
D-25-2-T-III	T	67	3	71	0	138		10.7
D-25-2-T-IV	T	68	2	65	0	133		12.3
D-25-2-B-I	C	35	35	4	0	39		11.1
	T	57	13	0	0	57		
D-25-2-B-II	C	47	23	34	2	81		11.5
	T	62	8	0	0	62	95	
D-25-2-B-III	C	55	15	44	2	99		11.9
	T	67	3	0	0	67		
D-25-2-B-IV	C	54	16	27	4	81		12.3
	T	66	4	2	0	68		
W-25-2-C-I	C	48	22	3	0	51		14.5
W-25-2-C-II	C	58	12	32	0	90	94	14.6
W-25-2-C-III	C	56	14	62	1	118		15.3
W-25-2-C-IV	C	62	8	39	1	101		14.3
W-25-2-T-I	T	68	2	46	0	114		14.3
W-25-2-T-II	T	65	5	82	2	147	91	14.2
W-25-2-T-III	T	65	5	21	0	86		14.5
W-25-2-T-IV	T	65	5	25	0	90		14.4
W-25-2-B-I	C	55	15	43	4	98		14.2
	T	62	8	22	0	84		
W-25-2-B-II	C	51	19	22	2	73		14.2
	T	61	9	10	0	71	89	
W-25-2-B-III	C	48	22	21	0	69		14.4
	T	63	7	1	0	64		
W-25-2-B-IV	C	59	11	29	0	88		14.0
	T	61	9	7	0	68		

* Refer to Table B1 for explanation of the code.

Table B38 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 2% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-2-C-I	C	37	33	36	0	73		10.5
D-25-2-C-II	C	41	29	20	0	61	96	11.4
D-25-2-C-III	C	44	25	9	0	53		11.8
D-25-2-C-IV	C	34	36	12	1	46		12.1
D-25-2-T-I	T	62	9	21	1	83		11.7
D-25-2-T-II	T	65	5	68	8	133	91	12.7
D-25-2-T-III	T	63	8	100	0	163		12.9
D-25-2-T-IV	T	65	6	98	0	163		12.2
D-25-2-B-I	C	38	32	14	0	52		11.2
	T	63	8	0	0	63		
D-25-2-B-II	C	44	27	13	1	57		11.9
	T	59	11	0	0	59	92	
D-25-2-B-III	C	45	26	34	1	79		12.4
	T	60	10	0	0	60		
D-25-2-B-IV	C	37	34	27	1	64		12.5
	T	61	9	0	0	61		
W-25-2-C-I	C	41	30	48	0	89		15.4
W-25-2-C-II	C	40	32	74	0	114	89	12.9
W-25-2-C-III	C	40	31	50	1	90		11.5
W-25-2-C-IV	C	31	41	61	0	92		10.0
W-25-2-T-I	T	62	10	109	4	171		13.7
W-25-2-T-II	T	63	8	95	1	158	89	13.2
W-25-2-T-III	T	61	9	55	3	116		14.5
W-25-2-T-IV	T	64	6	59	1	123		15.0
W-25-2-B-I	C	39	31	42	0	81		14.1
	T	53	17	2	0	55		
W-25-2-B-II	C	43	27	32	2	75		14.4
	T	49	22	3	0	52	83	–
W-25-2-B-III	C	51	18	31	0	82		14.5
	T	56	15	7	0	63		
W-25-2-B-IV	C	35	36	43	2	78		12.1
	T	47	23	34	1	81		

* Refer to Table B1 for explanation of the code.

Table B39 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 2% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-2-C-I	C	36	34	6	1	42		10.9
D-25-2-C-II	C	45	26	16	2	61	92	11.6
D-25-2-C-III	C	42	28	4	1	46		11.9
D-25-2-C-IV	C	41	29	13	0	54		12.6
D-25-2-T-I	T	62	8	33	0	95		12.0
D-25-2-T-II	T	76	4	52	2	128	87	12.5
D-25-2-T-III	T	85	4	64	2	149		12.8
D-25-2-T-IV	T	73	5	101	2	174		13.0
D-25-2-B-I	C	41	29	6	0	47		11.0
	T	61	9	0	0	61		
D-25-2-B-II	C	45	26	16	1	61		12.0
	T	62	8	0	0	62	89	
D-25-2-B-III	C	47	24	22	1	69		12.4
	T	64	7	0	0	64		
D-25-2-B-IV	C	39	31	25	0	64		12.5
	T	59	12	0	0	59		
W-25-2-C-I	C	31	46	38	2	69		13.8
W-25-2-C-II	C	48	27	36	6	84	86	14.8
W-25-2-C-III	C	30	42	42	3	72		15.2
W-25-2-C-IV	C	29	45	39	3	68		15.3
W-25-2-T-I	T	77	4	149	5	226		13.1
W-25-2-T-II	T	75	6	92	3	167	79	13.7
W-25-2-T-III	T	81	3	79	4	160		14.2
W-25-2-T-IV	T	71	2	50	1	121		14.6
W-25-2-B-I	C	22	48	20	2	42		13.6
	T	71	5	23	0	94		
W-25-2-B-II	C	29	40	18	6	47		14.3
	T	53	17	15	1	68	79	
W-25-2-B-III	C	38	32	23	1	61		14.8
	T	64	6	21	0	85		
W-25-2-B-IV	C	38	31	17	2	55		15.0
	T	60	9	17	1	77		

* Refer to Table B1 for explanation of the code.

Table B40 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 2% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-2-C-I	C	42	32	1	2	43		11.1
D-25-2-C-II	C	41	34	6	0	47	92	11.7
D-25-2-C-III	C	49	29	4	1	53		12.0
D-25-2-C-IV	C	42	31	5	1	47		12.1
D-25-2-T-I	T	94	11	7	0	101		12.3
D-25-2-T-II	T	107	15	12	0	119	85	11.9
D-25-2-T-III	T	119	17	12	0	131		12.7
D-25-2-T-IV	T	154	9	41	2	195		13.0
D-25-2-B-I	C	31	39	1	1	32		11.4
	T	55	16	0	0	55		
D-25-2-B-II	C	36	35	4	0	40		12.0
	T	57	14	0	0	57	86	
D-25-2-B-III	C	31	41	3	0	34		12.3
	T	57	14	0	0	57		
D-25-2-B-IV	C	29	42	2	0	31		12.5
	T	56	14	0	0	56		
W-25-2-C-I	C	44	32	13	0	57		13.6
W-25-2-C-II	C	40	36	12	0	52	84	13.5
W-25-2-C-III	C	33	38	10	0	43		14.2
W-25-2-C-IV	C	52	26	16	0	68		13.8
W-25-2-T-I	T	78	2	2	0	80		13.8
W-25-2-T-II	T	131	9	14	0	145	76	13.4
W-25-2-T-III	T	171	6	19	2	190		13.7
W-25-2-T-IV	T	175	5	62	3	237		14.4
W-25-2-B-I	C	48	24	19	1	67		14.2
	T	61	26	5	0	66		
W-25-2-B-II	C	41	29	23	1	64		13.6
	T	52	17	7	0	59	77	
W-25-2-B-III	C	41	37	17	2	58		14.0
	T	59	19	4	0	63		
W-25-2-B-IV	C	42	28	25	2	67		13.9
	T	55	22	8	0	63		

* Refer to Table B1 for explanation of the code.

