HGCA

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THE CONTROL OF INSECTS IN EXPORT GRAIN BY ADMIXTURE CHEMICALS

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THE CONTROL OF INSECTS IN EXPORT GRAIN BY ADMIXTURE CHEMICALS

by

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SUMMARY

For many years cargoes of grain exported from the United Kingdom have been accompanied by either trade-sourced certificates of quality, or Ministry of Agriculture, Fisheries and Food, Phytosanitary Certificates. These are not interchangeable. The Phytosanitary certificates are only required when the government of the importing country insists on the cargo complying with its quarantine procedures under International Plant Health regulations.

To achieve "freedom from live [invertebrate] pests", required under both trade and government quality procedures, many cargoes are sprayed with admixture (contact) insecticides, a recognised method of disinfestation for inland stored grain. However, despite earlier HGCA-funded research, there are many gaps in our knowledge concerning the effects of these insecticides on several species in cold grain over extended exposure periods. This project addresses these questions.

Six species of beetles, representing common grain and food storage pests on various international quarantine lists, were placed on separately-sprayed batches of grain, using three UK-approved admixture insecticides, and looked at (as separate replicates) every two-days over 28 days. A total of 13,440 insects were used in over 4,000 replicates, and the test temperatures, attempting to simulate winter grain exports, were 10, 7.5, 5 and 3°C.

The insects showed varying abilities to withstand low temperatures: there was some survival in all species at 10 and 7.5°C, but only the grain weevil and rust-red grain beetle showed survival at both 5 and 3°C, by the end of the trial.

Exposure to each of the insecticides speeded up 100% kill at all temperatures, except at 3°C. Here, the effects of natural mortality and insecticidal action are not clearly defined but, again, in all cases, 100% kill was achieved by the end of the experiment.

There is considerable variation of reaction between the six species of insects, the three insecticides and the four temperatures. Traders or inspectors referring to these results for guidance in dockside situations must ensure that insect identifications are correct, and that average grain cargo temperatures are obtained from frequent monitoring, before estimating the effects during that particular voyage.

THE CONTROL OF INSECTS IN EXPORT GRAIN

BY ADMIXTURE CHEMICALS

1. BACKGROUND

Between 5 and 6 million tonnes of British grain are exported each year, from a large number of ports, to many overseas destinations. For some of this grain, Ministry of Agriculture, Fisheries and Food *Phytosanitary Certificates* are required to satisfy the import regulations of the governments of the importing countries. For other destinations, trade certificates of quality are needed, and both types of certificates are used by overseas banks as an important part of the documentation against which payment for the cargo is made.

The issue of either certificate is dependent upon the results of dockside assessments by inspectors, although MAFF Inspectors are guided by *international plant health* regulations, which are designed to be rigidly applied. For many years the discovery, by MAFF Inspectors, of *quarantine pests*, in any number, was sufficient to preclude the issue of a Certificate. In more recent times, and after extensive discussions with the exporters, based on HGCA Project Report No 6 "The Control of Insects in Export Grain", by D R Wilkin and D G Rowlands (available from HGCA for £5.00, postage and Packing inclusive), MAFF has modified its procedures to take account of the use of admixture pesticides applied at the time of loading. As a result, MAFF Inspectors are now required to judge the likely effects of the dockside application of approved insecticides, on insect species discovered during inspection of the grain being loaded.

The considerable difficulties involved in such estimates result from the lack of objective information on a number of fronts: the many different application techniques used; the particular way each insect species reacts to the chosen insecticide at a range of low temperatures; the results of prolonged exposures to insecticide-treated grain typified by many sea voyages.

2. BENEFITS TO GRAIN EXPORTING COMPANIES AND MAFF

The present document reports the results of an experiment designed to provide comprehensive data on the efficacy of admixture pesticides at low temperatures. Previous research, whilst involving some constraints, produced results of value

to MAFF and the export grain trade. The results produced, and the conclusions reached, from the present project, will be of considerable assistance to both the MAFF Inspectors, for the issue of Phytosanitary Certificates, and to the UK Grain Exporters. The latter will be able to make considered judgements on the benefits of sanctioning admixture treatments, and the serious financial risks of Certificate "clausing", or even refusal, should be greatly reduced.

The present system of inspections and rejected grain, or claused/refused certificates, costs the export industry considerable, but not quantified, sums each year. Additionally, there are occasions where an export shipment is delayed at the port of destination while protracted negotiations are undertaken to resolve the problems of claused or otherwise modified certificates, caused by the discovery of live quarantine or other serious grain pests at the time of loading. If the dockside inspectors had access to authoritative information on the effectiveness of the pesticide being applied to the cargo much, if not all, of this expensive delay could be avoided, to the benefit of the traders, and therefore, to the whole UK grain industry.

3. PROGRAMME OF RESEARCH

a) Objectives

To evaluate the effectiveness at low temperatures of three organophosphorus pesticides admixed with wheat, on six important insect pests of export grain. The evaluations were extended for a 28-day period to simulate the effects of prolonged exposure during a typical winter export sea voyage.

b) Materials

i) Grain: English wheat, variety Mercia, with a moisture content between 14 and 15% (determined by BS 4317:3:1987), was used. The grain, initially assessed as free from pesticide residues, was sieved before use.

ii) Insects: where possible, strains of insects shown in laboratory tests to exhibit some resistant to organophosphorus pesticides were used. Four primary grain pests, a major food storage pest, and a common grain storage species frequently the cause of rejections, were used. They were selected for their significance in UK grain storage, and for their presence on the quarantine lists of many overseas countries. The species are as follows:

Sitophilus granarius (grain weevil)
Sitophilus oryzae (rice weevil)
Oryzaephilus surinamensis (saw-toothed grain beetle)
Cryptolestes ferrugineus (rust-red grain beetle)
Tribolium castaneum (rust-red flour beetle)
Ahasverus advena (foreign grain beetle)

The insects had been bred up in the laboratory at 25°C and 70%rh, with the exception of *Cryptolestes*, which had been reared at 30°C and 70%rh. The resistance status of the insects used (2 - 4 week-old adults) is given in Table 8.

iii) Insecticides: emulsifiable concentrates of pirimiphos-methyl (Actellic - 25% ai), etrimfos (Satisfar - 50% ai) and chlorpyrifos methyl (Reldan - 50% ai), supplied as commercial formulations, were used for the trial. These were diluted in distilled water according to the manufacturers' label recommendations, and applied at the following approved (under the 1986 Control of Pesticides Regulations) application rates:-

pirimiphos-methyl	4.0	mg/kg
etrimfos	4.0	mg/kg
chlorpyrifos methyl	4.5	mg/kg

c) Methods

i) Acclimatisation of Insects: the test insect cultures were left to acclimatise for 2 days at the appropriate test temperatures. Sufficient insects were available to compensate for mortality during acclimatisation.

ii) Treatment of Grain: Each insecticide was applied, using a hand-held paint spray gun, to grain as it was tumbled in a concrete mixer. The grain was tumbled for a further 5 minutes after treatment to ensure thorough mixing. (CSL Operating Procedure *PPI 011*)

Immediately after tumbling, samples of the treated grain were removed for biological assays and chemical analysis.

iii) Preparation of Bioassays: For the insect bioassays, 3 jars for each species/insecticide/temperature combination, plus 3 control jars per species/temperature combination were set up. Sufficient jars were prepared to enable a separate set of 3 replicates to be assessed at 2-day intervals, for a 28-day exposure period, or until 2 consecutive 100% mortality counts were achieved, whichever was the sooner.

