Project title:	Spinach: Further studies on forecasting migrations of *Aphis fabae* into spinach crops
Project number:	FV 407a
Project leader:	Rosemary Collier, University of Warwick
Report:	Final, February 2014
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Key staff:	Rosemary Collier
Location of project:	Warwick Crop Centre, University of Warwick
Industry Representative:	Shaun Clarkson, Vitacress
Date project commenced:	1 June 2013
Date project completed (or expected completion date):	28 February 2014

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Rosemary Collier
Director, Warwick Crop Centre
University of Warwick

Signature .... Date ....

CONTENTS

GROWER SUMMARY

Headline

A forecast based on mean daily air temperature, averaged over a defined period in the spring-early summer, together with the latitude and longitude of the location, can be used to forecast the timing of the spring/summer migration of *Aphis fabae*.

Background

The black bean aphid (*Aphis fabae*) has a very large range of summer hosts, of which spinach is one. The principal crops involved are field beans, broad beans and sugar beet, as well as most forms of garden bean. Some common wild hosts include dock, poppies, goosefoot and fat hen.

Aphis fabae overwinters mainly as eggs on spindle bushes, and a few other shrub species, and occasionally, in warmer locations, as mobile stages on members of the pea/bean family (wild hosts or winter beans). The eggs hatch from late February to early April and colonies develop on young leaves and shoots of the winter host. Winged forms are produced in May/June and these migrate to summer hosts. Reproduction continues throughout the summer, further winged forms are produced in response to crowding and these spread within crops and invade new crops. Populations usually peak in July/August. In autumn *A. fabae* migrates back to spindle and winter eggs are laid. Winged forms of *Aphis fabae* are captured in the suction traps operated by the Rothamsted Insect Survey.

Several researchers have developed forecasting systems for infestations of *A. fabae* on beans or sugar beet. Some of these have relied on counting aphids, either eggs on overwintering hosts or mobile stages on crops. However, a paper by Way *et al* (1981) considered an approach using both egg counts and suction trap samples to forecast infestations in field beans. They concluded that information on the spring migration from spindle and also the autumn migration back to spindle was useful. The forecasting system they developed was used in the UK for a number of years.

Previous studies on other pest species indicated relationships between pest activity/abundance and weather data (either day-degree forecasts or statistical relationships). In Project FV 407, Rothamsted suction trap data from two sites and regional weather data were summarised and analysed to determine whether there were any relationships that could be developed for *A. fabae*. The timing of migration of winged aphids varied from year to year and site to site and there was a very strong correlation with the mean temperature (summarised over different periods leading up to the spring and summer migrations). The high correlation coefficients and the similarity of the fitted lines for the two sites (slope and intercept) indicated that there is a robust relationship with temperature and that the timing of key events should be highly predictable using accumulated temperatures (day-degrees). Such day-degree forecasts have been used successfully for other pest aphids that overwinter as eggs on woody hosts (e.g. willow-carrot aphid, lettuce root aphid – used on the HDC Pest Bulletin). Relationships between temperature or rainfall and aphid abundance were also investigated in FV 407 but there were no significant correlations.

Summary

The project consisted of four objectives:

Objective 1. Use suction trap data and daily weather data to develop a day-degree forecast for Aphis fabae *to predict the start of the spring migration and the timing of different stages of the summer migration.*

Two sets of aphid monitoring data from the Rothamsted Insect Survey were used to develop a day-degree forecast for *Aphis fabae*. These were records of the capture of *A. fabae* at Rothamsted Research between 1965 and 1999 and records of captures at a number of sites between 1981 and 1988. The day-degrees to the capture of the first aphid and to the capture of 10 and 50% of the total number of aphids captured up to 31st August were calculated using two methods. As the threshold temperature for development of *A. fabae* is unknown, day-degrees were accumulated using a range of threshold temperatures between -2 and 8^{o}C. Similarly, as the end point of egg diapause (the overwintering stage) is undefined, different start dates for day-degree accumulations were tried e.g. from 1 January, 1 February or 1 March. Although there were consistent statistical relationships it was not possible to identify a constant day-degree sum that could be used to predict the aphid migration. In all instances the day-degree sum was greater when the aphid migration occurred later in the year.

An alternative approach was explored using the strong relationships between the timing of the spring/summer migration by *A. fabae* and mean air temperature identified in project FV 407. A data set consisting of 423 location x year combinations was used to explore these relationships. It became apparent that, apart from the mean air temperature, the location of

the site appeared to influence the relationships quite strongly. Therefore to investigate the nature of the relationships with mean temperature (and latitude and longitude) a series of regression analyses were run on the full data set. These were:

- First aphid against Mean Temperature Jan-Apr
- 10% aphids against Mean Temperature Jan-Apr
- 10% aphids against Mean Temperature Jan-May
- 50% aphids against Mean Temperature Jan-Apr
- 50% aphids against Mean Temperature Jan-May
- 50% aphids against Mean Temperature Jan-Jun

For each of these, the analysis started with a simple linear regression for the whole data set. For the analyses of 10% aphids and 50% aphids against different explanatory variables, the 'percentage variance accounted for' indicated that using the mean temperature over a longer period provided a better fitting model. A simple linear regression 'with groups' analysis was then applied, allowing both the intercept and slope of the fitted relationship to change between locations. In every case, there was evidence for differences in the intercepts between locations, but not for differences in the slopes, therefore indicating a series of parallel lines representing the 15 locations. For each of the parallel line models, the intercept parameters for the 15 locations were extracted and a multiple linear regression was applied for these against both latitude and longitude. All showed evidence for the intercepts varying with both latitude and longitude.

The final output in each set of analyses was for a multiple linear regression model including the appropriate mean temperature variable and both latitude and longitude. These analyses again all showed significant effects of both latitude and longitude (effectively influencing the intercept of the fitted line for each location) as well as of mean temperature. These overall fitted models (Table A) could be used to predict the timing of aphid activity at any location (in the UK) in any particular year using the appropriate air temperature data.

Table A. Fitted equations for multiple linear regression models between dates of first, 10% and 50% capture and mean air temperature over different periods and latitude and longitude. All were statistically significant (p<0.001).

Measure of timing of aphid activity	Mean temperature during	Fitted equation (Time in days from 1 January)
First	Jan-Apr	Time=64-9.70*mean temp+2.67*latitude+4.19*longitude
10%	Jan-Apr	Time=60-7.78*mean temp+3.24*latitude+1.21*longitude
10%	Jan-May	Time=96-9.11*mean temp+2.88*latitude+1.04*longitude
50%	Jan-Apr	Time=57-5.23*mean temp+3.32*latitude+2.15*longitude
50%	Jan-May	Time=82-6.15*mean temp+3.07*latitude+2.04*longitude
50%	Jan-Jun	Time=110-7.07*mean temp+2.81*latitude+1.93*longitude

Objective 2. Validate day-degree forecast and method of predicting abundance using any available historical crop monitoring data.

To validate the forecast based on mean temperature, latitude and longitude, the predicted dates for first, 10% and 50% capture were calculated using the equations in Table A. The absolute differences between observed and predicted dates were then calculated and used to calculate the mean deviation between observed and predicted dates, shown in Table B. The predictions for the capture of the first aphid were the least consistent (January-April temperatures) and those for capture of 50% aphids were most consistent, with an average of just over a week. Consistency was improved by using weather data over a longer period of time. The predictions appeared to be least accurate for Rosewarne, followed by Preston. However, it is important to bear in mind that the trap records were from different runs of years for each site.

Table B. Mean absolute difference between observed and predicted dates of activity for all site x year combinations.

	Latitude	Longitude	First (Jan-Apr)	10% (Jan-Apr)	10% (Jan-May)	50% (Jan-Apr)	50% (Jan-May)	50% (Jan-Jun)
Starcross	50.37	3.27	10	13	13	10	9	9
Rosewarne	50.50	5.19	16	17	16	14	14	14
Wye	51.10	-0.56	11	10	9	7	7	7
Writtle	51.43	-0.25	13	10	9	8	8	8
Rothamsted	51.48	0.21	13	10	9	7	7	7
Brooms Barn	52.15	-0.33	10	9	9	8	8	8
Kirton	52.55	0.30	13	9	9	10	10	10
Hereford	52.70	2.39	18	11	11	11	10	10
Preston	53.45	2.42	19	9	8	11	11	11
High Mowthorpe	54.50	0.39	22	12	12	9	9	9
Newcastle	54.58	1.37	15	12	11	11	10	10
Ayr	55.28	4.33	19	12	12	8	9	8
East Craigs	55.57	3.18	24	13	12	7	7	6
Dundee	56.27	3.30	20	10	10	8	8	7
Elgin	57.38	3.19	19	13	12	8	8	8
Mean			16.07	11.25	10.93	9.09	8.88	8.82
Max			24	17	16	14	14	14
Min			10	9	8	7	7	6

Objective 3 . Analyse these data for relationships that might help to predict abundance.

There was no relationship between the numbers of aphids captured and latitude of the suction trap location. Nor was there any evidence of a relationship between the numbers caught in the spring/summer migration and the size of the autumn migration in the previous year. Similarly there appeared to be no relationship between the warmth of the spring and the numbers of aphids captured.

Objective 4 . Develop a method of predicting relative abundance in the summer as early as possible from real-time suction trap data.

By predicting the date of 10% activity it might be possible to use the numbers captured by that predicted date to predict the total number of aphids captured during the summer (up to 31 August). Examples of the relationship between the actual captures up to 31 August and the predicted capture up to 31 August (based on the numbers captured at the predicted date of 10% activity) showed that whilst there was a large amount of scatter, this might provide an estimate of the final numbers captured, but would not be completely reliable.

Financial Benefits

This proposal is in direct response to a request from industry and the intention is to provide information that will inform an improved control strategy for *Aphis fabae* on spinach.

Action Points

- The fitted equations describing the relationship between aphid activity and mean temperature, latitude and longitude will be used in the HDC Pest Bulletin in 2014.

- Spreadsheets containing the equations can be supplied to growers for use with their own air temperature data in 2014.

- Even without a forecast, growers can regularly update themselves on the numbers of *A. fabae* captured by Rothamsted suction traps in the current season http://www.rothamsted.ac.uk/insect-survey/STAphidBulletin.php.

- To reinforce this, information on suction trap catches will be added to the HDC Pest Bulletin updates.

SCIENCE SECTION

Introduction

The black bean aphid (*Aphis fabae*) has a very large range of summer hosts, of which spinach is one. The principal host crops involved are field beans, broad beans and sugar beet, as well as most forms of garden bean. Some common wild hosts include dock, poppies, goosefoot and fat hen.