Table B41 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 5% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-5-C-I	C	21	49	7	0	28		11.8
D-25-5-C-II	C	44	26	11	0	55	96	11.8
D-25-5-C-III	C	54	15	13	0	67		12.3
D-25-5-C-IV	C	49	21	6	0	55		12.0
D-25-5-T-I	T	67	3	21	0	88		12.3
D-25-5-T-II	T	68	2	23	0	91	96	12.4
D-25-5-T-III	T	68	2	19	0	87		12.7
D-25-5-T-IV	T	68	2	24	0	92		11.5
D-25-5-B-I	C	52	18	2	0	54		12.6
	T	45	26	0	0	45		
D-25-5-B-II	C	45	26	1	0	46		11.7
	T	62	8	0	0	62	97	
D-25-5-B-III	C	52	18	0	0	52		12.0
	T	68	2	0	0	68		
D-25-5-B-IV	C	57	13	1	0	58		11.9
	T	69	1	2	0	71		
W-25-5-C-I	C	57	12	23	0	80		15.1
W-25-5-C-II	C	52	18	15	0	67	93	14.8
W-25-5-C-III	C	61	9	17	0	78		15.1
W-25-5-C-IV	C	47	24	21	0	68		15.5
W-25-5-T-I	T	65	5	35	0	100		15.0
W-25-5-T-II	T	63	7	29	0	92	90	15.2
W-25-5-T-III	T	67	3	31	0	98		15.5
W-25-5-T-IV	T	61	9	32	0	93		15.3
W-25-5-B-I	C	51	19	19	0	70		14.9
	T	62	9	9	0	71		
W-25-5-B-II	C	54	16	13	0	67		14.9
	T	64	7	5	0	69	88	-
W-25-5-B-III	C	55	16	22	0	77		14.9
	T	61	9	8	0	69		
W-25-5-B-IV	C	49	21	11	0	60		15.1
	T	61	10	7	0	68		

* Refer to Table B1 for explanation of the code.

Table B42 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 5% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-5-C-I	C	11	59	16	0	27		11.6
D-25-5-C-II	C	33	37	12	0	45	94	11.2
D-25-5-C-III	C	39	31	7	0	46		11.4
D-25-5-C-IV	C	42	28	13	0	55		11.8
D-25-5-T-I	T	44	26	3	0	47		11.5
D-25-5-T-II	T	60	10	7	0	67	93	12.4
D-25-5-T-III	T	66	4	30	0	96		11.3
D-25-5-T-IV	T	62	8	38	0	100		11.7
D-25-5-B-I	C	26	44	0	0	26		11.7
	T	44	27	0	0	44		
D-25-5-B-II	C	35	36	1	0	36		12.1
	T	40	29	0	0	40	94	
D-25-5-B-III	C	29	41	8	0	37		12.0
	T	64	6	0	0	64		
D-25-5-B-IV	C	26	44	22	0	48		11.4
	T	68	2	26	0	94		
W-25-5-C-I	C	43	27	47	0	90		14.2
W-25-5-C-II	C	39	32	36	0	75	87	14.6
W-25-5-C-III	C	42	28	43	0	85		14.9
W-25-5-C-IV	C	40	30	39	0	79		14.9
W-25-5-T-I	T	63	7	56	1	119		14.7
W-25-5-T-II	T	62	8	46	0	108	84	14.6
W-25-5-T-III	T	60	10	59	0	119		14.8
W-25-5-T-IV	T	59	11	44	2	103		14.9
W-25-5-B-I	C	38	33	37	0	75		14.6
	T	57	14	11	0	68		
W-25-5-B-II	C	36	34	25	1	61		14.9
	T	55	16	12	0	67	86	–
W-25-5-B-III	C	42	29	22	1	64		14.9
	T	54	16	13	0	67		
W-25-5-B-IV	C	44	26	41	0	85		14.9
	T	53	18	8	0	61		

* Refer to Table B1 for explanation of the code.

Table B43 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 5% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-5-C-I	C	16	56	11	0	27		11.9
D-25-5-C-II	C	39	31	6	0	45	93	11.5
D-25-5-C-III	C	54	16	9	5	63		11.2
D-25-5-C-IV	C	47	22	2	0	49		11.7
D-25-5-T-I	T	38	32	4	0	42		11.6
D-25-5-T-II	T	68	3	42	1	110	90	12.0
D-25-5-T-III	T	68	2	70	0	138		11.5
D-25-5-T-IV	T	63	8	52	1	115		11.7
D-25-5-B-I	C	31	39	1	1	32		11.2
	T	48	23	0	0	48		
D-25-5-B-II	C	34	36	3	0	37		11.7
	T	52	19	0	0	52	90	
D-25-5-B-III	C	36	33	12	0	48		12.0
	T	45	27	0	0	45		
D-25-5-B-IV	C	40	29	0	1	40		11.5
	T	60	12	0	2	60		
W-25-5-C-I	C	34	36	31	1	65		15.0
W-25-5-C-II	C	30	45	23	0	53	86	15.1
W-25-5-C-III	C	29	46	21	1	50		15.2
W-25-5-C-IV	C	35	36	33	2	68		15.2
W-25-5-T-I	T	65	6	1	6	66		14.8
W-25-5-T-II	T	69	1	29	10	98	79	15.1
W-25-5-T-III	T	69	1	101	4	170		15.4
W-25-5-T-IV	T	64	7	70	32	134		15.3
W-25-5-B-I	C	31	39	14	1	45		15.0
	T	53	17	15	0	68		
W-25-5-B-II	C	33	38	9	1	42		15.1
	T	49	22	11	0	60	82	
W-25-5-B-III	C	37	33	12	2	49		15.2
	T	54	15	16	0	70		
W-25-5-B-IV	C	34	36	10	2	44		15.3
	T	52	16	9	0	61		

* Refer to Table B1 for explanation of the code.

Table B44 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 5% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-5-C-I	C	2	68	12	3	14		10.4
D-25-5-C-II	C	36	34	10	1	46	92	10.8
D-25-5-C-III	C	47	23	14	2	61		11.2
D-25-5-C-IV	C	34	36	8	2	42		11.5
D-25-5-T-I	T	49	21	15	2	64		10.6
D-25-5-T-II	T	52	19	19	2	71	88	11.2
D-25-5-T-III	T	50	20	18	3	68		11.2
D-25-5-T-IV	T	53	18	16	1	69		11.5
D-25-5-B-I	C	5	65	0	0	5		10.5
	T	42	29	0	0	42		
D-25-5-B-II	C	38	32	4	0	42		11.0
	T	50	20	0	1	50	89	
D-25-5-B-III	C	44	26	15	2	59		11.4
	T	35	35	2	0	37		
D-25-5-B-IV	C	38	32	28	3	66		11.5
	T	58	12	13	5	71		
W-25-5-C-I	C	39	31	13	0	52		15.4
W-25-5-C-II	C	33	38	9	1	42	85	15.0
W-25-5-C-III	C	34	36	12	1	46		15.3
W-25-5-C-IV	C	37	33	11	1	48		15.3
W-25-5-T-I	T	89	5	23	2	112		15.2
W-25-5-T-II	T	83	9	19	3	102	79	15.4
W-25-5-T-III	T	88	7	17	2	105		15.4
W-25-5-T-IV	T	84	6	26	1	110		15.4
W-25-5-B-I	C	41	29	15	1	56		15.0
	T	51	19	7	1	58		
W-25-5-B-II	C	33	38	11	1	44		15.1
	T	47	22	2	2	49	81	
W-25-5-B-III	C	41	29	11	1	52		15.2
	T	45	26	4	0	49		
W-25-5-B-IV	C	40	30	15	1	55		15.1
	T	54	16	3	0	57		

* Refer to Table B1 for explanation of the code.