For each replicate, 50 g aliquots of each batch of treated grain were placed in 120 ml wide-necked glass jars, the inside necks of which had been treated with PTFE suspension to prevent the escape of insects. Fifty gram aliquots of untreated grain were similarly prepared as controls.

The appropriate numbers of jars of grain were conditioned overnight at the test temperatures: 3, 5, 7.5 and 10°C. For grain at 14 - 15% moisture content, this was sufficient low temperature exposure to allow equilibrium to be reached.

Batches of 20 insects were counted from the cultures and each batch transferred to a jar of grain.

iv) Bioassay Assessment

For each assessment, the appropriate number of jars was removed from the test temperatures and kept at a laboratory temperature of around 25°C for about 1 hour. Assessments were then made by tipping the grain from each jar in turn onto a white tray and recording the responses as follows:

Live: able to walk more or less normally.

Dead: no movement or occasional sporadic twitching of appendages.

Note: earlier work, reported in HGCA Project Report No. 6, was carried out over a 10 day exposure period, with mortality assessed daily. The present research extended the exposure period to 28 days, to simulate longer sea voyages, with mortality assessments every two days. Experience with other low-temperature research work has shown that mortality can be difficult to assess accurately. Therefore this project adopted the "safer" view that 100% kill would be recorded only on the second consecutive 100% mortality count. The tables reproduced at the end of this report show that it is possible for a batch of replicates to indicate 100% kill, but that the subsequent batch may be less than 100%. Thus two consecutive 100% motality counts is likely to be the more reliable assessment of complete kill. However, with this method of assessment, it is possible that complete kill may have occurred in some test lots one or two days before the second 100% mortality count.

4. RESULTS

a) Pesticide Residues

The organophosphorus pesticides were applied to the grain at the approved (labelled) rates. Samples of grain were removed after treatment for residue analysis. The intended application rates, and the residues detected, are given below:

Pesticide	Intended Application Rate	Residue detected (± 10%)
pirimiphos-methyl	4.0 mg/kg	3.63 mg/kg
chlorpyrifos methyl	4.5 mg/kg	5.02 mg/kg
etrimfos	4.0 mg/kg	3.34 mg/kg

Experience in many other experiments would suggest that the residues of pirimiphos-methyl and etrimfos, as detected, are

in line with the losses to be expected in normal, careful, application. The slightly higher-than-expected residue of chlorpyrifos methyl may be due to sampling and/or residue analysis variation.

The experimental results are given in Tables 1 to 6 and Figures 1 to 6, and are summarised in Table 7.

b) Insect Responses

See also **Table 8 - $KD_{99.9}$ Values: 1 HOUR EXPOSURES ON TREATED FILTER PAPERS**

i) ***Sitophilus granarius***

In the untreated controls, a proportion of the test insects survived the full 28 days at each of the temperatures. At 28 days, the mortality in these insects rose from 2% at 10°C to 87% at 3°C.

In the presence of insecticide, 100% kill occurred within 10 days at 10°C for both primiphos-methyl and etrimfos, and within 4 days for chlorpyrifos methyl. At 3°C the exposure time needed for 100% kill increased to 22 - 26 days.

The greater sensitivity of this insect strain to chlorpyrifos methyl was clearly evident in the tests at 5°C and above, but was substantially reduced at 3°C, where there was little difference between the insecticides in the time to 100% kill.

ii) ***Sitophilus oryzae***

This species was much less tolerant of the cold than was *S. granarius*. All control insects died within 6 days at 3°C and within 20 days at 5°C.

There was little difference between the three insecticides in the time to 100% kill. The time increased, from 8 - 10 days at 10°C, to 14 - 16 days at 5°C. However, at 3°C the time fell to 6 - 8 days, equal to that of the unexposed, control insects.

The $KD_{99.9}$s for this species were reflected in the results: the time taken for 100% kill was similar for chlorpyrifos methyl and etrimfos, but about 2 days longer for pirimiphos-methyl.

iii) ***Oryzaephilus surinamensis***

A proportion of the insects on untreated grain survived for the full 28 days at all temperatures except at 3°C, where there was complete mortality within 16 days.

The results for the primiphos-methyl and chlorpyrifos methyl treatments were identical, with 100% kill occurring within four days at 10°C, increasing to 12 days at 3°C. The etrimfos treatment resulted in 100% kill within four days at all temperatures except 3°C, where it took 8 days.

Despite the higher $KD_{99.9}$ for pirimiphos-methyl, this was not apparent in the results for the time to achieve 100% kill.

iv) *Cryptolestes ferrugineus*

At all four test temperatures a proportion of the control insects survived for the full 28 days, with mortality increasing from about 10% at 10°C and 7.5°C, to 82% at 3°C.

The results for pirimiphos-methyl and etrimfos show that at 5°C and 7.5°C both treatments achieved 100% kill within 6 days. At 3°C the time for etrimfos remained at 6 days whilst that for pirimiphos-methyl increased to 26 days. At the higher temperature of 10°C, 100% kill occurred within 4 days with etrimfos, but with pirimiphos-methyl the time increased to 12 days - twice that recorded for 7.5°C. This result with pirimiphos-methyl should be viewed with some caution, since a single 100% mortality figure had been recorded earlier, at 4 days.

The $KD_{99.9}$ values for this strain of *Cryptolestes*, in relation to this trial, show it to be most sensitive to etrimfos, and least sensitive to pirimiphos-methyl. The present results show chlorpyrifos methyl to be much less effective at low temperatures.

v) *Tribolium castaneum*

At 28 days the mortality of the control insects was 7% at 10°C and 92% at 7.5°C. All insects died within 24 days at 5°C, and within 12 days at 3°C.

At 10°C, chlorpyrifos methyl achieved 100% kill within 6 days, pirimiphos-methyl within 8 days and etrimfos within 10 days. At 7.5°C the results were the same except for pirimiphos-methyl, where the time increased to 14 days. At 5°C the time increased with chlorpyrifos methyl (10 days) and etrimfos (16 days), but decreased slightly with pirimiphos-methyl (12 days). At 3°C all times decreased by 2 - 4 days, to 8 - 10 days, in line with the 12 days taken for control insects to die at this temperature.

The $KD_{99.9}$s were borne out in the trial. Chlorpyrifos methyl achieved the shortest time to 100% kill at each temperature, although pirimiphos-methyl has the lowest $LD_{99.9}$.

vi) *Ahasverus advena*

This species showed high mortality in the control insects at day 28: 97% dead at 10°C, 95% at 7.5°C. Complete mortality occurred within 20 days at 5°C, and at about 16 days at 3°C.