Aphis fabae overwinters mainly as eggs on spindle bushes *(Euonymus europaeus*), and a few other shrub species, and occasionally, in warmer locations, as mobile stages on members of the pea/bean family (wild hosts or winter beans). The eggs hatch from late February to early April and colonies develop on young leaves and shoots of the winter host. Winged forms are produced in May/June and these migrate to summer hosts. Reproduction continues throughout the summer, further winged forms are produced in response to crowding and these spread within crops and invade new crops. Populations usually peak in July/August. In autumn *A. fabae* migrates back to spindle and winter eggs are laid (Rothamsted Research, 2012). Winged forms of *A. fabae* are captured in the suction traps operated by the Rothamsted Insect Survey. Figure 1.1 shows the weekly total numbers of *A. fabae* captured in the suction trap at Broom's Barn in Suffolk in 1973.

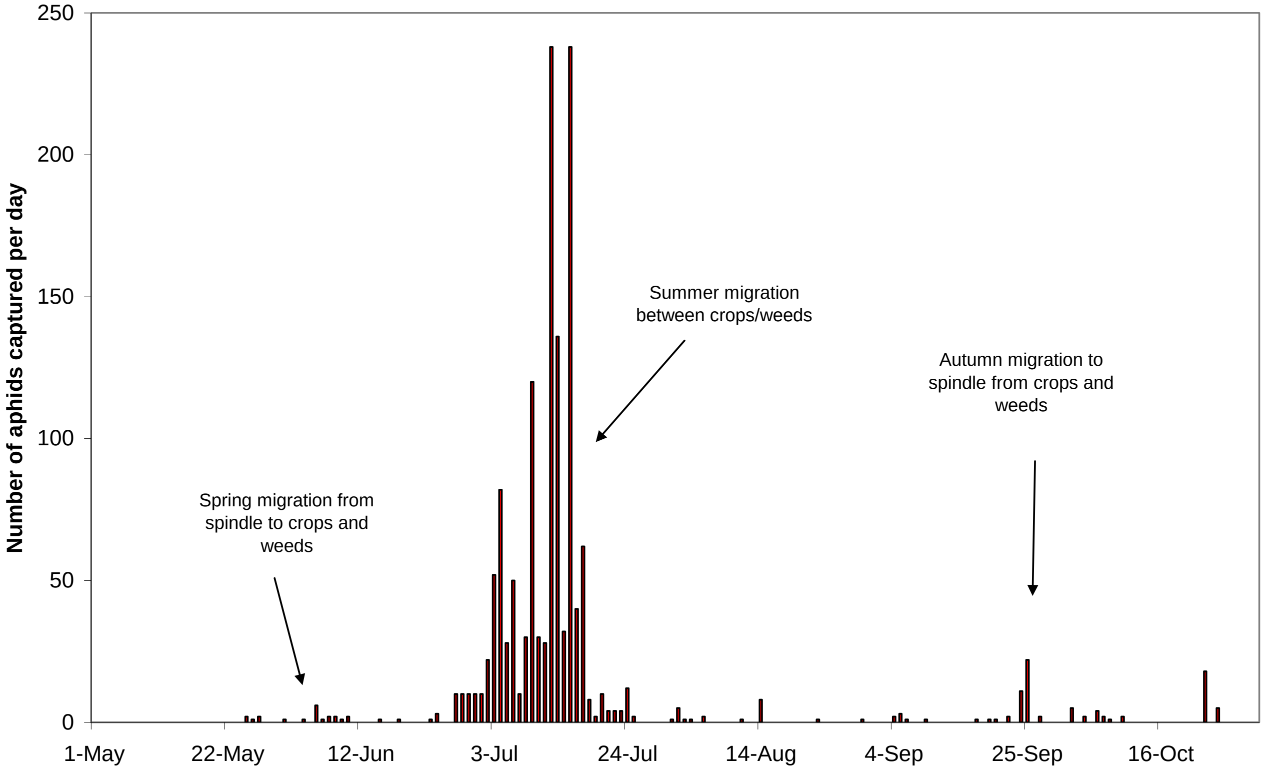

Figure 1.1. Typical pattern of aphid migration as indicated by suction trap samples (for data from Broom's Barn in 1973). The three phases of migration are indicated.

Figure 1.2 shows the total numbers of female *A. fabae* caught at Broom's Barn from 1966 to 2006, presented as cumulative numbers on each date (from FV 407). A small number of male aphids were captured in the autumn as the winged aphids were returning to spindle to overwinter. These data are not shown. In project FV 407, the date used to separate the summer and autumn flights was 31 August.

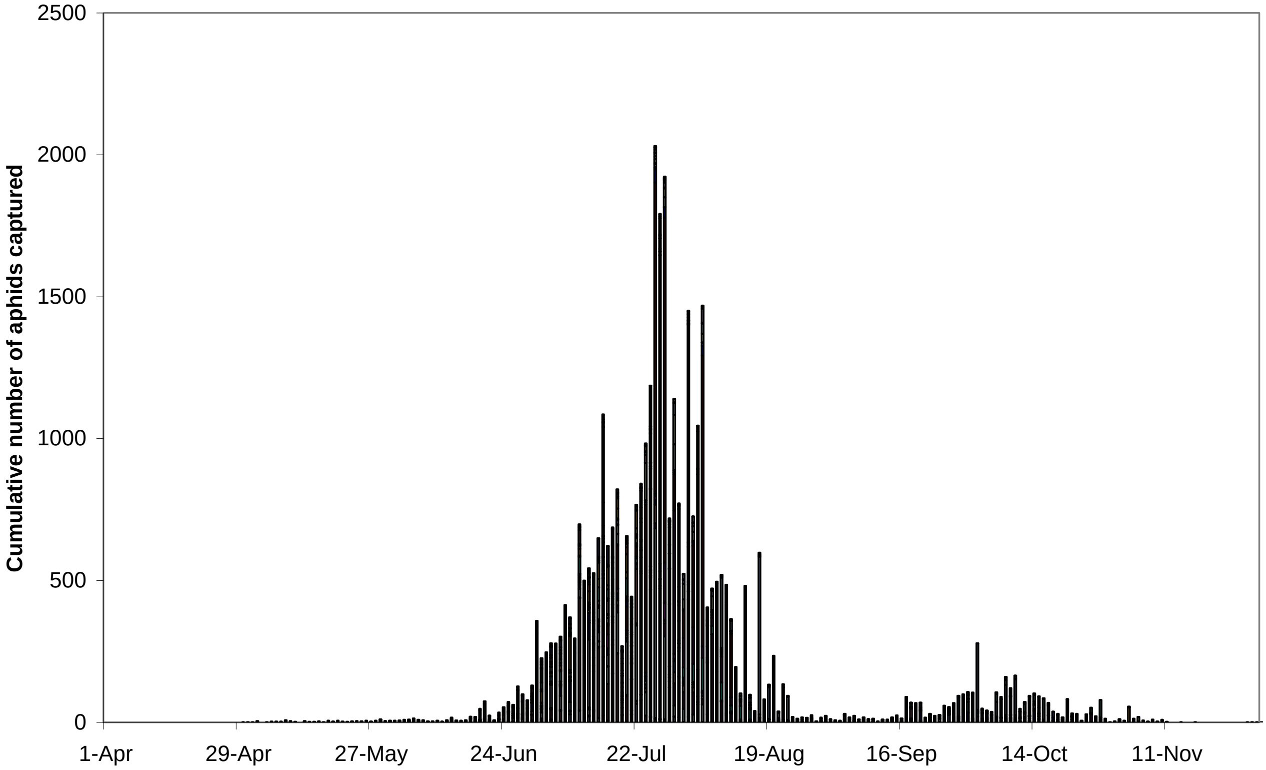

Figure 1.2. Cumulative numbers of female *A. fabae* caught at Broom's Barn between 1966 and 2006.

Several researchers have developed forecasting systems for infestations of *A. fabae* on beans or sugar beet. Some of these have relied on counting aphid eggs on overwintering hosts. However, a paper by Way *et al.* (1981) considered an approach using both egg counts and suction trap samples to forecast infestations in field beans. They concluded that information on the spring migration from spindle and also the autumn migration back to spindle was useful. The forecasting system they developed was used in the UK for a number of years.

Previous studies on other pest species indicated relationships between pest activity/abundance and weather data (either day-degree forecasts or statistical relationships). In Project FV 407, Rothamsted suction trap data from two sites and regional weather data were summarised and analysed to determine whether there were any relationships that could be developed for *A. fabae*. The timing of migration of winged aphids varied from year to year and site to site and there was a very strong correlation with the mean temperature (summarised over different periods leading up to the spring and summer migrations). The high correlation coefficients and the similarity of the fitted lines for the two sites (slope and intercept) indicated that there is a robust relationship with temperature and that the timing of key events should be highly predictable using accumulated temperatures (day-degrees). Such day-degree forecasts have been used successfully for other pest aphids that overwinter as eggs on woody hosts (e.g. willow-carrot aphid, lettuce root aphid – used on the HDC Pest Bulletin). The aim of this project was to determine whether this approach would be feasible for *A. fabae*. Relationships between temperature or rainfall and aphid abundance were also investigated in FV 407 but there were no significant correlations.

Experimental

Whole data set

The data consisted of captures from suction traps at 17 locations, some of which had run since 1965 (Rothamsted and Broom's Barn). Some of the traps are no longer running (e.g. High Mowthorpe, Aberystwyth). Weather records were available for dates up to 1999 but data sets were not always complete. However, there were sufficient data sets and individual records to establish relationships with temperature, latitude and longitude. Virtually all the traps were run between 1981 and 1988 and so this was used as the core data set for some comparisons.

Objective 1. Use suction trap data and daily weather data to develop a day-degree forecast for A. fabae *to predict the start of the spring migration and the timing of different stages of the summer migration*

Rothamsted data set

The Rothamsted data set consisted of trap capture data from 1965 to 1999 with corresponding weather records. The data set is summarised in Table 2.1.

Table 2.1. The Rothamsted data set 1965 to 1999.