Table B45 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 10% CO_2 at exposure time of 2 wk.

Sample	Insect type	Adult Count: First count Live	First count Dead	Inc. count Live	Inc. count Dead	Total survival	Mean germ. (%)	m.c. (% wb)
D-25-10-C-I	C	42	37	0	0	42		11.9
D-25-10-C-II	C	34	36	0	0	34	95	11.6
D-25-10-C-III	C	32	38	4	0	36		12.1
D-25-10-C-IV	C	44	26	3	0	47		12.0
D-25-10-T-I	T	69	1	6	0	75		11.9
D-25-10-T-II	T	69	1	5	0	74	96	11.5
D-25-10-T-III	T	70	0	27	1	97		12.1
D-25-10-T-IV	T	69	1	22	0	91		12.7
D-25-10-B-I	C	41	29	0	0	41		12.6
	T	63	7	4	0	67		
D-25-10-B-II	C	33	38	0	1	33		11.3
	T	57	14	1	0	58	96	
D-25-10-B-III	C	39	31	0	0	39		11.8
	T	62	8	2	0	64		
D-25-10-B-IV	C	36	34	1	0	37		12.0
	T	58	23	4	0	62		
W-25-10-C-I	C	46	23	15	0	61		13.8
W-25-10-C-II	C	49	21	11	0	60	91	14.2
W-25-10-C-III	C	56	14	16	0	72		14.3
W-25-10-C-IV	C	53	17	10	0	63		14.5
W-25-10-T-I	T	61	9	25	0	86		13.9
W-25-10-T-II	T	59	11	22	0	81	92	14.2
W-25-10-T-III	T	65	5	22	1	87		14.5
W-25-10-T-IV	T	67	3	24	2	91		14.6
W-25-10-B-I	C	46	24	13	0	59		13.6
	T	61	10	6	0	67		
W-25-10-B-II	C	43	28	9	0	52		14.1
	T	55	16	5	0	60	92	
W-25-10-B-III	C	51	19	12	0	63		14.3
	T	56	14	6	0	62		
W-25-10-B-IV	C	55	16	10	0	65		14.3
	T	59	12	7	1	66		

* Refer to Table B1 for explanation of the code.

Table B46 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 10% CO_2 at exposure time of 4 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-10-C-I	C	32	38	5	0	37		11.6
D-25-10-C-II	C	21	48	2	0	23	94	11.5
D-25-10-C-III	C	24	46	8	1	32		12.5
D-25-10-C-IV	C	25	45	20	3	45		11.8
D-25-10-T-I	T	53	17	18	0	71		11.5
D-25-10-T-II	T	59	11	11	0	70	95	11.6
D-25-10-T-III	T	60	10	11	1	71		12.2
D-25-10-T-IV	T	61	9	6	0	67		12.4
D-25-10-B-I	C	27	42	2	0	29		11.6
	T	56	15	2	0	58		
D-25-10-B-II	C	21	49	0	0	21		11.8
	T	48	23	1	0	49	94	
D-25-10-B-III	C	23	47	0	0	23		11.5
	T	49	22	1	0	50		
D-25-10-B-IV	C	24	46	0	0	24		11.7
	T	54	16	4	0	58		
W-25-10-C-I	C	31	39	31	0	62		15.2
W-25-10-C-II	C	33	37	25	0	58	91	14.6
W-25-10-C-III	C	42	28	27	0	69		14.5
W-25-10-C-IV	C	39	31	25	0	64		14.5
W-25-10-T-I	T	59	11	41	0	100		15.3
W-25-10-T-II	T	60	10	33	2	93	86	14.1
W-25-10-T-III	T	60	10	35	1	95		14.5
W-25-10-T-IV	T	60	9	39	2	99		14.7
W-25-10-B-I	C	29	41	27	1	56		14.7
	T	51	19	12	1	63		
W-25-10-B-II	C	31	40	19	1	50		14.4
	T	55	16	2	1	57	87	
W-25-10-B-III	C	35	34	21	0	56		15.4
	T	57	14	5	0	62		
W-25-10-B-IV	C	33	37	26	1	59		14.5
	T	49	21	5	0	54		

* Refer to Table B1 for explanation of the code.

Table B47 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 10% CO_2 at exposure time of 6 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-10-C-I	C	35	36	0	0	35		12.4
D-25-10-C-II	C	29	41	0	0	29	94	10.8
D-25-10-C-III	C	28	42	8	1	36		10.5
D-25-10-C-IV	C	35	35	10	0	45		11.6
D-25-10-T-I	T	30	40	0	0	30		10.4
D-25-10-T-II	T	65	5	29	7	94	92	11.3
D-25-10-T-III	T	66	4	20	0	86		11.8
D-25-10-T-IV	T	68	2	39	1	107		12.0
D-25-10-B-I	C	34	36	0	0	34		11.4
	T	53	18	0	0	53		
D-25-10-B-II	C	28	43	1	0	29		10.5
	T	42	28	0	0	42	91	
D-25-10-B-III	C	32	38	2	0	34		11.2
	T	55	16	0	1	55		
D-25-10-B-IV	C	31	39	12	1	43		12.3
	T	41	30	7	2	48		
W-25-10-C-I	C	26	43	21	1	47		14.0
W-25-10-C-II	C	24	46	12	2	36	89	14.4
W-25-10-C-III	C	33	38	17	2	50		14.4
W-25-10-C-IV	C	34	35	15	1	49		14.4
W-25-10-T-I	T	61	9	19	1	80		14.2
W-25-10-T-II	T	62	8	19	2	81	83	14.5
W-25-10-T-III	T	67	3	16	1	83		14.6
W-25-10-T-IV	T	67	2	22	3	89		14.7
W-25-10-B-I	C	27	43	14	0	41		14.1
	T	46	24	4	0	50		
W-25-10-B-II	C	29	41	11	1	40		14.5
	T	45	26	4	0	49	85	
W-25-10-B-III	C	35	36	9	2	44		14.4
	T	52	19	6	0	58		
W-25-10-B-IV	C	32	39	15	1	47		14.4
	T	56	15	16	1	72		

* Refer to Table B1 for explanation of the code.

Table B48 First count and incubation count of adults of *C. ferrugineus* and *T. castaneum* in wheat 'AC Barrie' at 25°C and 10% CO_2 at exposure time of 8 wk.