In all insecticide tests 100% kill occurred within 4 days (the shortest time possible with two consecutive counts), except for chlorpyrifos methyl at 3°C, where the time increased to 10 days.

The differences in $KD_{99.9}$ values were not reflected in the test results.

5. DISCUSSION

With a large number of individual species/pesticide/ temperature combinations, simple generalisations are difficult to make. The results demonstrate the marked differences in the ability of different storage pest beetle species to withstand temperatures well below their thresholds for development. The data also show the extent to which the effectiveness of insecticide treatments can be reduced at low temperatures. It appears that, in some species at least, this loss of efficacy is offset by natural mortality at very low temperatures.

By the end of the experiment, all of the test insects on treated grain had been controlled, indicating that, on long sea voyages, the choice of chemical may be less critical than the quality of the insecticide spray application. However, small (2°C) changes in temperature can have a dramatic effect on the success of a treatment, and this effect varies with the species and the pesticide. For example, *Oryzaephilus* was controlled in 12 days or less by all three insecticides at all four temperatures. *Sitophilus granarius* required 22 - 26 days exposure to insecticide at 3°C, but the closely-related *Sitophilus oryzae*, under similar conditions, succumbed within 8 days, (correct identification of the pest therefore being critical). The temperature of the grain would be an increasingly important factor the shorter the voyage, since some of the species were controlled only at, or towards, the end of the 28-day exposure period, at the lower temperatures.

It can be seen, from Table 7, that chlorpyrifos methyl consistently achieves 100% kill most rapidly against *Sitophilus granarius* and *Tribolium castaneum*, but is not the quickest against *S. oryzae*. Etrimfos appears the most rapid insecticide against *Oryzaephilus surinamensis* and *Cryptolestes ferrugineus* at most temperatures, but, except at 3°C, all test insecticides appeared to work equally well against *Ahasverus advena*.

At individual (test) temperatures the speed of action of each insecticide against the spectrum of insect species is less consistent. However, in the range of circumstances as covered in this experiment, etrimfos gave the most rapid control overall.

6. CONCLUSIONS

An initial note of caution must be sounded regarding the use of these data. The test insects were all laboratory-reared strains, conditioned over many generations to 25 or 30°C. Their reactions to the low test temperatures may not be typical of "field" populations of these species.

In practice an exporter will have chosen the pesticide, (or the choice may have been dictated by the contract), before loading takes place. The species of insect pest will not be known in advance and, in any case, the spray admixture will often be done prophylactically. Therefore, the information in the tables and graphs may be of greatest use in predicting the likely outcome of a pre-arranged pesticide spray operation once pests have been discovered and identified, and the range of grain temperatures for that cargo has been established by sampling during loading.

For the longer sea voyages, over three weeks in duration, there is little to guide the selection of a pesticide, and availability and cost may be more important factors.

For shorter voyages, especially carrying grain which is likely to be very cold, as is often the case late in the winter, etrimfos appears, on average, to offer the fastest kill times against the widest range of species.

An example of the practical use of these data can be given. If etrimfos were to be used as a prophylactic spray treatment of export grain, the results of this experiment would indicate that the voyage length, after application of the insecticide, would need to be at least 26 days to kill *Sitophilus granarius* in very cold grain (3°C), but that *Cryptolestes* and *Oryzaephilus* should be killed in about a week at the same temperature. It is interesting that our experimental controls for these species showed less than 100% mortality under the conditions in this example.

Once the choice of insecticide has been made, the results and interpretations in this report will enable those involved in the export and certification of British grain to suggest, with some confidence, the fate of the majority of insect species discovered at the point of loading. Unanswered

questions will then relate to the resistance status of insects discovered in sampling, the efficacy of the insecticide application system, and the possible effects on insect mortality caused by grain conveying systems. The latter is the subject of current HGCA research. In view of the known variations of application, and the equally well-known losses during application, these will become important factors to be considered in any future review of export grain practices.

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M P Kelly,

Table 1. Mean percentage mortality of *S. granarius* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	0 (0.0)	0 (0.0)	2 (2.2)	8 (2.4)	37 (9.8)	44 (11.1)	7 (4.7)	59 (7.5)	63 (8.5)	38 (13.6)	77 (8.5)	77 (2.8)	66 (2.2)	87 (2.4)
	PM	17 (4.5)	2 (2.5)	2 (2.4)	50 (7.1)	92 (6.2)	75 (4.1)	93 (2.4)	97 (4.7)	90 (4.1)	92 (8.5)	100 (0.0)	100 (0.0)	–	–
	CPM	14 (9.5)	88 (4.7)	80 (4.1)	100 (0.0)	97 (2.4)	100 (0.0)	97 (2.3)	100 (0.0)	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–
	ETR	10 (7.3)	25 (4.1)	38 (6.2)	55 (10.8)	83 (1.7)	88 (3.5)	75 (4.7)	83 (2.4)	90 (7.3)	92 (4.7)	95 (4.3)	100 (0.0)	100 (0.0)	–
5	Control	3 (2.4)	2 (2.4)	23 (2.4)	12 (10.3)	30 (12.2)	30 (4.1)	43 (10.3)	39 (7.4)	53 (6.9)	42 (7.2)	73 (13.1)	49 (5.0)	57 (4.7)	72 (8.5)
	PM	7 (2.6)	68 (2.4)	50 (8.2)	85 (4.1)	100 (0.0)	89 (1.0)	87 (9.4)	* (*)	95 (6.7)	98 (2.4)	100 (0.0)	100 (0.0)	–	–
	CPM	5 (7.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	0 (0.0)	43 (2.4)	80 (6.8)	88 (8.5)	100 (0.0)	92 (6.2)	95 (4.1)	100 (0.0)	100 (0.0)	–	–	–	–	–

Table 1. (continued- *S. granarius*)

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	0 (0.0)	2 (2.4)	0 (0.0)	5 (0.1)	13 (8.5)	20 (9.4)	8 (2.4)	12 (6.2)	42 (11.8)	22 (4.7)	* (*)	17 (8.9)	40 (8.2)	28 (8.5)
	PM	2 (2.4)	45 (12.2)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
	CPM	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	2 (2.4)	83 (6.2)	95 (4.1)	93 (2.4)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–
10	Control	0 (0.0)	2 (2.4)	0 (0.0)	0 (0.0)	5 (4.1)	0 (0.0)	0 (0.0)	0 (0.0)	13 (6.2)	3 (2.4)	0 (0.0)	0 (0.0)	2 (2.4)	2 (2.4)
	PM	5 (4.1)	85 (8.2)	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	15 (4.1)	88 (10.3)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–

- denotes where counts were discontinued, 100% having been reached
* denotes where replicates were not able to be assessed
Figures in parenthesis are standard deviations about the mean value.