	Total number in year	No. of days after 1st January			Aphids to 15 June	Aphids to 31 August
		First aphid	10% aphids	50% aphids		
1965	472	132	164	199	80	470
1966	157	153	187	205	5	106
1967	827	147	183	193	31	827
1968	25	182	186	204	0	19
1969	2314	148	200	209	11	2305
1970	1134	161	197	216	1	1130
1971	94	144	187	204	3	90
1972	561	162	201	205	2	516
1973	643	141	175	189	51	611
1974	534	137	180	198	18	528
1975	505	158	201	209	1	499
1976	155	107	159	178	20	152
1977	1388	173	212	221	0	1386
1978	187	153	199	211	3	178
1979	793	160	196	208	2	792
1980	25	202	205	209	0	12
1981	855	139	191	199	8	849
1982	90	151	195	212	1	58
1983	347	150	187	194	7	343
1984	148	165	197	207	1	144
1985	120	149	194	204	3	119
1986	592	165	207	224	1	574
1987	115	147	171	205	3	115
1988	35	169	176	194	0	30
1989	464	137	156	182	57	463
1990	80	128	166	184	9	79
1991	525	157	192	207	3	524
1992	84	149	179	181	2	84
1993	284	130	181	198	4	282
1994	1469	150	194	201	5	1467
1995	597	122	186	199	18	596

	Total number in year	No. of days after 1st January			Aphids to 15 June	Aphids to 31 August
		First aphid	10% aphids	50% aphids		
1996	106	156	198	204	2	104
1997	104	120	168	187	10	102
1998	76	128	138	181	17	68
1999	632	134	180	188	11	625
Mean	472	149 (29 May)	185 (4 Jul)	200 (19 Jul)	11	464
Max	2314	202 (21 Jul)	212 (31 Jul)	224 (12 Aug)	80	2305
Min	25	107 (17 Apr)	138 (18 May)	178 (27 Jun)	0	12

Over the 35 years (1965-99) between 25 and 2314 aphids were captured in a year (mean 472). The earliest date on which the first aphid was captured was 16th April (1976) and the latest date was 20th July (1980) – a difference of 95 days. The mean date of first capture was 29th May. The earliest date by which 10% aphids were captured was 18th May (1998) and the latest was 31st July (1977) – a difference of 74 days. The mean date of 10% capture was 4th July. Similarly, the earliest date by which 50% aphids were captured was 27th June (1976) and the latest was 12th August (1986) – a difference of 46 days. The mean date of 50% capture was 19th July. Between 0 and 11 aphids were captured before 15 June in any one year and between 12 and 2305 aphids were captured before 31 August (the date used in FV 407 to separate the summer and autumn flights).

Day-degrees above a range of bases were calculated in two ways:

i) A simple method:

0.5 * (MAX + MIN) – BASE) (assuming all negative values are 0)

ii) A more complex method that takes account of periods when the minimum temperature is below the threshold temperature (Meteorological Office equations):

Case		Day-degrees
1	MAX ≤ BASE	0
2	MIN ≥ BASE	0.5 * (MAX + MIN) - BASE
3	MAX – BASE > BASE – MIN > 0	0.5 * (MAX-BASE) - 0.25 * (BASE-MIN)
4	0 < MAX – BASE < BASE - MIN	0.25 * (MAX – BASE)

Figure 2.1 shows the numbers of accumulated day-degrees calculated using the two methods for Rothamsted in 1976 (warm spring) and 1979 (cold spring) using base temperatures of 0 or 4^{o}C. This shows that the two methods of calculating accumulated day-degrees produced very similar results but the precise relationship between them varied depending on the weather and the threshold used.

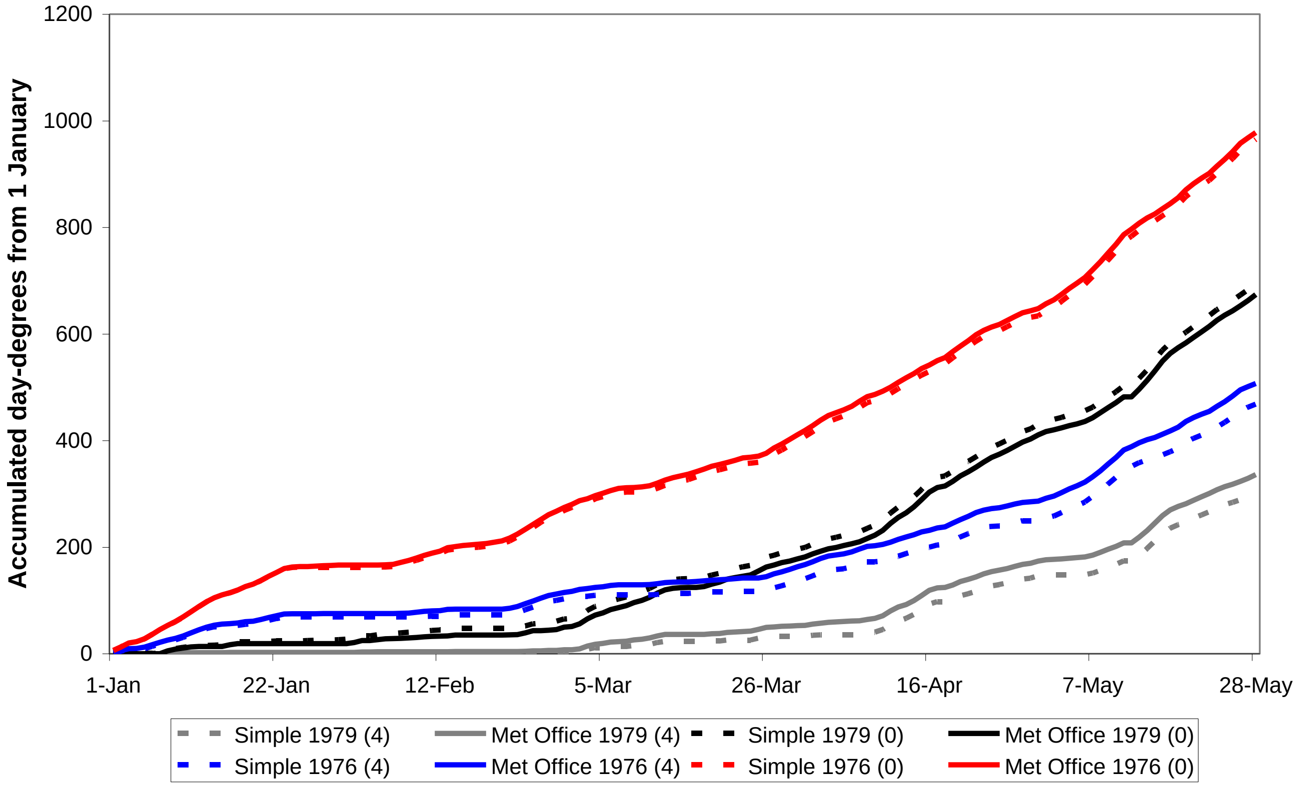

Figure 2.1. Numbers of accumulated day-degrees calculated using the two methods for Rothamsted in 1976 (warm spring) and 1979 (cold spring) using base temperatures of 0 or 4^{o}C.

The dates of first capture, 10% capture and 50% capture (considering all aphids caught to 31 August as in FV 407) (Table 2.1) were compared with the mean air temperature estimated over different periods (January-April and January-May) and with accumulated day-degrees using the two methods of estimation.

Figures 2.2-2.4 show the relationships between these dates and mean temperature sums. There was a fair amount of scatter. However, as shown in FV 407, the date of capture (first, 10%, 50%) was negatively correlated with the mean temperature. The correlations were strongest with the temperature from January to May inclusive and with the date of 50% capture.

This basic relationship would allow for the development of simple forecasts based on these relationships i.e. at the end of April it would be possible to predict the timing of activity and this prediction would improve if made at the end of May.

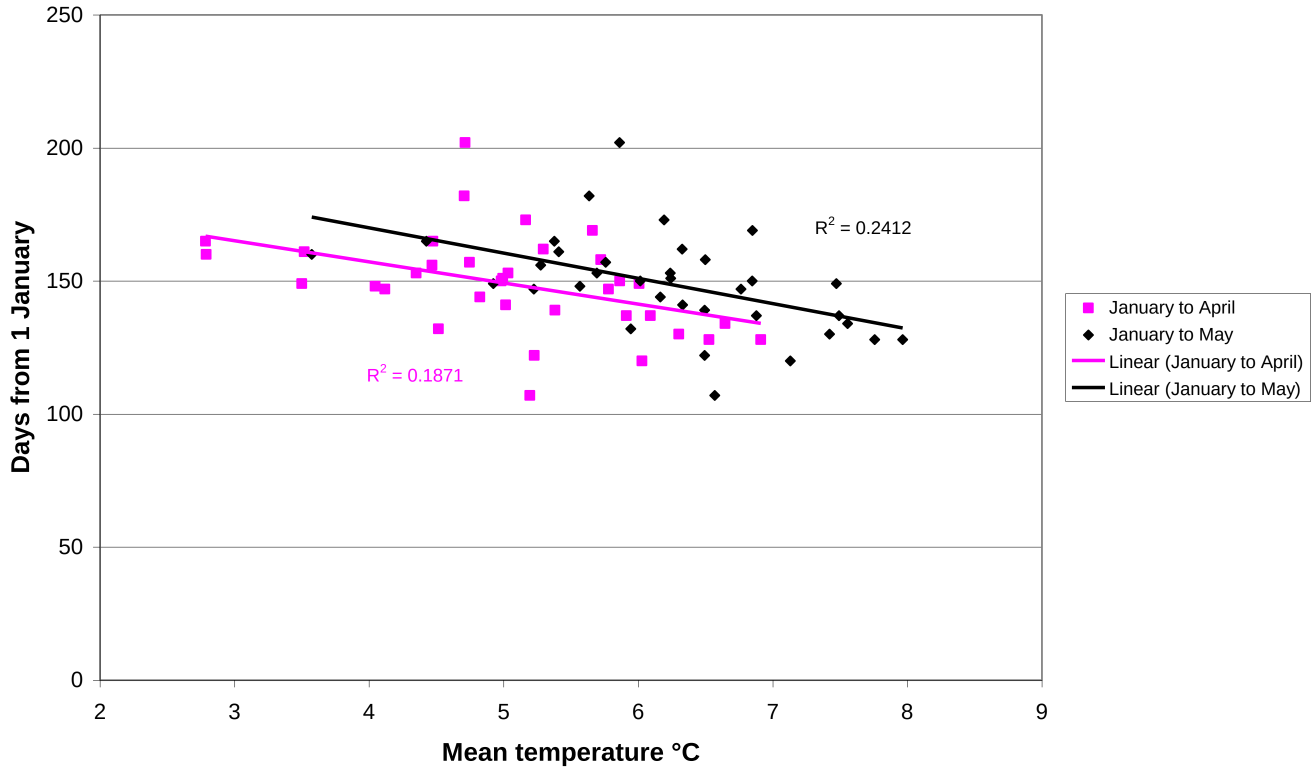

Figure 2.2. Relationship between date first aphid captured each year and mean temperature.