Sample	Insect type	Adult Count				Total survival	Mean germ. (%)	m.c. (% wb)
		First count		Inc. count				
		Live	Dead	Live	Dead			
D-25-10-C-I	C	26	44	0	2	26		10.2
D-25-10-C-II	C	21	49	1	1	22	93	11.0
D-25-10-C-III	C	27	42	5	2	32		11.5
D-25-10-C-IV	C	23	47	9	2	32		11.7
D-25-10-T-I	T	39	31	12	0	51		10.6
D-25-10-T-II	T	41	29	15	3	56	90	11.3
D-25-10-T-III	T	41	29	11	0	52		11.8
D-25-10-T-IV	T	43	27	17	3	60		12.2
D-25-10-B-I	C	27	43	0	0	27		10.1
	T	21	49	0	0	21		
D-25-10-B-II	C	19	51	0	0	19		10.8
	T	17	54	0	0	17	90	
D-25-10-B-III	C	26	43	3	1	29		11.3
	T	59	11	0	0	59		
D-25-10-B-IV	C	19	51	12	1	31		11.5
	T	45	25	0	0	45		
W-25-10-C-I	C	31	39	12	1	43		14.4
W-25-10-C-II	C	30	40	8	0	38	87	14.6
W-25-10-C-III	C	33	36	11	2	44		14.8
W-25-10-C-IV	C	34	36	9	1	43		14.9
W-25-10-T-I	T	56	14	18	2	74		14.5
W-25-10-T-II	T	53	17	12	0	65	82	14.8
W-25-10-T-III	T	62	8	14	1	76		14.9
W-25-10-T-IV	T	66	4	16	1	82		15.0
W-25-10-B-I	C	23	47	8	3	31		14.5
	T	39	31	3	1	42		
W-25-10-B-II	C	21	48	4	0	25		14.6
	T	41	29	4	0	45	84	
W-25-10-B-III	C	29	41	7	1	36		14.7
	T	49	21	9	1	58		
W-25-10-B-IV	C	30	41	6	2	36		14.8
	T	45	26	4	0	49		

* Refer to Table B1 for explanation of the code.

APPENDIX C

Table C1. Experimental design for determination of survivorship and interspecific competition of *Cryptolestes ferrugineus* and *Tribolium castaneum* at various temperatures, humidities, and CO_2 concentrations (4 replicates for each treatment).

Treatment Number (RH%, temp°C, CO_2%)	Population category	Code
I (50, 15, 0.03)	Single species, *C. ferrugineus* (C)	D-15-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-15-am-T-I, II, III, IV
	Mixed species, both (B)	D-15-am-B-I, II, III, IV
II (75, 15, 0.03)	Single species, *C. ferrugineus* (C)	W-15-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-15-am-T-I, II, III, IV
	Mixed species, both (B)	W-15-am-B-I, II, III, IV
III (50, 15, 2)	Single species, *C. ferrugineus* (C)	D-15-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-15-2-T-I, II, III, IV
	Mixed species, both (B)	D-15-2-B-I, II, III, IV
IV (75, 15, 2)	Single species, *C. ferrugineus* (C)	W-15-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-15-2-T-I, II, III, IV
	Mixed species, both (B)	W-15-2-B-I, II, III, IV
V (50, 15, 5)	Single species, *C. ferrugineus* (C)	D-15-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-15-5-T-I, II, III, IV
	Mixed species, both (B)	D-15-5-B-I, II, III, IV
VI (75, 15, 5)	Single species, *C. ferrugineus* (C)	W-15-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-15-5-T-I, II, III, IV
	Mixed species, both (B)	W-15-5-B-I, II, III, IV
VII (50, 15, 10)	Single species, *C. ferrugineus* (C)	D-15-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-15-10-T-I, II, III, IV
	Mixed species, both (B)	D-15-10-B-I, II, III, IV

Treatment Number (RH%, temp°C, CO_2%)	Population category	Code
VIII (75, 15, 10)	Single species, *C. ferrugineus* (C)	W-15-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-15-10-T-I, II, III, IV
	Mixed species, both (B)	W-15-10-B-I, II, III, IV
IX (50, 20, 0.03)	Single species, *C. ferrugineus* (C)	D-20-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-20-am-T-I, II, III, IV
	Mixed species, both (B)	D-20-am-B-I, II, III, IV
X (75, 20, 0.03)	Single species, *C. ferrugineus* (C)	W-20-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-20-am-T-I, II, III, IV
	Mixed species, both (B)	W-20-am-B-I, II, III, IV
XI (50, 20, 2)	Single species, *C. ferrugineus* (C)	D-20-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-20-2-T-I, II, III, IV
	Mixed species, both (B)	D-20-2-B-I, II, III, IV
XII (75, 20, 2)	Single species, *C. ferrugineus* (C)	W-20-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-20-2-T-I, II, III, IV
	Mixed species, both (B)	W-20-2-B-I, II, III, IV
XIII (50, 20, 5)	Single species, *C. ferrugineus* (C)	D-20-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-20-5-T-I, II, III, IV
	Mixed species, both (B)	D-20-5-B-I, II, III, IV
XIV (75, 20, 5)	Single species, *C. ferrugineus* (C)	W-20-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-20-5-T-I, II, III, IV
	Mixed species, both (B)	W-20-5-B-I, II, III, IV
XV (50, 20, 10)	Single species, *C. ferrugineus* (C)	D-20-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-20-10-T-I, II, III, IV
	Mixed species, both (B)	D-20-10-B-I, II, III, IV

Treatment Number (RH%, temp°C, CO_2%)	Population category	Code
XVI (75, 20, 10)	Single species, *C. ferrugineus* (C)	W-20-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-20-10-T-I, II, III, IV
	Mixed species, both (B)	W-20-10-B-I, II, III, IV
XVII (50, 25, 0.03)	Single species, *C. ferrugineus* (C)	D-25-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-25-am-T-I, II, III, IV
	Mixed species, both (B)	D-25-am-B-I, II, III, IV
XVIII (75, 25, 0.03)	Single species, *C. ferrugineus* (C)	W-25-am-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-25-am-T-I, II, III, IV
	Mixed species, both (B)	W-25-am-B-I, II, III, IV
XIX (50, 25, 2)	Single species, *C. ferrugineus* (C)	D-25-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-25-2-T-I, II, III, IV
	Mixed species, both (B)	D-25-2-B-I, II, III, IV
XX (75, 25, 2)	Single species, *C. ferrugineus* (C)	W-25-2-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-25-2-T-I, II, III, IV
	Mixed species, both (B)	W-25-2-B-I, II, III, IV
XXI (50, 25, 5)	Single species, *C. ferrugineus* (C)	D-25-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-25-5-T-I, II, III, IV
	Mixed species, both (B)	D-25-5-B-I, II, III, IV
XXII (75, 25, 5)	Single species, *C. ferrugineus* (C)	W-25-5-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-25-5-T-I, II, III, IV
	Mixed species, both (B)	W-25-5-B-I, II, III, IV
XIII (50, 25, 10)	Single species, *C. ferrugineus* (C)	D-25-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	D-25-10-T-I, II, III, IV
	Mixed species, both (B)	D-25-10-B-I, II, III, IV

Treatment Number ($RH\%$, temp °C, $CO_2\%$)	Population category	Code
XXIV (75, 25, 10)	Single species, *C. ferrugineus* (C)	W-25-10-C-I, II, III, IV
	Single species, *T. castaneum* (T)	W-25-10-T-I, II, III, IV
	Mixed species, both (B)	W-25-10-B-I, II, III, IV

The meaning of characters in the column Code are: D and W refer to dry (12% wb) and wet (15% wb) grain, respectively; next two digits represent temperature in °C; next lowercase characters 'am' refer to ambient CO_2 level and a number in place of 'am' refers to CO_2 concentration in percentage; next uppercase letters C, T, and B refer to species as shown in column population category; and the Roman numerals I, II, III, IV represent the four replicates.