Table 2. Mean percentage mortality of *S. oryzae* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	62 (10.3)	100 (0.0)	100 (0.0)	100 (0.0)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	PM	53 (2.0)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
	CPM	88 (6.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	60 (7.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
5	Control	0 (0.0)	0 (0.0)	5 (4.1)	25 (10.8)	52 (13.1)	72 (9.3)	97 (2.4)	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–
	PM	2 (2.5)	8 (2.4)	34 (2.9)	67 (6.2)	98 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–
	CPM	63 (2.4)	67 (8.5)	88 (6.2)	85 (7.1)	92 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–
	ETR	28 (2.4)	48 (15.5)	93 (4.7)	90 (0.0)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–

Table 2. (continued- *S. oryzae*)

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (4.7)	3 (2.4)	8 (2.4)	23 (9.4)	58 (12.5)	82 (4.7)	91 (6.5)	85 (10.8)	93 (9.4)	98 (2.5)
	PM	2 (2.4)	25 (7.1)	43 (6.2)	87 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–
	CPM	32 (10.3)	90 (4.3)	93 (5.0)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	ETR	35 (8.7)	97 (4.7)	95 (4.1)	97 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–
10	Control	0 (0.0)	0 (0.0)	5 (4.1)	0 (0.0)	0 (0.0)	5 (0.0)	6 (5.9)	7 (2.4)	4 (5.0)	10 (8.2)	19 (4.5)	15 (4.1)	18 (6.2)	27 (5.9)
	PM	3 (2.4)	84 (1.9)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
	CPM	40 (13.6)	87 (6.2)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
	ETR	51 (3.1)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–

- denotes where counts were discontinued, 100% having been reached
* denotes where replicates were not able to be assessed
Figures in parenthesis are standard deviations about the mean value.

Table 3. Mean percentage mortality of *O. surinamensis* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	32 (8.2)	44 (29.8)	83 (4.9)	61 (19.0)	100 (0.0)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–
	PM	86 (5.8)	93 (4.7)	98 (2.4)	95 (4.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	CPM	53 (7.7)	82 (8.6)	92 (4.1)	97 (2.3)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	ETR	98 (2.1)	98 (2.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
5	Control	2 (2.4)	7 (2.4)	28 (12.0)	41 (9.2)	40 (7.1)	52 (3.6)	65 (7.6)	90 (7.1)	97 (4.7)	90 (4.1)	95 (4.3)	88 (9.4)	98 (2.4)	98 (2.4)
	PM	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	CPM	68 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–

Table 3. (continued- *O. surinamensis*)

Temp (oC)	Pesticide	2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	7 (6.2)	0 (0.0)	8 (4.7)	8 (2.1)	23 (5.6)	10 (4.1)	33 (15.7)	53 (4.7)	40 (0.0)	52 (6.2)	* (*)	54 (1.0)	58 (10.3)	42 (8.5)
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
10	Control	0 (0.0)	2 (2.2)	8 (4.7)	10 (6.9)	12 (6.2)	10 (0.2)	10 (10.8)	16 (2.5)	23 (15.2)	15 (7.1)	13 (9.2)	25 (7.1)	23 (2.4)	26 (1.1)
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–

- denotes where counts were discontinued, 100% having been reached
* denotes where replicates were not able to be assessed.
Figures in parenthesis are standard deviations about the mean value.

Table 4. Mean percentage mortality of *C. ferrugineus* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	2 (2.2)	0 (0.0)	12 (8.5)	12 (9.4)	44 (26.8)	19 (9.2)	23 (2.4)	38 (9.4)	41 (2.9)	61 (0.0)	43 (4.7)	46 (7.8)	57 (6.2)	82 (12.5)
	PM	20 (10.6)	100 (0.0)	87 (4.5)	85 (4.1)	77 (8.5)	60 (12.2)	93 (2.4)	98 (2.4)	93 (2.4)	97 (4.7)	98 (2.5)	100 (0.0)	100 (0.0)	–
	CPM	23 (26.2)	43 (4.7)	37 (9.2)	66 (2.9)	95 (7.1)	90 (3.8)	80 (7.1)	97 (2.4)	88 (6.2)	* (*)	93 (6.2)	97 (2.4)	100 (0.0)	100 (0.0)
	ETR	90 (8.2)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
5	Control	2 (2.4)	2 (2.4)	7 (2.3)	* (*)	0 (0.0)	14 (2.1)	17 (13.2)	20 (8.2)	38 (4.7)	53 (6.3)	29 (10.0)	40 (4.1)	22 (2.4)	22 (2.4)
	PM	85 (8.2)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	CPM	4 (2.9)	23 (13.0)	43 (15.5)	* (*)	77 (4.7)	76 (13.4)	98 (2.4)	98 (2.4)	98 (2.5)	100 (0.0)	98 (2.5)	100 (0.0)	100 (0.0)	–
	ETR	78 (8.3)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–

Table 4. (continued- *C. ferrugineus*)

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	0 (0.0)	0 (0.0)	6 (1.9)	2 (2.4)	5 (4.1)	0 (0.0)	8 (8.5)	13 (6.2)	10 (4.4)	17 (6.2)	* (*)	20 (7.1)	2 (2.4)	7 (2.4)
	PM	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	CPM	60 (16.3)	63 (6.2)	90 (7.1)	81 (2.6)	80 (4.1)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–
	ETR	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
10	Control	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	5 (4.1)	3 (2.4)	7 (6.2)	7 (6.2)	0 (0.0)	3 (2.4)	8 (8.5)	5 (0.1)	13 (9.4)	13 (2.4)
	PM	98 (2.4)	100 (0.0)	77 (6.8)	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	CPM	15 (6.9)	58 (11.8)	56 (4.3)	92 (2.4)	97 (2.4)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–

- denotes where counts were discontinued, 100% having been reached
* denotes where replicates were not able to be assessed
Figures in parenthesis are standard deviations about the mean value.

Table 5. Mean percentage mortality of *T. castaneum* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	3 (2.3)	72 (8.5)	78 (2.4)	95 (4.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	PM	11 (8.2)	92 (2.4)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
	CPM	97 (4.7)	90 (4.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
	ETR	87 (2.4)	87 (6.2)	97 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
5	Control	0 (0.0)	0 (0.0)	5 (4.1)	12 (8.5)	28 (5.0)	46 (7.4)	60 (7.1)	85 (10.8)	93 (2.4)	27 (11.8)	100 (0.0)	100 (0.0)	–	–
	PM	59 (11.7)	97 (4.7)	93 (9.4)	92 (7.6)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–
	CPM	48 (22.0)	97 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
	ETR	64 (2.8)	82 (8.5)	100 (0.0)	97 (4.5)	98 (2.4)	* (*)	100 (0.0)	100 (0.0)	–	–	–	–	–	–

Table 5. (continued- *T. castaneum*)

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	0 (0.0)	2 (2.4)	0 (0.0)	2 (2.4)	2 (2.4)	9 (6.5)	7 (4.7)	22 (6.2)	32 (10.3)	47 (14.8)	57 (2.4)	78 (6.2)	73 (2.4)	92 (2.4)
	PM	70 (7.1)	93 (2.4)	98 (2.4)	98 (2.4)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–
	CPM	84 (2.5)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	35 (17.8)	97 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
10	Control	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (2.4)	2 (2.4)	0 (0.0)	0 (0.0)	2 (2.4)	5 (4.1)	5 (0.0)	17 (10.3)	5 (4.1)	7 (2.3)
	PM	87 (2.4)	98 (2.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–
	CPM	88 (9.4)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–
	ETR	78 (6.2)	100 (0.0)	95 (7.1)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–

- denotes where counts were discontinued, 100% having been reached
* denotes where replicates were not able to be assessed
Figures in parenthesis are standard deviations about the mean value.