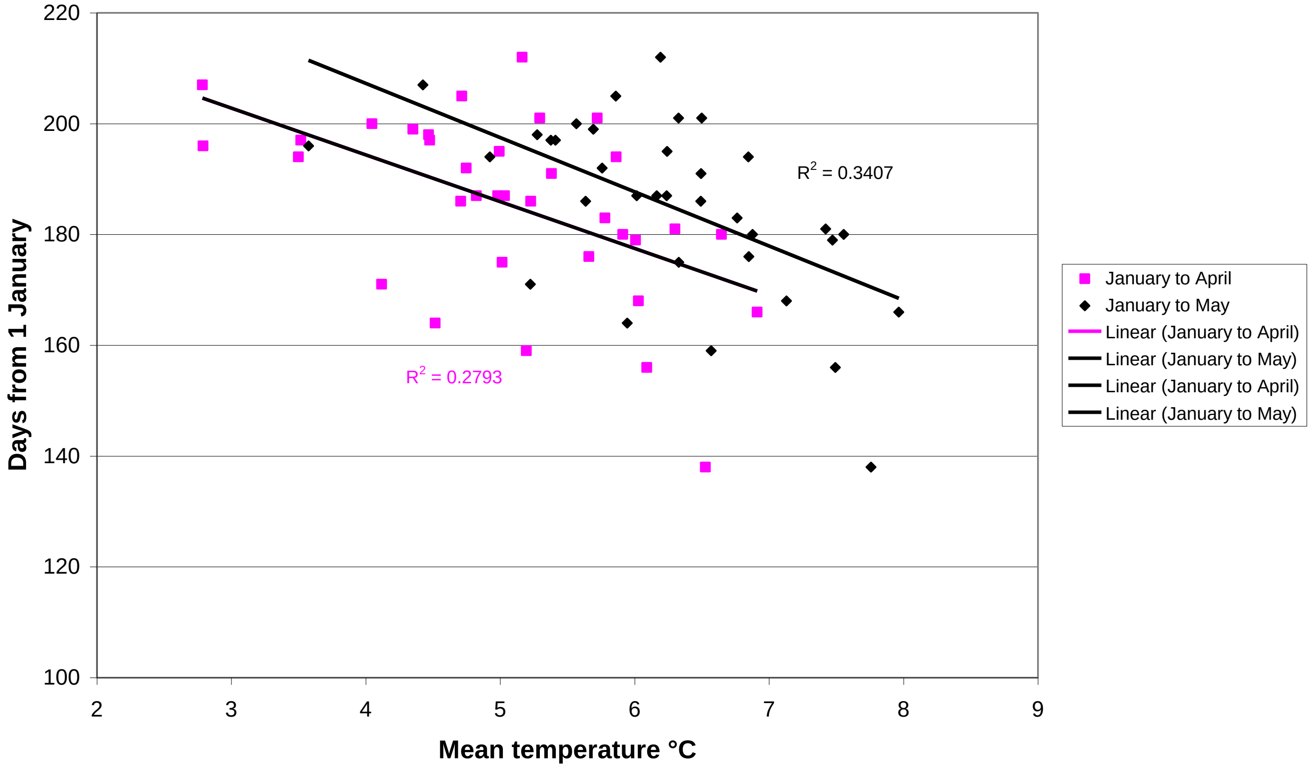

Figure 2.3. Relationship between date 10% aphids captured each year and mean temperature.

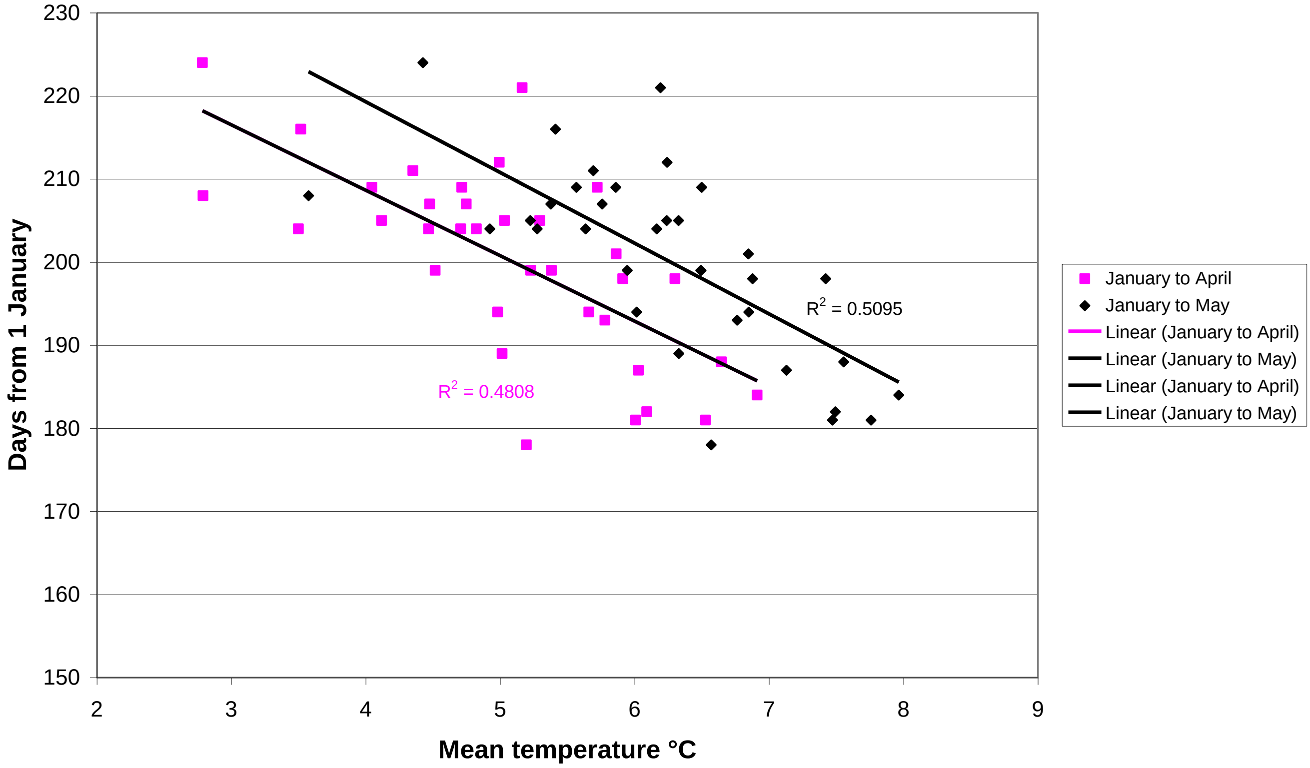

Figure 2.4. Relationship between date 50% aphids captured each year and mean temperature.

Figures 2.5-2.7 show the numbers of day-degrees (base 4°C) accumulated from 1 January to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

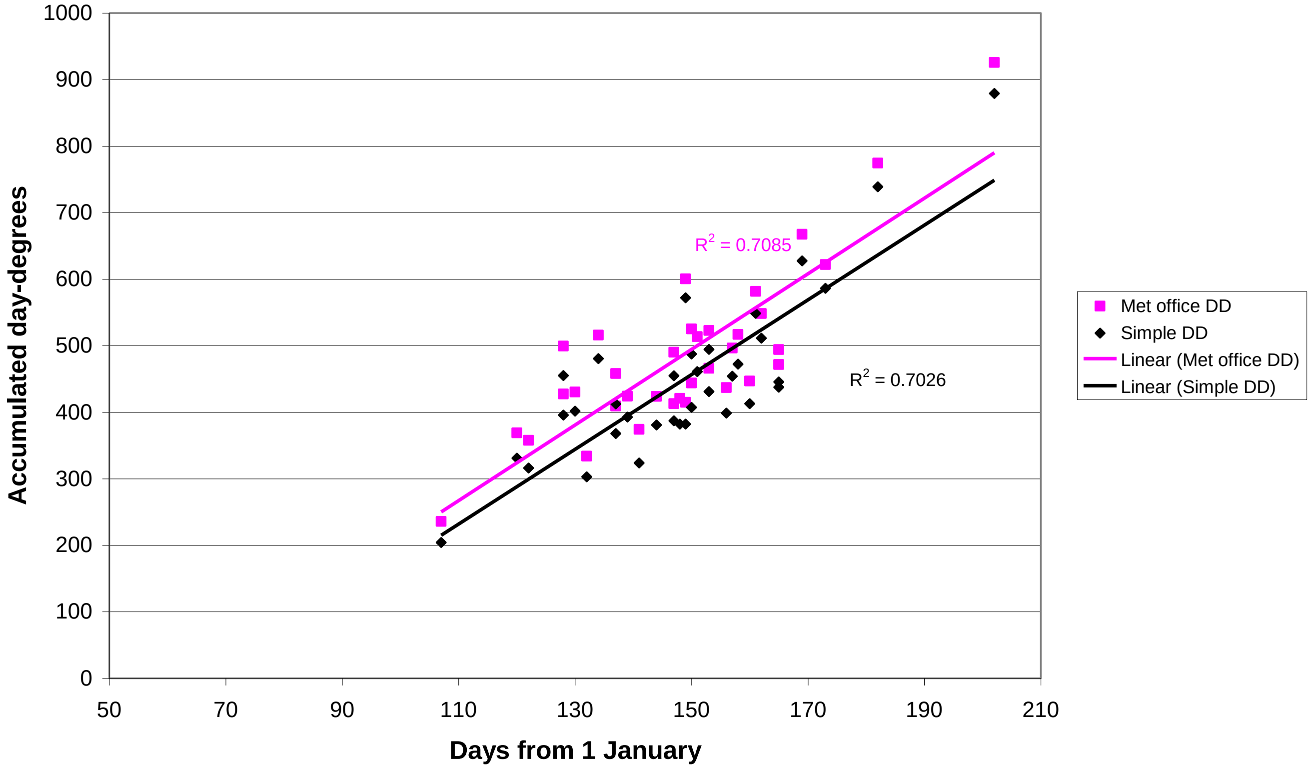

Figure 2.5. The numbers of day-degrees (base 4°C) accumulated to dates of first capture.