APPENDIX D

Table D1 Combined analysis of variance with 5-way classification for adult survival (first and incubation counts) of *Cryptolestes ferrugineus* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	452.36	226.18	619.42	<.0001
MC	1	608.64	608.64	1666.82	<.0001
TE*MC	2	16.59	8.30	22.72	<.0001
CO_2	3	1193.67	397.89	1089.66	<.0001
TE*CO_2	6	421.29	70.22	192.29	<.0001
MC*CO_2	3	19.42	6.47	17.73	<.0001
TE*MC*CO_2	6	125.56	20.93	57.31	<.0001
SPEF	1	21.48	21.48	58.82	<.0001
TE*SPEF	2	6.78	3.39	9.29	0.0001
MC*SPEF	1	0.87	0.87	2.39	0.1227
TE*MC*SPEF	2	15.50	7.75	21.23	<.0001
CO_2*SPEF	3	14.38	4.79	13.13	<.0001
TE*CO_2*SPEF	6	19.10	3.18	8.72	<.0001
MC*CO_2*SPEF	3	4.91	1.64	4.49	0.0040
TE*MC*CO_2*SPEF	6	16.84	2.81	7.69	<.0001
WK	3	166.70	55.57	152.17	<.0001
TE*WK	6	46.75	7.79	21.34	<.0001
MC*WK	3	30.75	10.25	28.07	<.0001
TE*MC*WK	6	39.24	6.54	17.91	<.0001
CO_2*WK	9	99.52	11.06	30.28	<.0001
TE*CO_2*WK	18	59.32	3.30	9.03	<.0001
MC*CO_2*WK	9	6.44	0.72	1.96	0.0419
TE*MC*CO_2*WK	18	30.12	1.67	4.58	<.0001
SPEF*WK	3	5.17	1.72	4.72	0.0029
TE*SPEF*WK	6	3.87	0.65	1.77	0.1037
MC*SPEF*WK	3	4.27	1.42	3.90	0.0090
TE*MC*SPEF*WK	6	8.97	1.49	4.09	0.0005
CO_2*SPEF*WK	9	6.32	0.70	1.92	0.0464
TE*CO_2*SPEF*WK	18	15.18	0.84	2.31	0.0017
MC*CO_2*SPEF*WK	9	6.69	0.74	2.04	0.0335
TE*MC*CO_2*SPEF*WK	18	12.78	0.71	1.94	0.0111
Error	576	210.33	0.37		

* Class variables in column source are: TE is the temperature at 3 levels (15, 20, and 25°C), MC is the moisture content at 2 levels [dry (12% wb) and wet (15% wb)], CO_2 is carbon dioxide at 4 levels (0.03, 2, 5, and 10%), SPEF is species effect at 2 levels (alone or single-species and both or mixed-species), and WK is exposure time in weeks at 4 levels (2, 4, 6, and 8 wk).

Table D2 Combined analysis of variance with 5-way classification for adult survival (first and incubation counts) of *Tribolium castaneum* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	658.59	329.30	800.22	<.0001
MC	1	112.89	112.89	274.34	<.0001
TE*MC	2	29.34	14.67	35.65	<.0001
CO_2	3	423.44	141.15	343.00	<.0001
TE*CO_2	6	274.52	45.75	111.18	<.0001
MC*CO_2	3	20.60	6.87	16.69	<.0001
TE*MC*CO_2	6	79.93	13.32	32.37	<.0001
SPEF	1	330.49	330.49	803.12	<.0001
TE*SPEF	2	327.08	163.54	397.42	<.0001
MC*SPEF	1	10.10	10.10	24.54	<.0001
TE*MC*SPEF	2	26.37	13.19	32.04	<.0001
CO_2*SPEF	3	45.56	15.19	36.90	<.0001
TE*CO_2*SPEF	6	101.84	16.97	41.24	<.0001
MC*CO_2*SPEF	3	36.32	12.11	29.42	<.0001
TE*MC*CO_2*SPEF	6	39.52	6.59	16.01	<.0001
WK	3	59.04	19.68	47.82	<.0001
TE*WK	6	46.11	7.68	18.67	<.0001
MC*WK	3	52.15	17.38	42.24	<.0001
TE*MC*WK	6	28.10	4.68	11.38	<.0001
CO_2*WK	9	124.46	13.83	33.60	<.0001
TE*CO_2*WK	18	40.42	2.25	5.46	<.0001
MC*CO_2*WK	9	53.18	5.91	14.36	<.0001
TE*MC*CO_2*WK	18	40.98	2.28	5.53	<.0001
SPEF*WK	3	21.56	7.19	17.47	<.0001
TE*SPEF*WK	6	15.68	2.61	6.35	<.0001
MC*SPEF*WK	3	4.25	1.42	3.44	0.0166
TE*MC*SPEF*WK	6	16.80	2.80	6.80	<.0001
CO_2*SPEF*WK	9	6.67	0.74	1.80	0.0651
TE*CO_2*SPEF*WK	18	39.76	2.21	5.37	<.0001
MC*CO_2*SPEF*WK	9	10.04	1.12	2.71	0.0042
TE*MC*CO_2*SPEF*WK	18	30.10	1.67	4.06	<.0001
Error	576	237.03	0.41		

Refer Table D1 for explanation of class variables under the column source.