Table 6. Mean percentage mortality of *A. advena* achieved at each temperature over 28 days.

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	Control	8 (6.2)	37 (14.6)	62 (9.4)	48 (16.7)	97 (4.7)	95 (4.1)	100 (0.0)	–	–	–	–	–	–	–
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	67 (11.8)	80 (7.1)	97 (4.7)	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
5	Control	0 (0.0)	0 (0.0)	12 (8.5)	0 (0.0)	35 (5.4)	44 (2.5)	84 (2.7)	95 (4.1)	100 (0.0)	100 (0.0)	–	–	–	–
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–

Table 6. (continued- *A. advena*)

Temp (oC)	Pesticide	Time after treatment (days)													
		2	4	6	8	10	12	14	16	18	20	22	24	26	28
7.5	Control	0 (0.0)	3 (4.7)	3 (2.4)	2 (2.4)	5 (7.1)	8 (6.2)	13 (2.4)	25 (8.2)	53 (8.5)	80 (8.2)	70 (4.1)	93 (4.6)	100 (0.0)	95 (0.0)
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
10	Control	2 (2.4)	5 (3.9)	5 (4.1)	3 (2.3)	12 (10.3)	8 (6.2)	43 (2.4)	57 (4.7)	60 (16.3)	38 (14.3)	60 (7.1)	82 (8.5)	33 (37.0)	97 (2.4)
	PM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	CPM	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–
	ETR	100 (0.0)	100 (0.0)	–	–	–	–	–	–	–	–	–	–	–	–

– denotes where counts were discontinued, 100% mortality having been reached
* denotes where replicates were not able to be assessed
Figures in parenthesis are standard deviations about the mean value.

Table 7. TIME TAKEN FOR 100% KILL (days)

Species	Pesticide	Temperature (°C)			
		3	5	7.5	10
S. granarius	Control	>28(87)	>28(72)	>28(28)	>28(2)
	PM	24	24	8	10
	CPM	22	6	6	4
	Etrim	26	18	14	10
S. oryzae	Control	6	20	>28(98)	>28(27)
	PM	8	16	14	10
	CPM	6	14	12	8
	Etrim	6	14	14	8
O. surinamensis	Control	16	>28(98)	>28(42)	>28(26)
	PM	12	6	6	4
	CPM	12	6	6	4
	Etrim	8	4	4	4
C. ferrugineus	Control	>28(82)	>28(22)	>28(7)	>28(13)
	PM	26	6	6	12
	CPM	28	26	16	16
	Etrim	6	6	6	4
T. castaneum	Control	12	24	>28(92)	>28(7)
	PM	10	12	14	8
	CPM	8	10	6	6
	Etrim	10	16	10	10
A. advena	Control	~16	20	>28(95)	>28(97)
	PM	4	4	4	4
	CPM	10	4	4	4
	Etrim	4	4	4	4

Note: 100% kill was defined as the second consecutive count at which all test insects were dead. Since counts were at 2-day intervals, the minimum possible time was 4 days.
Figures in parentheses are percent mortality at 28 days.

Table 8

$KD_{99.9}$ VALUES - 1 HOUR EXPOSURES ON TREATED FILTER PAPERS

Species	PM	CPM	Et
S. granarius	24.4	2.4	28.6
S. oryzae	7.0	4.7	3.1
O. surinamensis	7.3	4.2	3.6
C ferrugineus	2.9	1.9	0.9
T. castaneum	27.4	3.4	17.7
A. advena	2.6	1.2	1.3