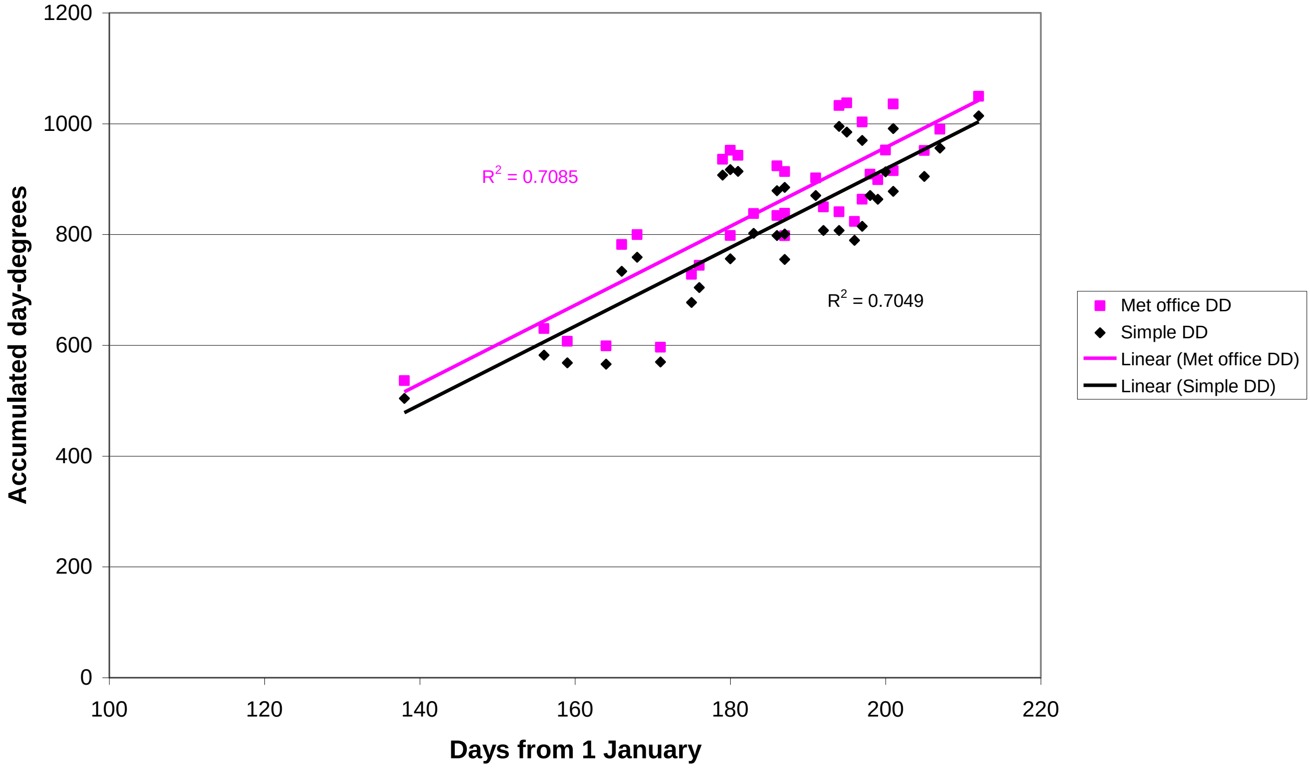

Figure 2.6. The numbers of day-degrees (base 4^{o}C) accumulated to dates of 10% capture.

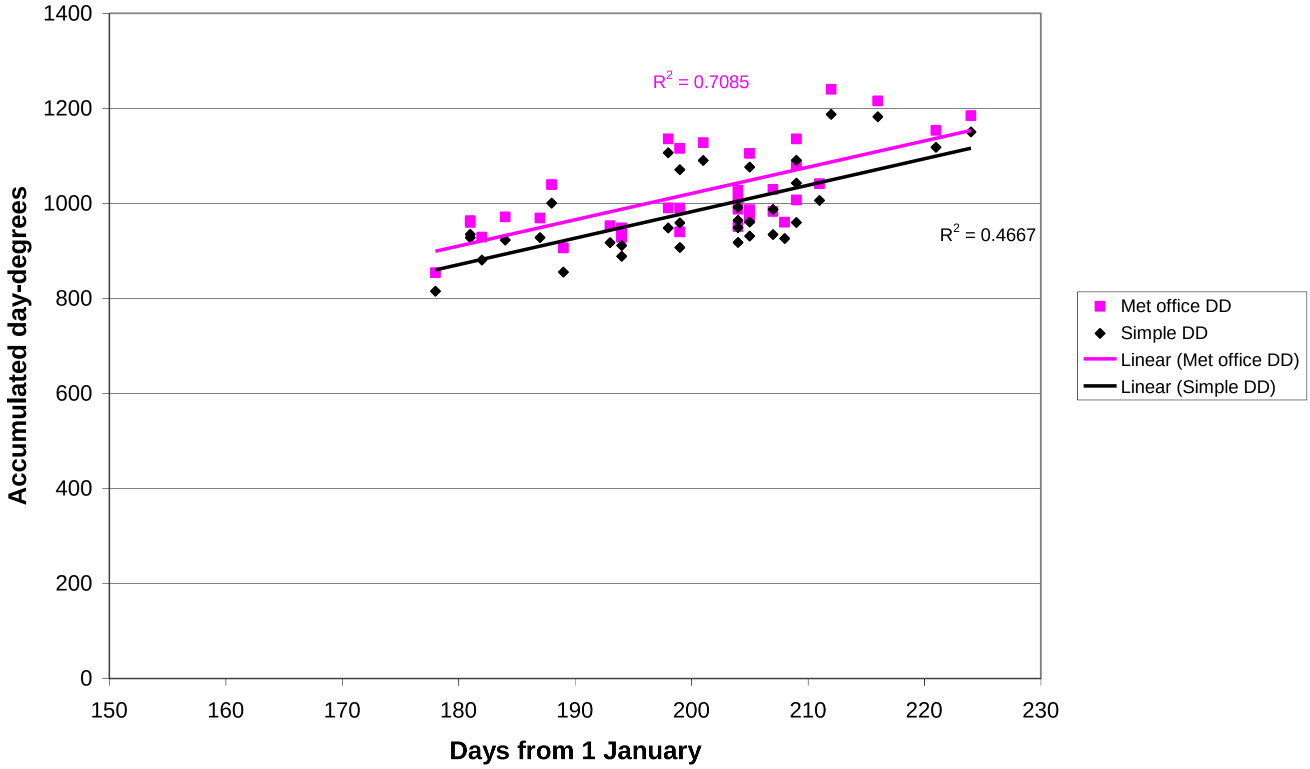

Figure 2.7. The numbers of day-degrees (base 4^{o}C) accumulated to dates of 50% capture.

Figures 2.8-2.10 show the numbers of day-degrees (base 4°C) accumulated from 1 January, 1 February and 1 March to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

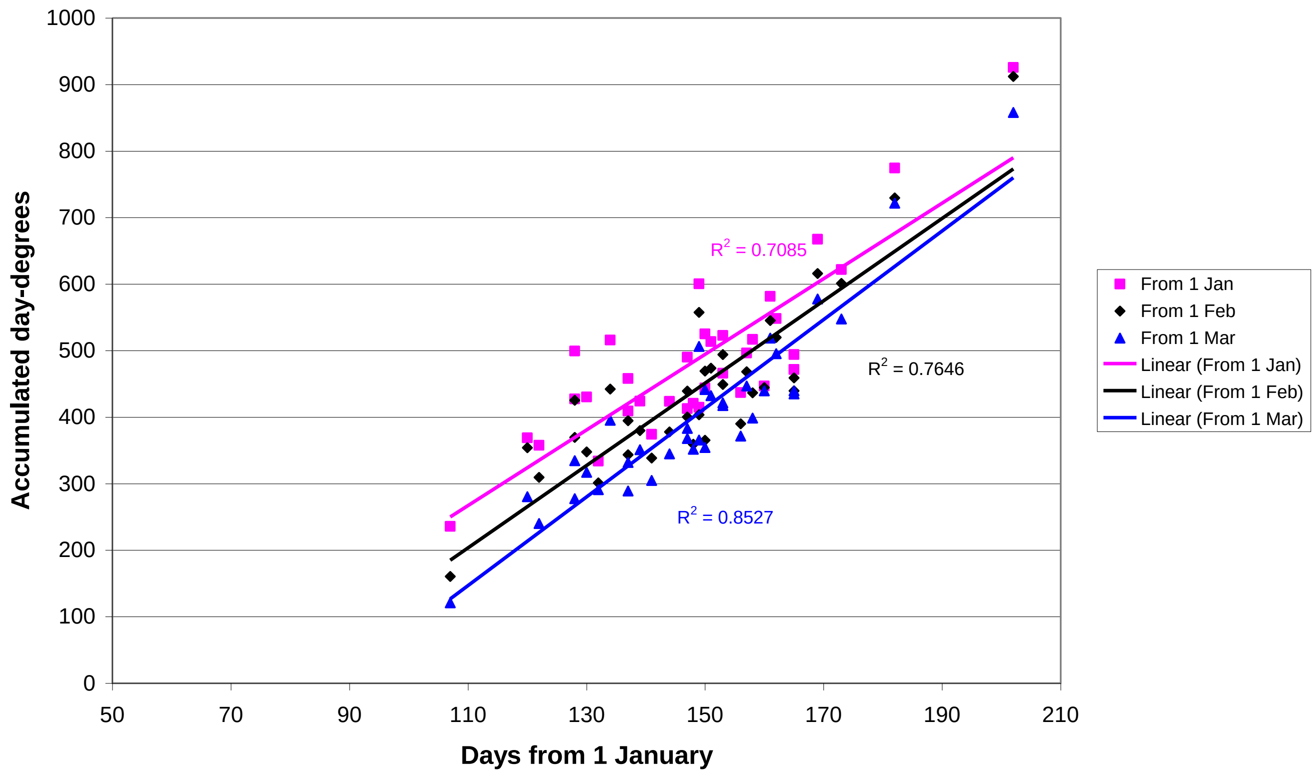

Figure 2.8. The numbers of day-degrees (base 4°C) accumulated from 1 January, 1 February and 1 March to dates of first capture.