Table D3 Combined analysis of variance with 5-way classification for adults from first count of *Cryptolestes ferrugineus* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	5500.47	2750.24	90.30	<.0001
MC	1	34749.42	34749.42	1140.88	<.0001
TE*MC	2	11123.35	5561.68	182.60	<.0001
CO_2	3	79243.24	26414.41	867.23	<.0001
TE*CO_2	6	16999.39	2833.23	93.02	<.0001
MC*CO_2	3	2517.36	839.12	27.55	<.0001
TE*MC*CO_2	6	6325.18	1054.20	34.61	<.0001
SPEF	1	447.13	447.13	14.68	0.0001
TE*SPEF	2	70.71	35.35	1.16	0.3140
MC*SPEF	1	130.02	130.02	4.27	0.0393
TE*MC*SPEF	2	140.13	70.06	2.30	0.1011
CO_2*SPEF	3	330.59	110.20	3.62	0.0131
TE*CO_2*SPEF	6	1138.76	189.79	6.23	<.0001
MC*CO_2*SPEF	3	114.14	38.05	1.25	0.2911
TE*MC*CO_2*SPEF	6	521.34	86.89	2.85	0.0096
WK	3	26619.41	8873.14	291.32	<.0001
TE*WK	6	2841.98	473.66	15.55	<.0001
MC*WK	3	1515.23	505.08	16.58	<.0001
TE*MC*WK	6	3473.80	578.97	19.01	<.0001
CO_2*WK	9	3384.33	376.04	12.35	<.0001
TE*CO_2*WK	18	1246.16	69.23	2.27	0.0020
MC*CO_2*WK	9	1455.15	161.68	5.31	<.0001
TE*MC*CO_2*WK	18	2734.00	151.89	4.99	<.0001
SPEF*WK	3	203.92	67.97	2.23	0.0835
TE*SPEF*WK	6	216.12	36.02	1.18	0.3138
MC*SPEF*WK	3	220.55	73.52	2.41	0.0657
TE*MC*SPEF*WK	6	198.36	33.06	1.09	0.3697
CO_2*SPEF*WK	9	676.28	75.14	2.47	0.0091
TE*CO_2*SPEF*WK	18	1273.75	70.76	2.32	0.0016
MC*CO_2*SPEF*WK	9	448.04	49.78	1.63	0.1021
TE*MC*CO_2*SPEF*WK	18	648.17	36.01	1.18	0.2702
Error	576	17544.00	30.46		

Refer Table D1 for explanation of class variables under the column source.

Table D4 Combined analysis of variance with 5-way classification for adults from first count of *Tribolium castaneum* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	7007.00	3503.50	84.50	<.0001
MC	1	6440.33	6440.33	155.34	<.0001
TE*MC	2	3320.52	1660.26	40.04	<.0001
CO_2	3	26664.48	8888.16	214.38	<.0001
TE*CO_2	6	10903.38	1817.23	43.83	<.0001
MC*CO_2	3	2469.43	823.14	19.85	<.0001
TE*MC*CO_2	6	4491.41	748.57	18.06	<.0001
SPEF	1	11891.26	11891.26	286.81	<.0001
TE*SPEF	2	5823.75	2911.88	70.23	<.0001
MC*SPEF	1	154.08	154.08	3.72	0.0544
TE*MC*SPEF	2	657.83	328.92	7.93	0.0004
CO_2*SPEF	3	868.98	289.66	6.99	0.0001
TE*CO_2*SPEF	6	2313.70	385.62	9.30	<.0001
MC*CO_2*SPEF	3	389.01	129.67	3.13	0.0254
TE*MC*CO_2*SPEF	6	497.45	82.91	2.00	0.0639
WK	3	1710.72	570.24	13.75	<.0001
TE*WK	6	17365.67	2894.28	69.81	<.0001
MC*WK	3	7494.29	2498.10	60.25	<.0001
TE*MC*WK	6	1148.95	191.49	4.62	0.0001
CO_2*WK	9	21406.62	2378.51	57.37	<.0001
TE*CO_2*WK	18	8992.98	499.61	12.05	<.0001
MC*CO_2*WK	9	2847.36	316.37	7.63	<.0001
TE*MC*CO_2*WK	18	3124.08	173.56	4.19	<.0001
SPEF*WK	3	9040.93	3013.64	72.69	<.0001
TE*SPEF*WK	6	8423.28	1403.88	33.86	<.0001
MC*SPEF*WK	3	153.13	51.04	1.23	0.2976
TE*MC*SPEF*WK	6	960.99	160.17	3.86	0.0009
CO_2*SPEF*WK	9	3020.16	335.57	8.09	<.0001
TE*CO_2*SPEF*WK	18	8727.07	484.84	11.69	<.0001
MC*CO_2*SPEF*WK	9	155.36	17.26	0.42	0.9266
TE*MC*CO_2*SPEF*WK	18	1286.77	71.49	1.72	0.0316
Error	576	23881.00	41.46		

Refer Table D1 for explanation of class variables under the column source.

Table D5 Combined analysis of variance with 5-way classification for adults from incubation count of *Cryptolestes ferrugineus* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	2606.29	1303.14	2414.06	<.0001
MC	1	477.72	477.72	884.97	<.0001
TE*MC	2	172.80	86.40	160.05	<.0001
CO_2	3	729.03	243.01	450.18	<.0001
TE*CO_2	6	733.43	122.24	226.45	<.0001
MC*CO_2	3	38.58	12.86	23.83	<.0001
TE*MC*CO_2	6	64.89	10.82	20.04	<.0001
SPEF	1	32.85	32.85	60.85	<.0001
TE*SPEF	2	20.28	10.14	18.78	<.0001
MC*SPEF	1	5.91	5.91	10.95	0.0010
TE*MC*SPEF	2	6.88	3.44	6.37	0.0018
CO_2*SPEF	3	31.74	10.58	19.60	<.0001
TE*CO_2*SPEF	6	23.15	3.86	7.15	<.0001
MC*CO_2*SPEF	3	4.83	1.61	2.98	0.0309
TE*MC*CO_2*SPEF	6	40.47	6.75	12.50	<.0001
WK	3	98.46	32.82	60.80	<.0001
TE*WK	6	77.05	12.84	23.79	<.0001
MC*WK	3	19.84	6.61	12.25	<.0001
TE*MC*WK	6	22.68	3.78	7.00	<.0001
CO_2*WK	9	68.04	7.56	14.00	<.0001
TE*CO_2*WK	18	134.33	7.46	13.82	<.0001
MC*CO_2*WK	9	12.25	1.36	2.52	0.0077
TE*MC*CO_2*WK	18	36.35	2.02	3.74	<.0001
SPEF*WK	3	5.74	1.91	3.54	0.0145
TE*SPEF*WK	6	4.90	0.82	1.51	0.1718
MC*SPEF*WK	3	5.61	1.87	3.47	0.0161
TE*MC*SPEF*WK	6	26.15	4.36	8.07	<.0001
CO_2*SPEF*WK	9	5.63	0.63	1.16	0.3188
TE*CO_2*SPEF*WK	18	19.24	1.07	1.98	0.0093
MC*CO_2*SPEF*WK	9	8.59	0.95	1.77	0.0713
TE*MC*CO_2*SPEF*WK	18	13.12	0.73	1.35	0.1509
Error	576	310.93	0.54		

Refer Table D1 for explanation of class variables under the column source.

Table D6 Combined analysis of variance with 5-way classification for adults from incubation count of *Tribolium castaneum* using data from all the experimental tests.