$KD_{99.9}$ values expressed in ug/cm^2

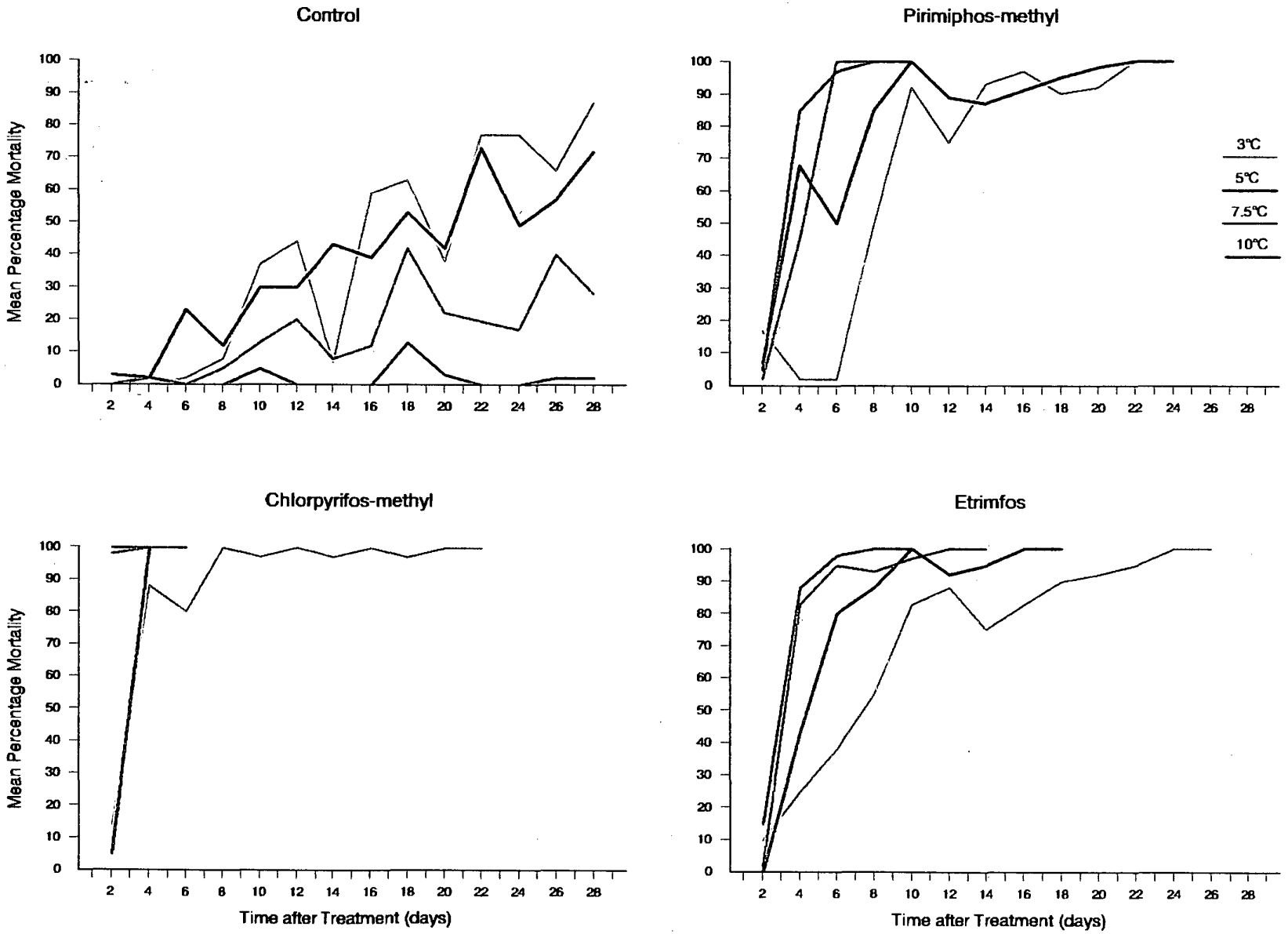

Figure 1. Mean percentage mortality of *S. granarius* on four treatments of wheat at different temperatures.

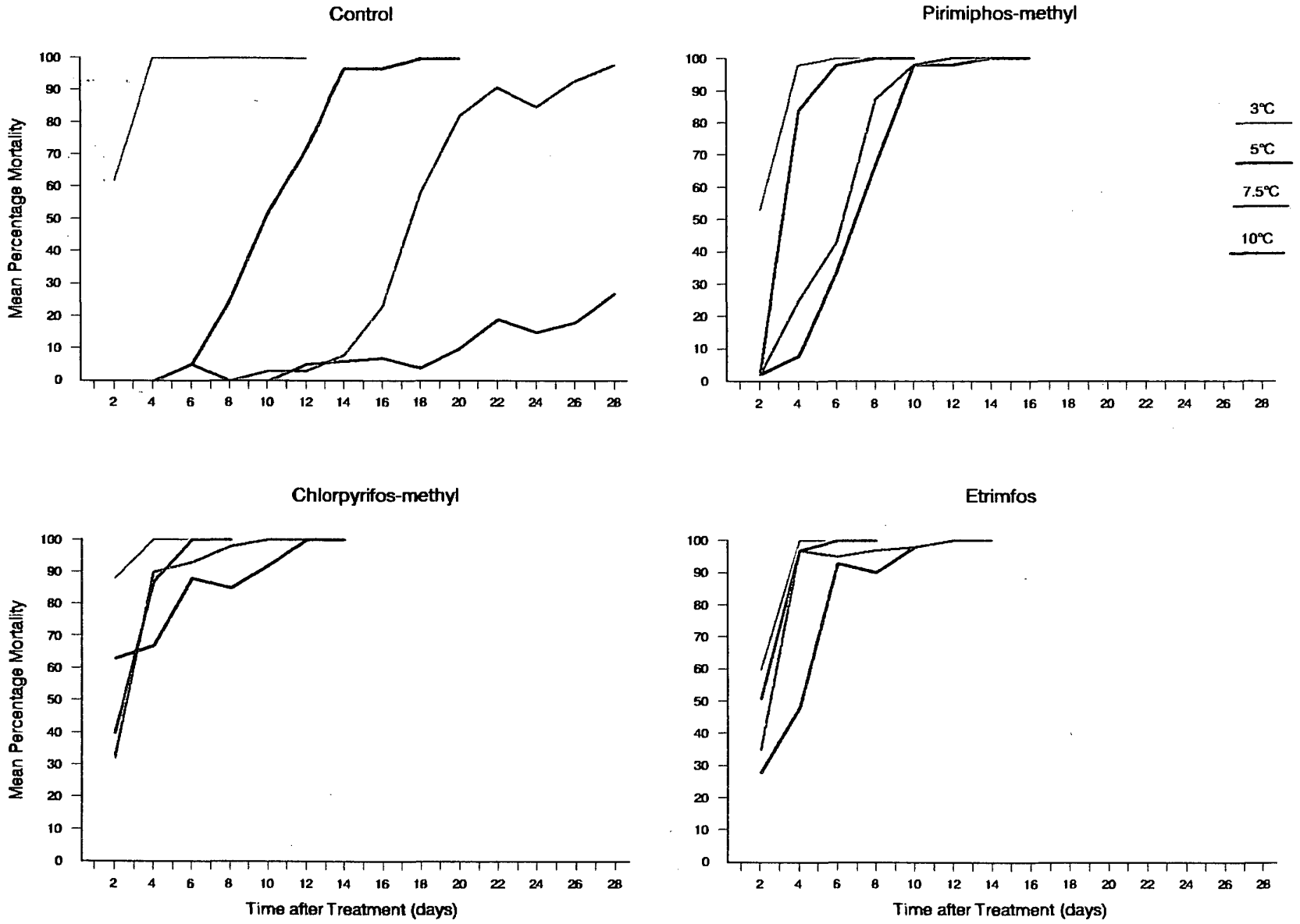

Figure 2. Mean percentage mortality of *S. oryzae* on four treatments of wheat at different temperatures.