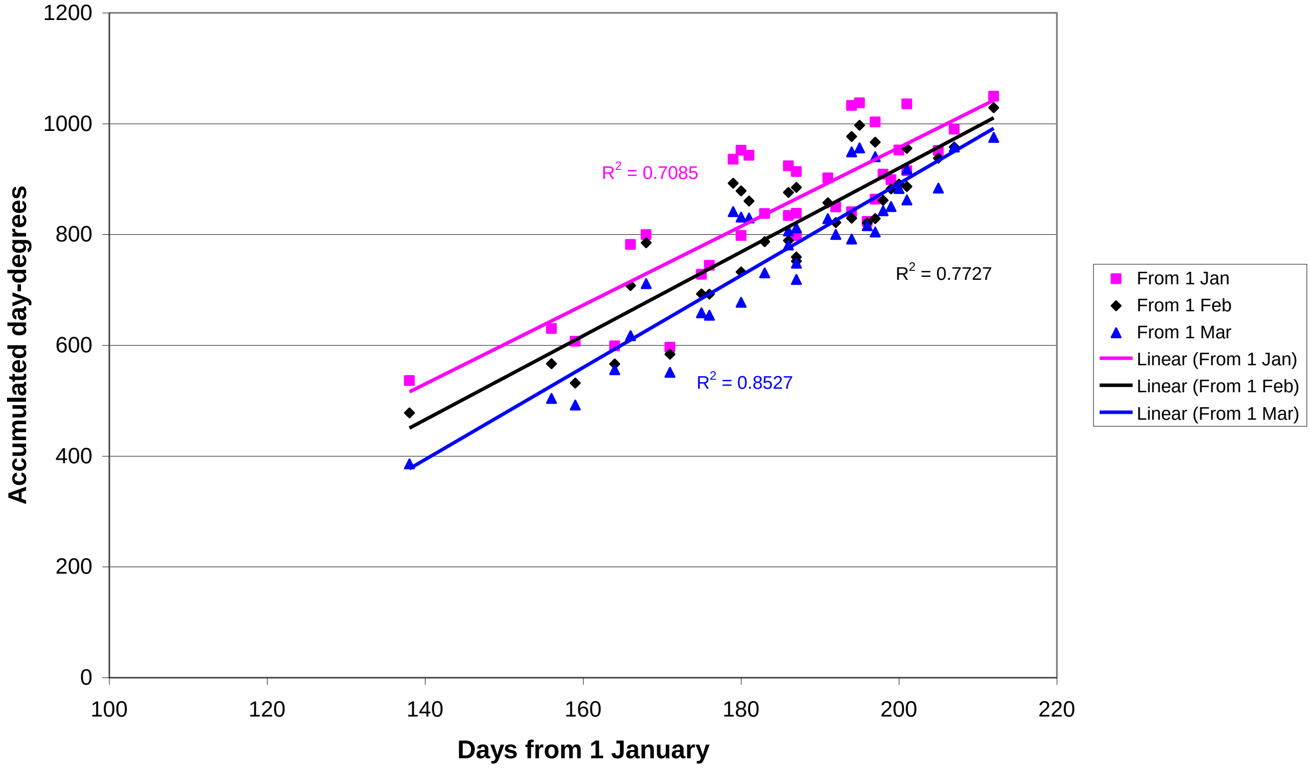

Figure 2.9. The numbers of day-degrees (base 4°C) accumulated from 1 January, 1 February and 1 March to dates of 10% capture.

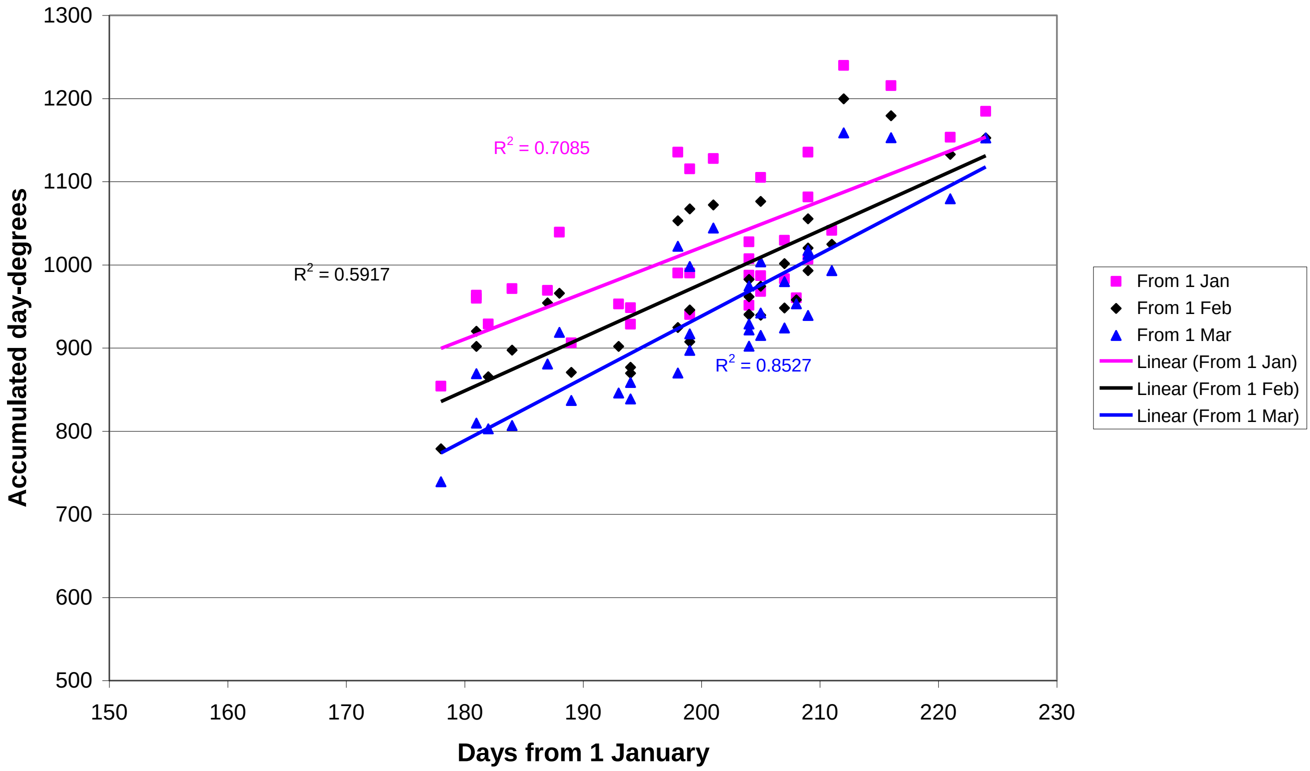

Figure 2.10. The numbers of day-degrees (base 4°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

Figures 2.11-2.13 show the numbers of day-degrees (base 2°C) accumulated from 1 January to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

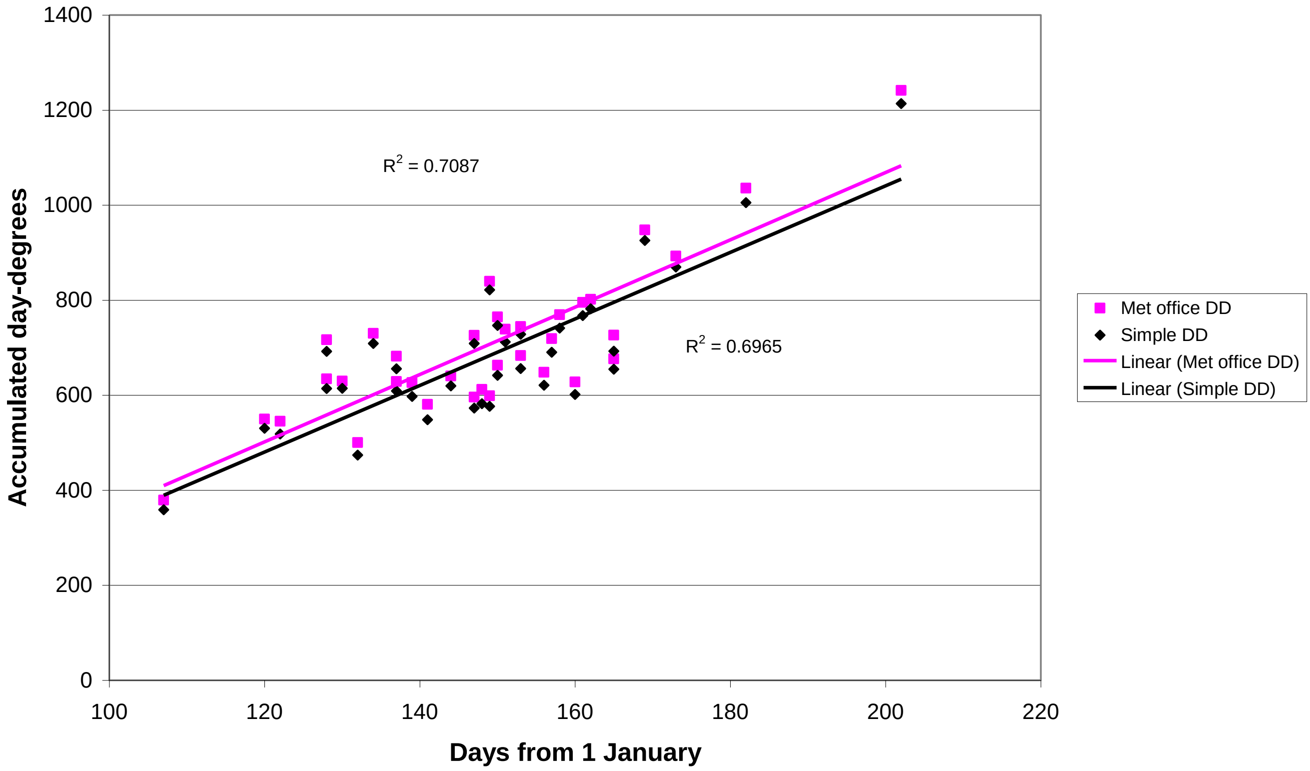

Figure 2.11. The numbers of day-degrees (base 2°C) accumulated to dates of first capture.

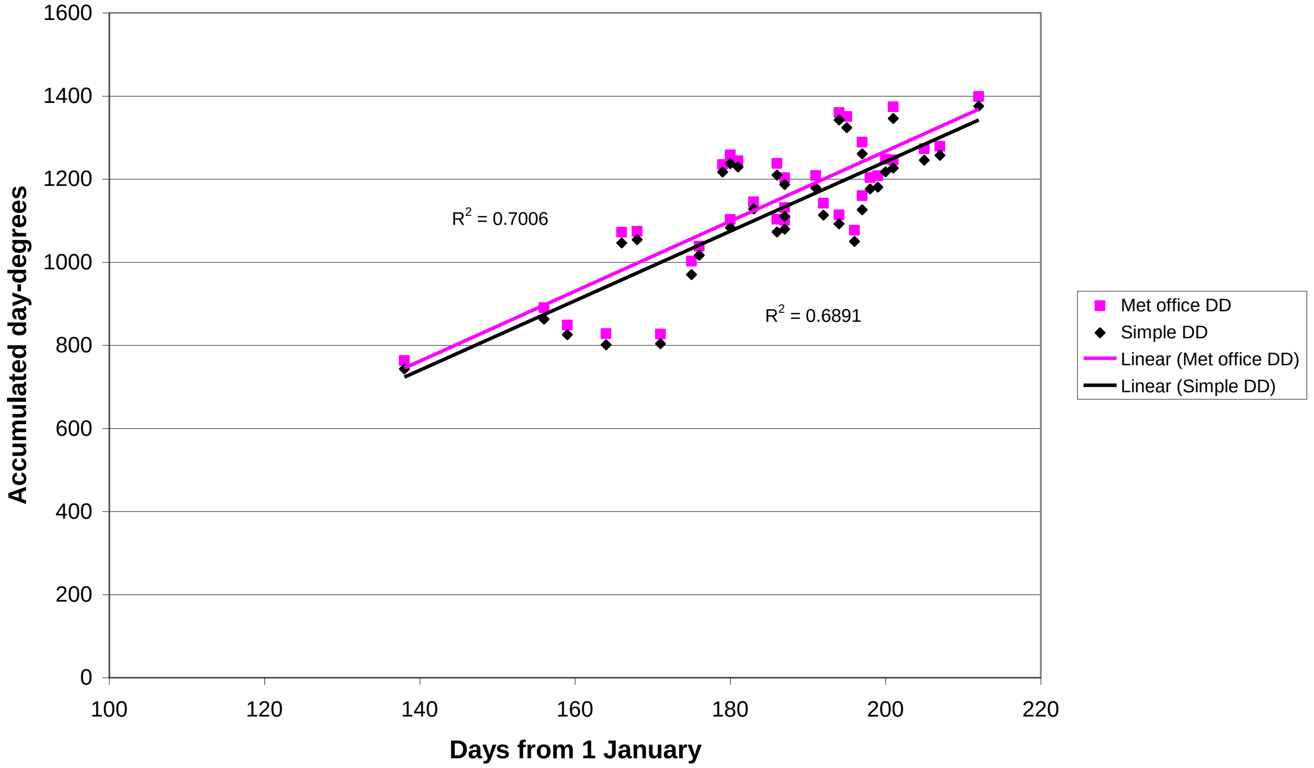

Figure 2.12. The numbers of day-degrees (base 2°C) accumulated to dates of 10% capture.