Source*	DF	Type III SS	Mean Square	F Value	Pr > F
TE	2	3074.23	1537.12	2260.43	<.0001
MC	1	94.71	94.71	139.28	<.0001
TE*MC	2	112.16	56.08	82.47	<.0001
CO_2	3	407.58	135.86	199.79	<.0001
TE*CO_2	6	456.62	76.10	111.91	<.0001
MC*CO_2	3	8.41	2.80	4.12	0.0066
TE*MC*CO_2	6	6.87	1.15	1.68	0.1224
SPEF	1	702.71	702.71	1033.39	<.0001
TE*SPEF	2	758.22	379.11	557.51	<.0001
MC*SPEF	1	4.34	4.34	6.38	0.0118
TE*MC*SPEF	2	5.93	2.96	4.36	0.0132
CO_2*SPEF	3	109.30	36.43	53.58	<.0001
TE*CO_2*SPEF	6	110.70	18.45	27.13	<.0001
MC*CO_2*SPEF	3	73.78	24.59	36.17	<.0001
TE*MC*CO_2*SPEF	6	172.44	28.74	42.26	<.0001
WK	3	36.12	12.04	17.70	<.0001
TE*WK	6	82.06	13.68	20.11	<.0001
MC*WK	3	2.47	0.82	1.21	0.3047
TE*MC*WK	6	40.20	6.70	9.85	<.0001
CO_2*WK	9	10.59	1.18	1.73	0.0791
TE*CO_2*WK	18	81.41	4.52	6.65	<.0001
MC*CO_2*WK	9	6.73	0.75	1.10	0.3613
TE*MC*CO_2*WK	18	22.48	1.25	1.84	0.0187
SPEF*WK	3	5.43	1.81	2.66	0.0472
TE*SPEF*WK	6	30.32	5.05	7.43	<.0001
MC*SPEF*WK	3	2.72	0.91	1.33	0.2622
TE*MC*SPEF*WK	6	19.76	3.29	4.84	<.0001
CO_2*SPEF*WK	9	20.14	2.24	3.29	0.0006
TE*CO_2*SPEF*WK	18	62.38	3.47	5.10	<.0001
MC*CO_2*SPEF*WK	9	31.66	3.52	5.17	<.0001
TE*MC*CO_2*SPEF*WK	18	47.06	2.61	3.84	<.0001
Error	576	391.69	0.68		

Refer Table D1 for explanation of class variables under the column source.

Table D7 Type 3 tests of fixed effects from mixed model analysis of variance for the adults from first count of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Cryptolestes ferrugineus, dry (12% wb), single-species controls	TE	2	144	69.18	<.0001	15	16.401
	CO_2	3	144	224.49	<.0001	20	41.297
	CO_2*TE	6	144	13.69	<.0001	25	81.193
	WK	3	144	55.55	<.0001		
	WK*TE	6	144	6.32	<.0001		
	CO_2*WK	9	144	1.33	0.2254		
	CO_2*WK*TE	18	144	1.16	0.3046		
Cryptolestes ferrugineus, wet (15% wb), single-species controls	TE	2	144	88.15	<.0001	15	18.266
	CO_2	3	144	294.04	<.0001	20	9.974
	CO_2*TE	6	144	75.50	<.0001	25	21.198
	WK	3	144	85.56	<.0001		
	WK*TE	6	144	11.33	<.0001		
	CO_2*WK	9	144	14.17	<.0001		
	CO_2*WK*TE	18	144	5.59	<.0001		
Cryptolestes ferrugineus, dry (12% wb), mixed-species combination	TE	2	144	55.19	<.0001	15	56.224
	CO_2	3	144	179.67	<.0001	20	39.682
	CO_2*TE	6	144	21.76	<.0001	25	35.542
	WK	3	144	96.69	<.0001		
	WK*TE	6	144	10.31	<.0001		
	CO_2*WK	9	144	3.20	0.0015		
	CO_2*WK*TE	18	144	2.48	0.0015		
Cryptolestes ferrugineus, wet (15% wb), mixed-species combination	TE	2	144	135.95	<.0001	15	17.340
	CO_2	3	144	281.51	<.0001	20	12.270
	CO_2*TE	6	144	79.25	<.0001	25	16.140
	WK	3	144	85.38	<.0001		
	WK*TE	6	144	9.22	<.0001		
	CO_2*WK	9	144	14.90	<.0001		
	CO_2*WK*TE	18	144	4.68	<.0001		

Refer Table D1 for explanation of class variables under the column effect.

Table D8 Type 3 tests of fixed effects from mixed model analysis of variance for the adults from first count of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Tribolium castaneum, dry (12% wb), single-species controls	TE	2	144	77.73	<.0001	15	14.938
	CO_2	3	144	88.24	<.0001	20	18.208
	CO_2*TE	6	144	22.33	<.0001	25	96.438
	WK	3	144	4.37	0.0056		
	WK*TE	6	144	33.17	<.0001		
	CO_2*WK	9	144	37.15	<.0001		
	CO_2*WK*TE	18	144	9.40	<.0001		
Tribolium castaneum, wet (15% wb), single-species controls	TE	2	144	31.52	<.0001	15	6.323
	CO_2	3	144	26.79	<.0001	20	15.167
	CO_2*TE	6	144	16.62	<.0001	25	147.350
	WK	3	144	41.22	<.0001		
	WK*TE	6	144	29.61	<.0001		
	CO_2*WK	9	144	10.20	<.0001		
	CO_2*WK*TE	18	144	5.89	<.0001		
Tribolium castaneum, dry (12% wb), mixed-species combination	TE	2	144	21.14	<.0001	15	91.401
	CO_2	3	144	70.88	<.0001	20	16.896
	CO_2*TE	6	144	5.91	<.0001	25	62.365
	WK	3	144	59.09	<.0001		
	WK*TE	6	144	3.03	0.0081		
	CO_2*WK	9	144	12.47	<.0001		
	CO_2*WK*TE	18	144	3.51	<.0001		
Tribolium castaneum, wet (15% wb), mixed-species combination	TE	2	144	56.65	<.0001	15	11.073
	CO_2	3	144	82.26	<.0001	20	5.005
	CO_2*TE	6	144	63.94	<.0001	25	12.354
	WK	3	144	27.75	<.0001		
	WK*TE	6	144	4.44	0.0004		
	CO_2*WK	9	144	16.81	<.0001		
	CO_2*WK*TE	18	144	4.86	<.0001		

Refer Table D1 for explanation of class variables under the column effect.

Table D9 Type 3 tests of fixed effects from mixed model analysis of variance for the adults from incubation count of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Cryptolestes ferrugineus, dry (12% wb), single-species controls	TE	2	144	459.13	<.0001	15	0.031
	CO_2	3	144	92.59	<.0001	20	0.226
	CO_2*TE	6	144	50.72	<.0001	25	1.172
	WK	3	144	5.91	0.0008		
	WK*TE	6	144	4.27	0.0005		
	CO_2*WK	9	144	1.73	0.0864		
	CO_2*WK*TE	18	144	2.19	0.0057		
Cryptolestes ferrugineus, wet (15% wb), single-species controls	TE	2	144	1559.74	<.0001	15	0.180
	CO_2	3	144	294.03	<.0001	20	0.488
	CO_2*TE	6	144	164.65	<.0001	25	0.635
	WK	3	144	64.05	<.0001		
	WK*TE	6	144	31.48	<.0001		
	CO_2*WK	9	144	10.67	<.0001		
	CO_2*WK*TE	18	144	9.47	<.0001		
Cryptolestes ferrugineus†, dry (12% wb), mixed-species combination	TE	2	144				
	CO_2	3	144				
	CO_2*TE	6	144				
	WK	3	144				
	WK*TE	6	144				
	CO_2*WK	9	144				
	CO_2*WK*TE	18	144				
Cryptolestes ferrugineus, wet (15% wb), mixed-species combination	TE	2	144	1858.73	<.0001	15	0.196
	CO_2	3	144	152.09	<.0001	20	0.816
	CO_2*TE	6	144	104.34	<.0001	25	0.247
	WK	3	144	21.90	<.0001		
	WK*TE	6	144	17.01	<.0001		
	CO_2*WK	9	144	5.50	<.0001		
	CO_2*WK*TE	18	144	7.94	<.0001		

† Analysis failed due to zero or negligible incubation count at 15 and 20°C.
Refer Table D1 for explanation of class variables under the column effect.