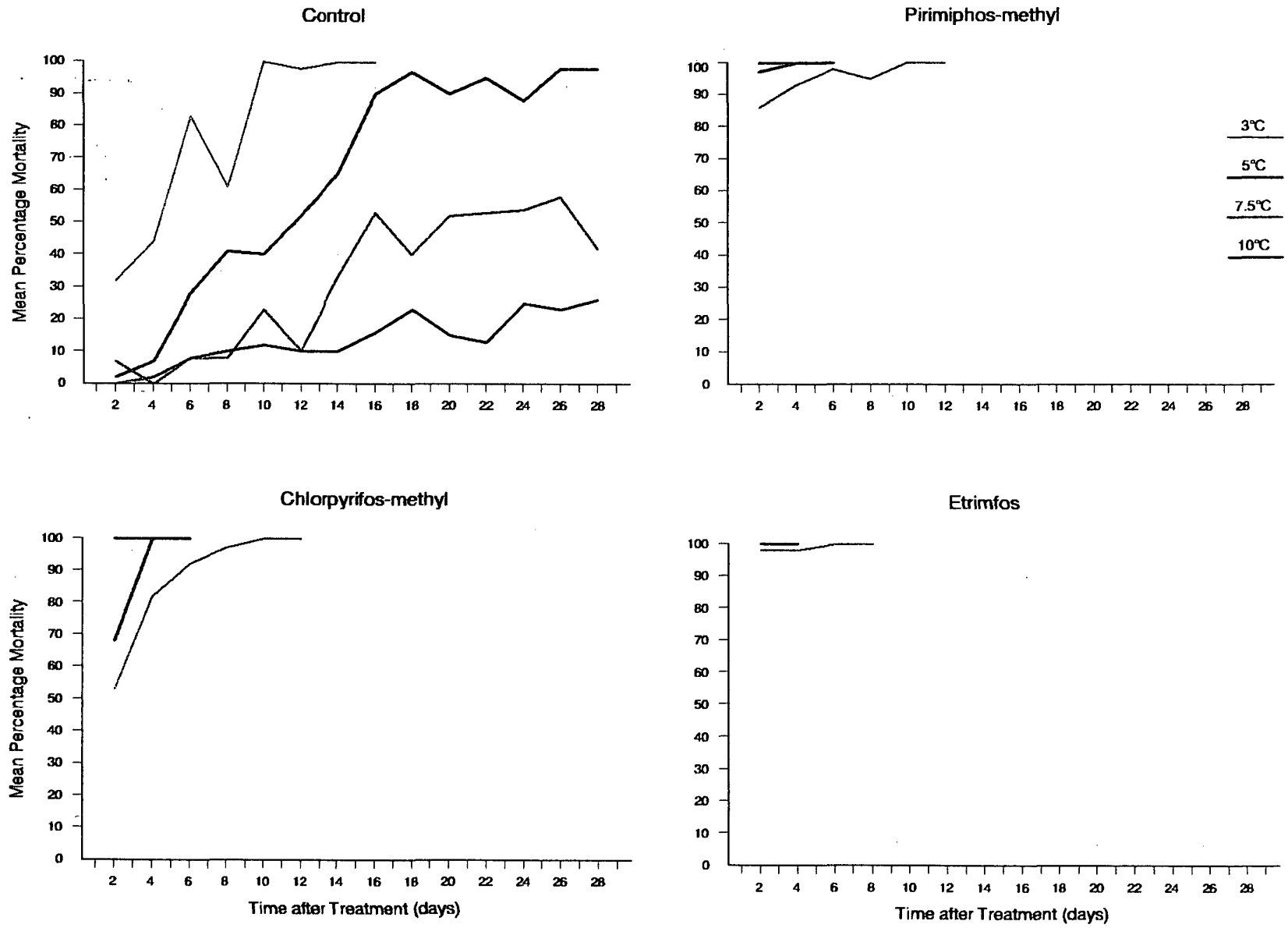

Figure 3. Mean percentage mortality of *O. surinamensis* on four treatments of wheat at different temperatures.

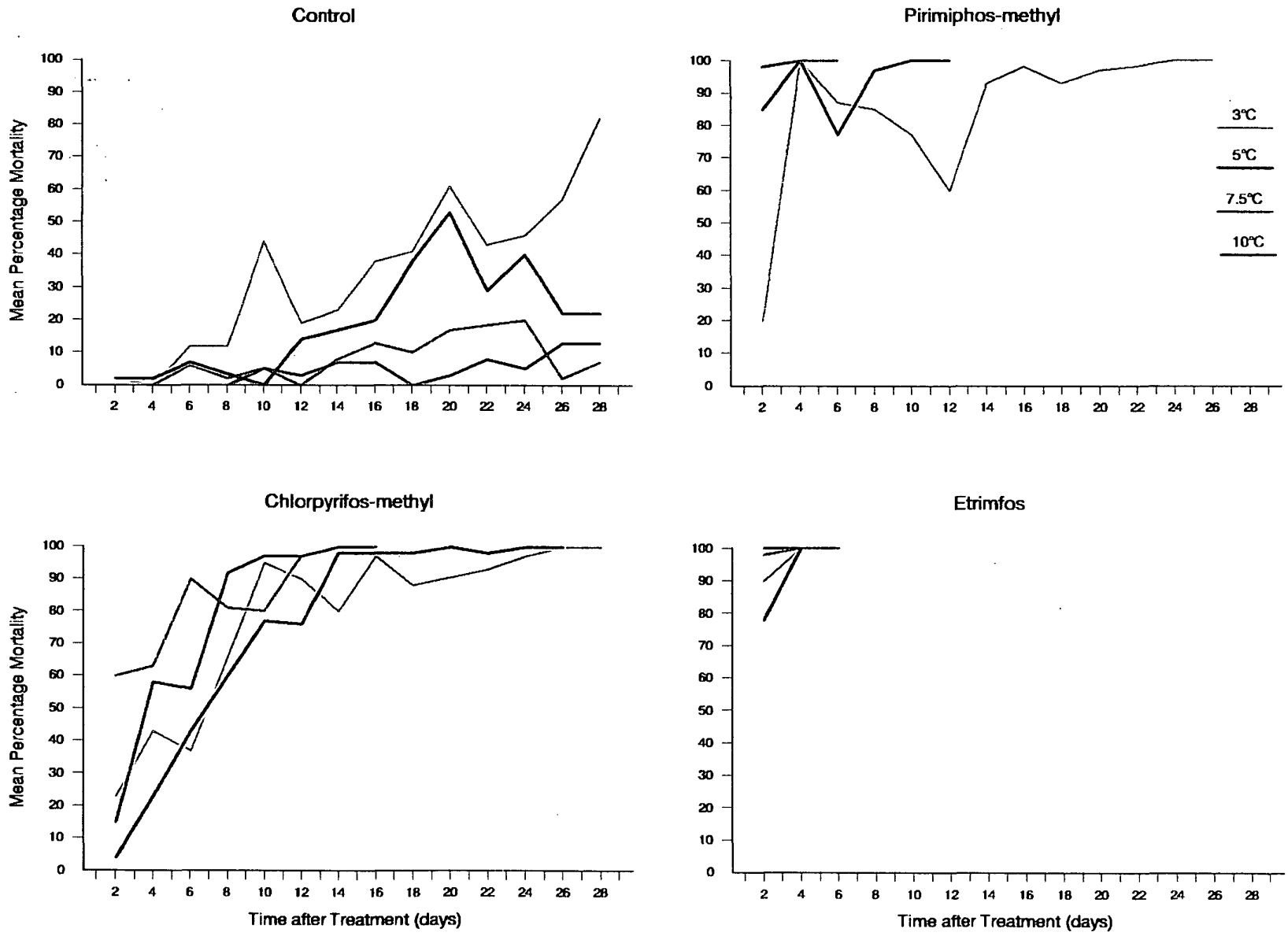

Figure 4. Mean percentage mortality of *C. ferrugineus* on four treatments of wheat at different temperatures.