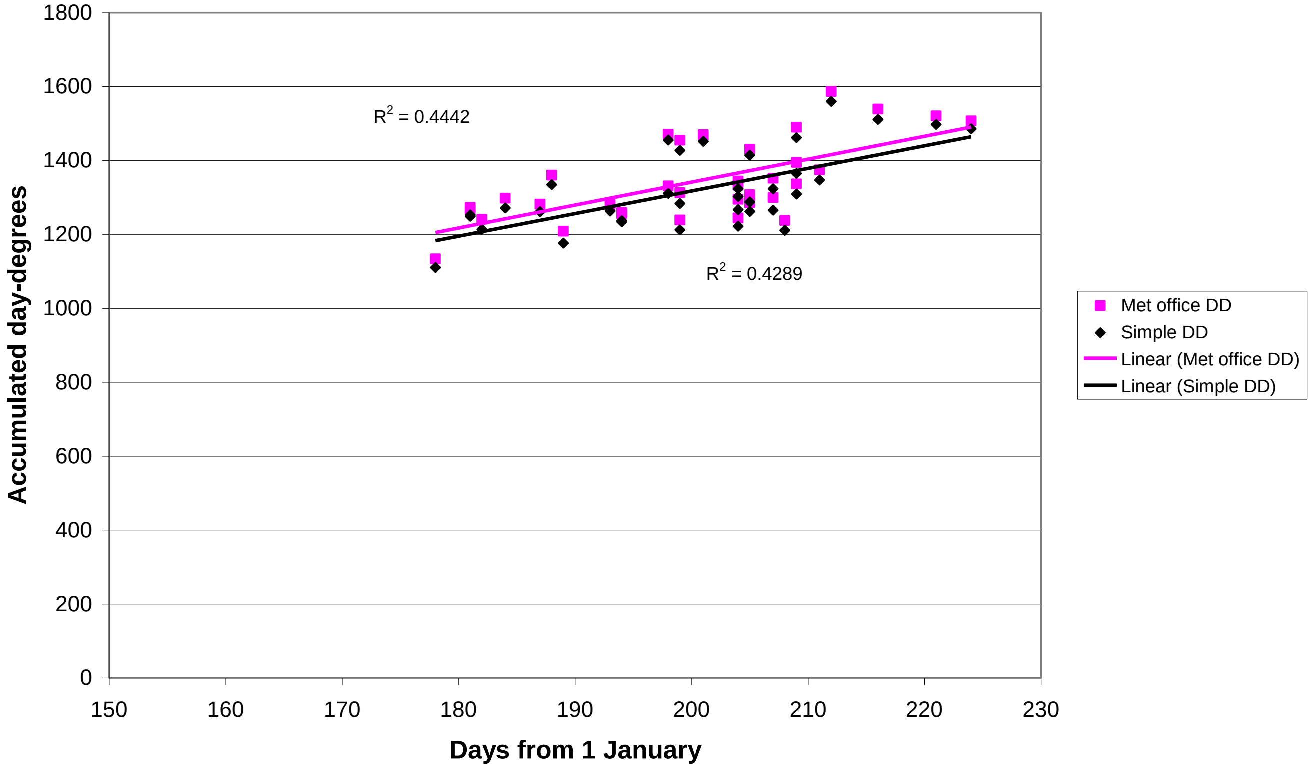

Figure 2.13. The numbers of day-degrees (base 2°C) accumulated to dates of 50% capture.

Figures 2.14-2.16 show the numbers of day-degrees (base 2^{o}C) accumulated from 1 January, 1 February and 1 March to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

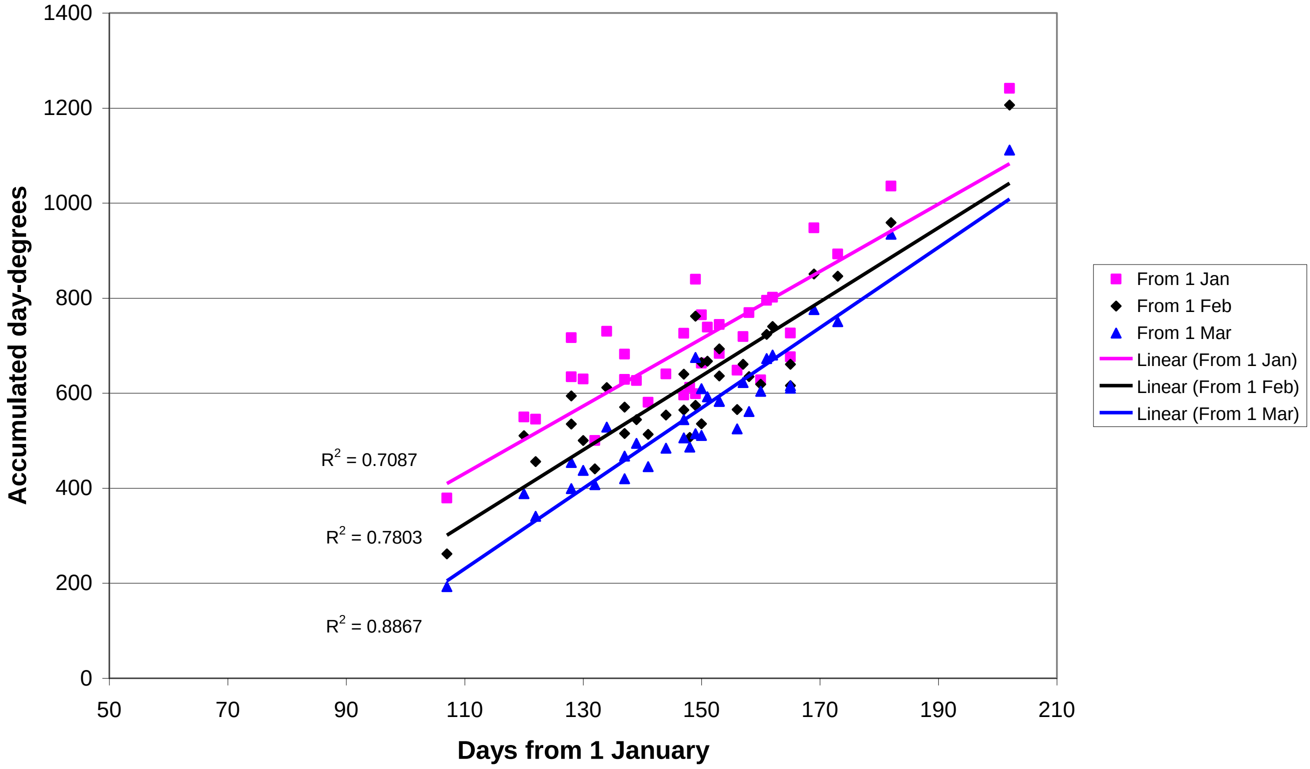

Figure 2.14 . The numbers of day-degrees (base 2^{o}C) accumulated from 1 January, 1 February and 1 March to dates of first capture.

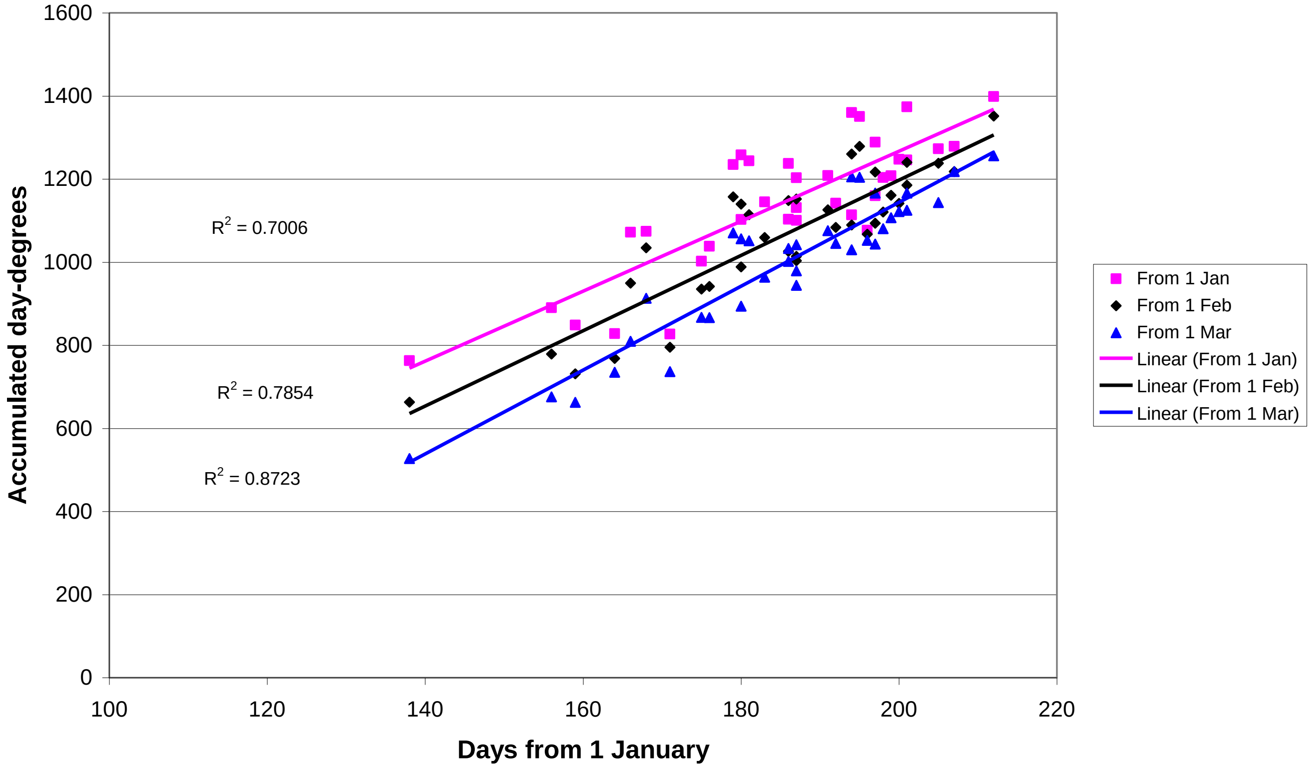

Figure 2.15. The numbers of day-degrees (base 2°C) accumulated from 1 January, 1 February and 1 March to dates of 10% capture.