Table D10 Type 3 tests of fixed effects from mixed model analysis of variance for the adults from incubation count of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Tribolium castaneum, dry (12% wb), single-species controls	TE	2	144	453.60	<.0001	15	0.078
	CO_2	3	144	40.64	<.0001	20	0.358
	CO_2*TE	6	144	27.05	<.0001	25	2.603
	WK	3	144	5.11	0.0022		
	WK*TE	6	144	4.03	0.0009		
	CO_2*WK	9	144	1.20	0.2966		
	CO_2*WK*TE	18	144	3.56	<.0001		
Tribolium castaneum, wet (15% wb), single-species controls	TE	2	144	858.35	<.0001	15	0.126
	CO_2	3	144	130.62	<.0001	20	0.610
	CO_2*TE	6	144	67.80	<.0001	25	2.283
	WK	3	144	6.74	0.0003		
	WK*TE	6	144	17.88	<.0001		
	CO_2*WK	9	144	3.90	0.0002		
	CO_2*WK*TE	18	144	5.48	<.0001		
Tribolium castaneum†, dry (12% wb), mixed-species combination	TE	2	144				
	CO_2	3	144				
	CO_2*TE	6	144				
	WK	3	144				
	WK*TE	6	144				
	CO_2*WK	9	144				
	CO_2*WK*TE	18	144				
Tribolium castaneum, wet (15% wb), mixed-species combination	TE	2	144	436.32	<.0001	15	0.016
	CO_2	3	144	11.84	<.0001	20	0.205
	CO_2*TE	6	144	9.77	<.0001	25	0.635
	WK	3	144	11.59	<.0001		
	WK*TE	6	144	11.77	<.0001		
	CO_2*WK	9	144	5.69	<.0001		
	CO_2*WK*TE	18	144	4.31	<.0001		

† Analysis failed due to zero or negligible incubation count at 15 and 20°C.
Refer Table D1 for explanation of class variables under the column effect.

Table D11 Type 3 tests of fixed effects from mixed model analysis of variance for the adult survival (first and incubation counts) of *Cryptolestes ferrugineus* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Cryptolestes ferrugineus, dry (12% wb), single-species controls	TE	2	144	68.82	<.0001	15	0.167
	CO_2	3	144	167.21	<.0001	20	0.058
	CO_2*TE	6	144	21.40	<.0001	25	0.069
	WK	3	144	31.52	<.0001		
	WK*TE	6	144	6.23	<.0001		
	CO_2*WK	9	144	7.49	<.0001		
	CO_2*WK*TE	18	144	2.20	0.0054		
Cryptolestes ferrugineus, wet (15% wb), single-species controls	TE	2	144	223.05	<.0001	15	0.007
	CO_2	3	144	469.49	<.0001	20	0.007
	CO_2*TE	6	144	116.50	<.0001	25	0.018
	WK	3	144	76.02	<.0001		
	WK*TE	6	144	11.93	<.0001		
	CO_2*WK	9	144	18.87	<.0001		
	CO_2*WK*TE	18	144	10.16	<.0001		
Cryptolestes ferrugineus, dry (12% wb), mixed-species combination	TE	2	144	87.27	<.0001	15	0.250
	CO_2	3	144	122.55	<.0001	20	0.027
	CO_2*TE	6	144	32.42	<.0001	25	0.118
	WK	3	144	44.41	<.0001		
	WK*TE	6	144	11.09	<.0001		
	CO_2*WK	9	144	4.11	<.0001		
	CO_2*WK*TE	18	144	3.02	0.0001		
Cryptolestes ferrugineus, wet (15% wb), mixed-species combination	TE	2	144	97.76	<.0001	15	0.010
	CO_2	3	144	319.83	<.0001	20	0.013
	CO_2*TE	6	144	84.00	<.0001	25	0.010
	WK	3	144	45.59	<.0001		
	WK*TE	6	144	11.11	<.0001		
	CO_2*WK	9	144	16.48	<.0001		
	CO_2*WK*TE	18	144	7.48	<.0001		

Refer Table D1 for explanation of class variables under the column effect.

Table D12 Type 3 tests of fixed effects from mixed model analysis of variance for the adult survival (first and incubation counts) of *Tribolium castaneum* in dry (12% wb) and wet (15% wb) grain in single and mixed species experimental tests.

Population category	Type 3 tests of fixed effects					Covariance parameter estimates	
	Effect	Num DF	Den DF	F Value	Pr > F	Temp (°C)	Residual
Tribolium castaneum, dry (12% wb), single-species controls	TE	2	144	151.36	<.0001	15	0.072
	CO_2	3	144	96.72	<.0001	20	0.007
	CO_2*TE	6	144	29.00	<.0001	25	0.066
	WK	3	144	42.49	<.0001		
	WK*TE	6	144	21.93	<.0001		
	CO_2*WK	9	144	34.57	<.0001		
	CO_2*WK*TE	18	144	18.54	<.0001		
Tribolium castaneum, wet (15% wb), single-species controls	TE	2	144	449.09	<.0001	15	0.002
	CO_2	3	144	123.12	<.0001	20	0.007
	CO_2*TE	6	144	65.90	<.0001	25	0.037
	WK	3	144	3.56	0.0160		
	WK*TE	6	144	11.95	<.0001		
	CO_2*WK	9	144	4.09	0.0001		
	CO_2*WK*TE	18	144	3.37	<.0001		
Tribolium castaneum, dry (12% wb), mixed-species combination	TE	2	144	18.86	<.0001	15	0.232
	CO_2	3	144	44.01	<.0001	20	0.173
	CO_2*TE	6	144	6.90	<.0001	25	0.047
	WK	3	144	38.34	<.0001		
	WK*TE	6	144	7.25	<.0001		
	CO_2*WK	9	144	18.72	<.0001		
	CO_2*WK*TE	18	144	4.42	<.0001		
Tribolium castaneum, wet (15% wb), mixed-species combination	TE	2	144	68.72	<.0001	15	0.003
	CO_2	3	144	60.42	<.0001	20	0.002
	CO_2*TE	6	144	32.86	<.0001	25	0.010
	WK	3	144	31.10	<.0001		
	WK*TE	6	144	4.34	0.0005		
	CO_2*WK	9	144	5.88	<.0001		
	CO_2*WK*TE	18	144	2.69	0.0006		

Refer Table D1 for explanation of class variables under the column effect.