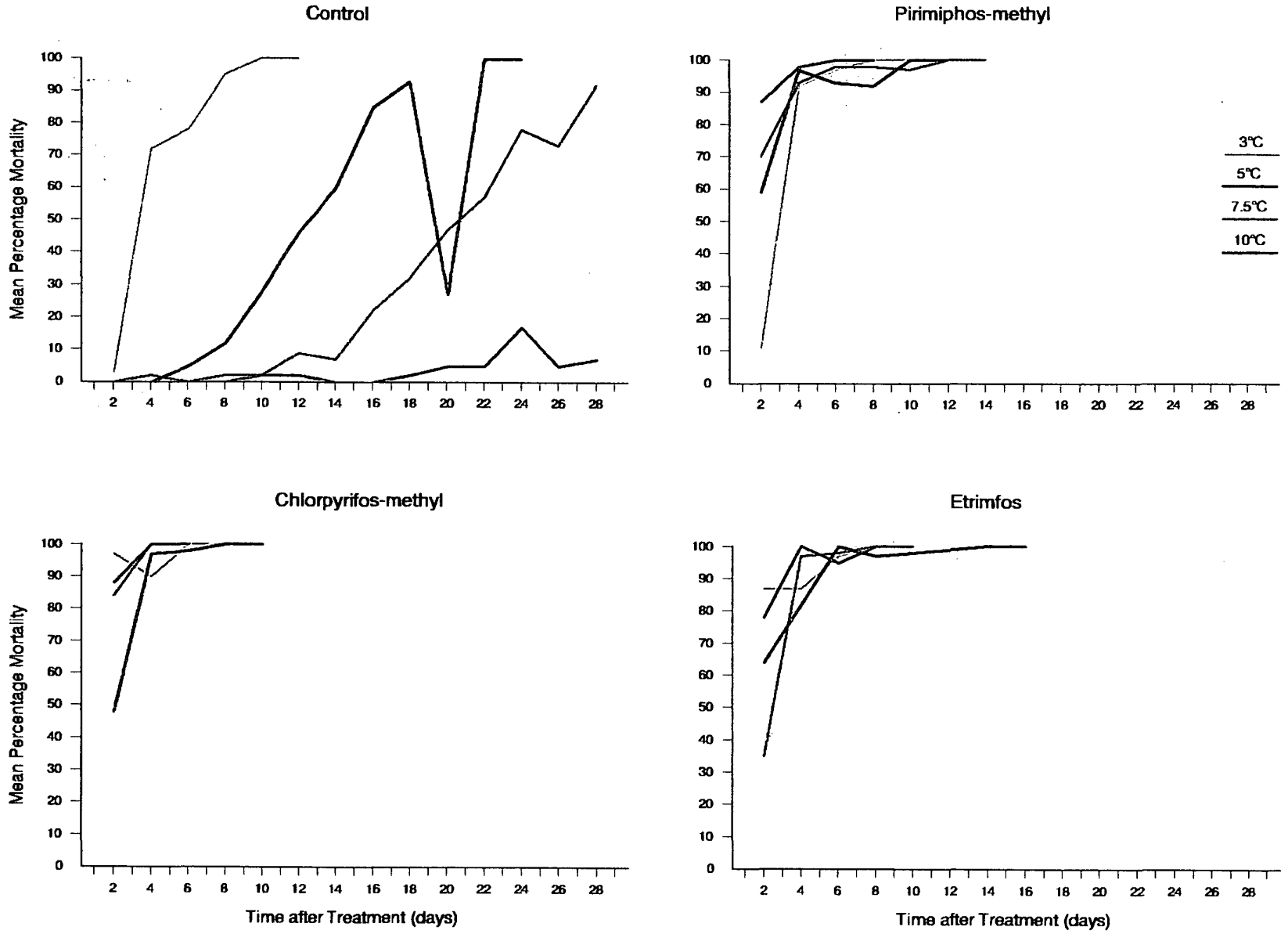

Figure 5. Mean percentage mortality of *T. castaneum* on four treatments of wheat at different temperatures.

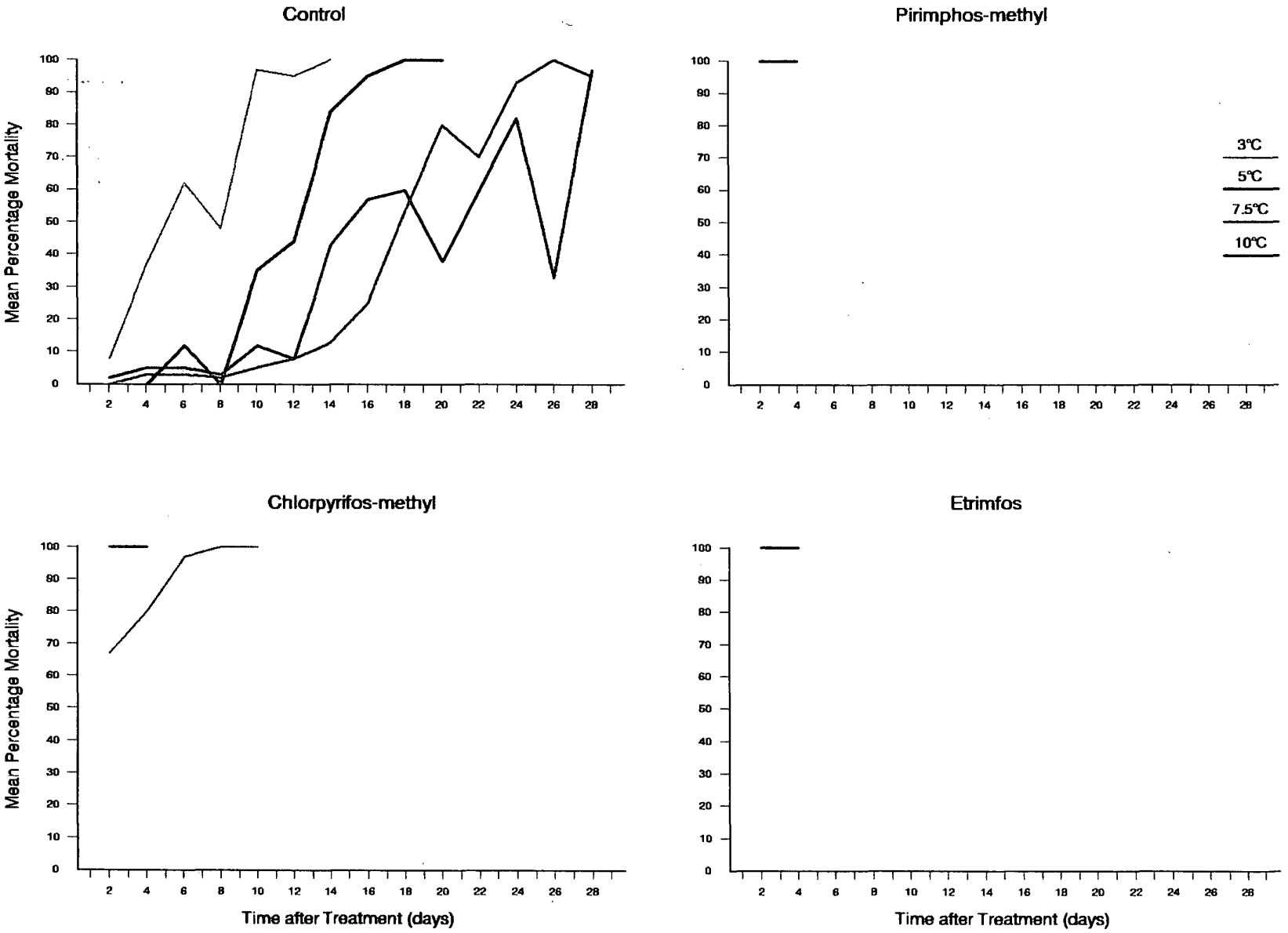

Figure 6. Mean percentage mortality of *A. advena* on four treatments of wheat at different temperatures.