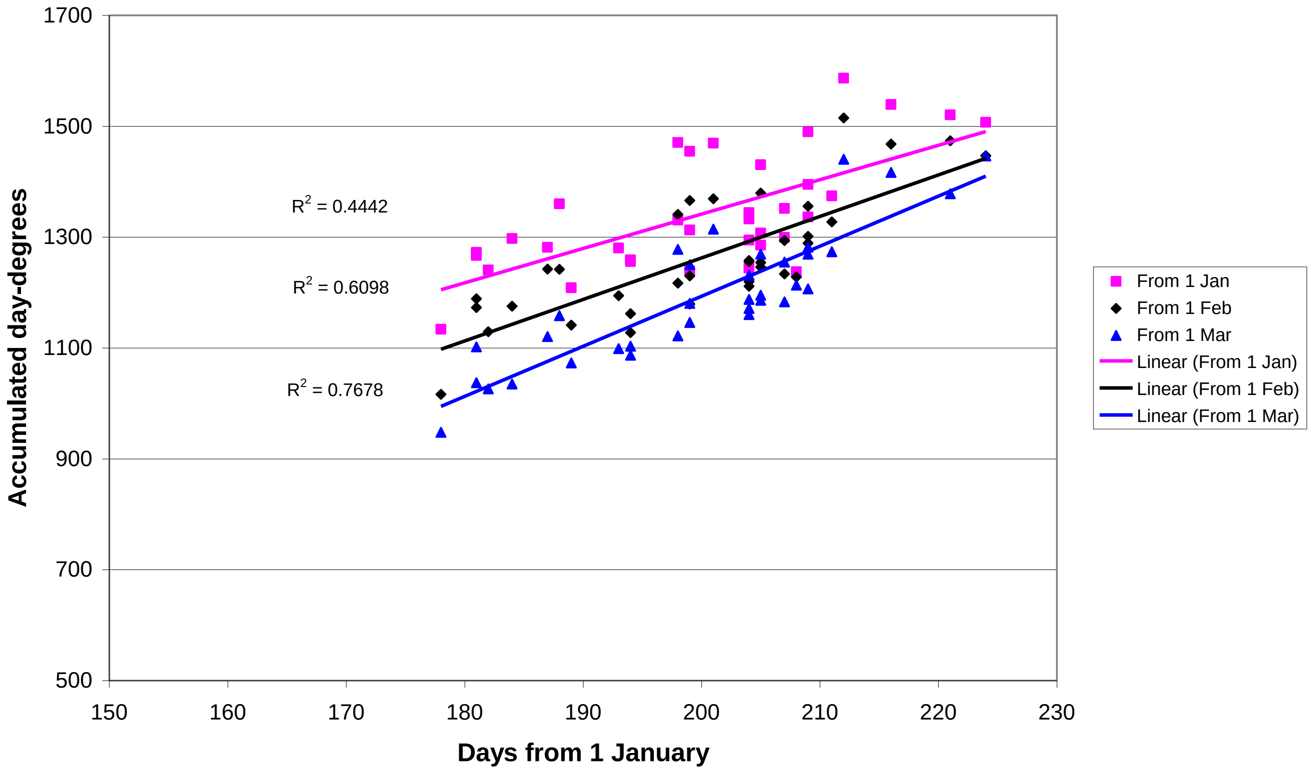

Figure 2.16. The numbers of day-degrees (base 2°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

Figures 2.17-2.19 show the numbers of day-degrees (base 0°C) accumulated from 1 January to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

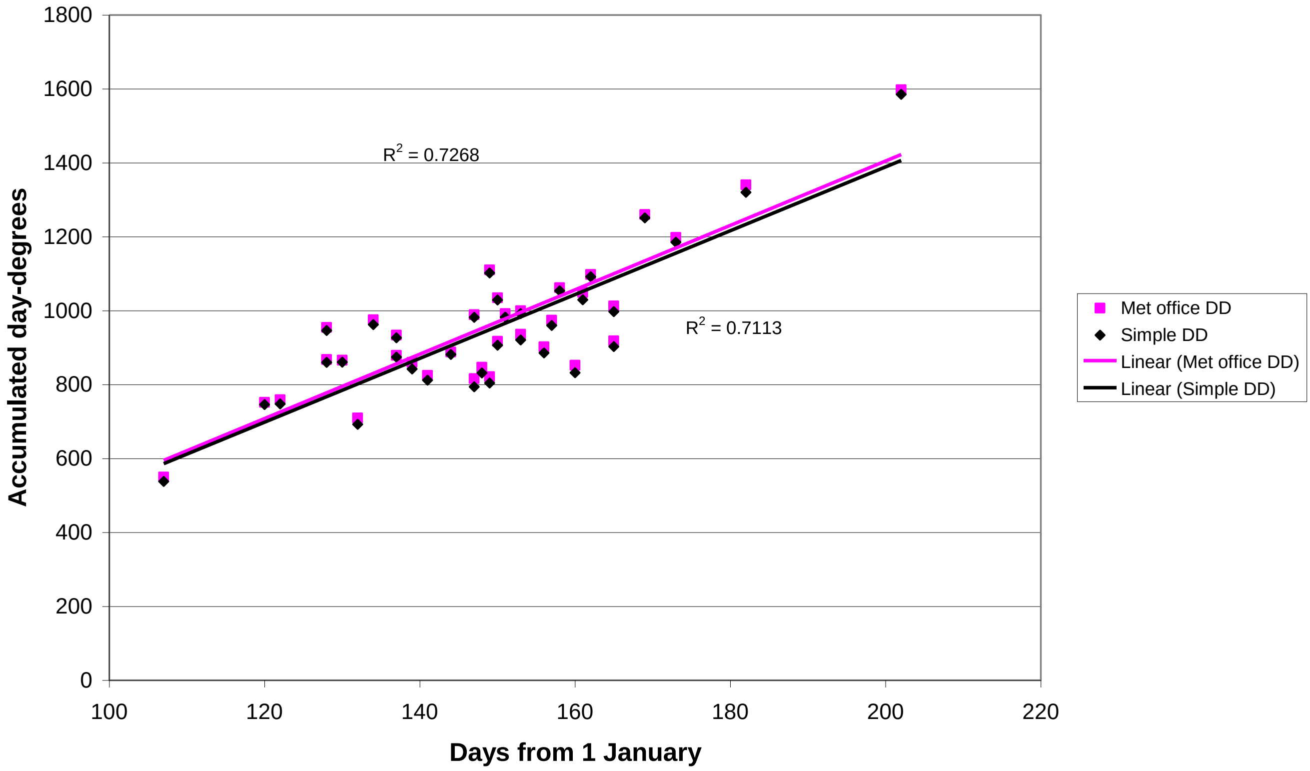

Figure 2.17. The numbers of day-degrees (base 0°C) accumulated to dates of first capture.

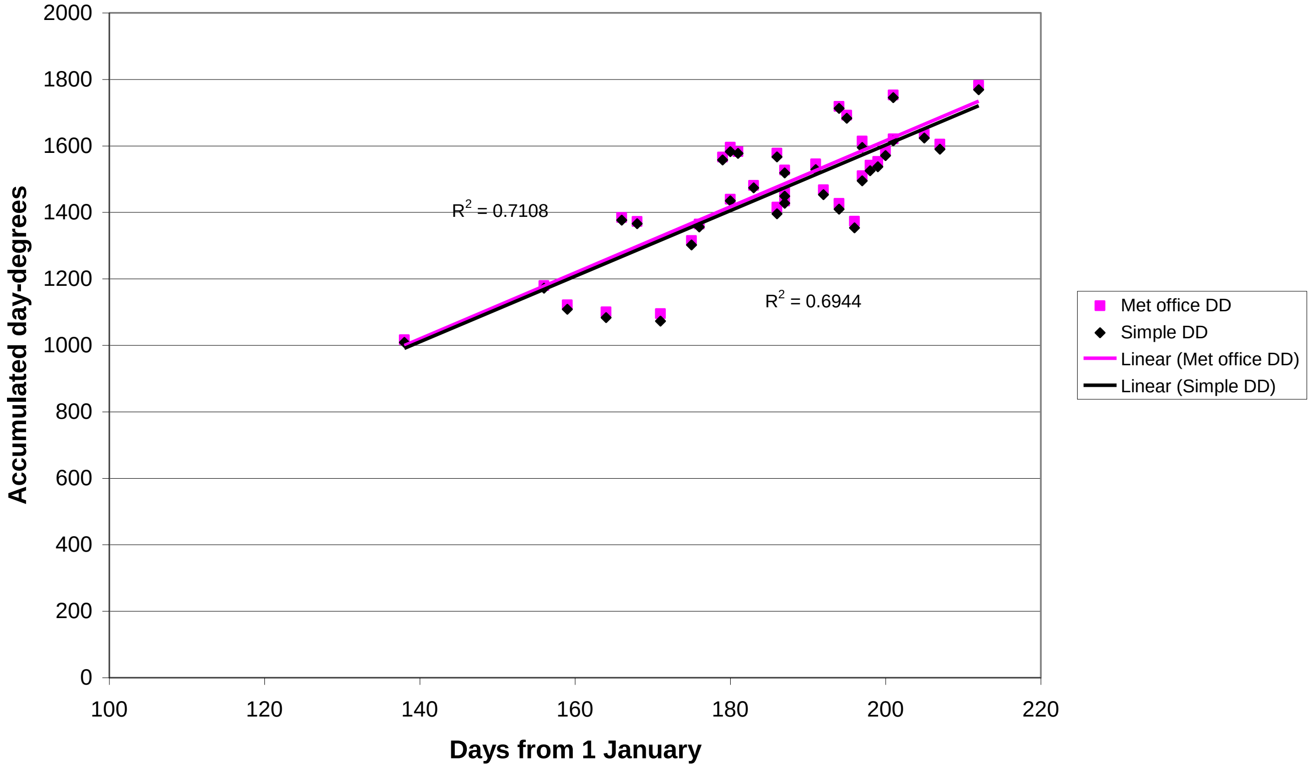

Figure 2.18. The numbers of day-degrees (base 0^{o}C) accumulated to dates of 10% capture.

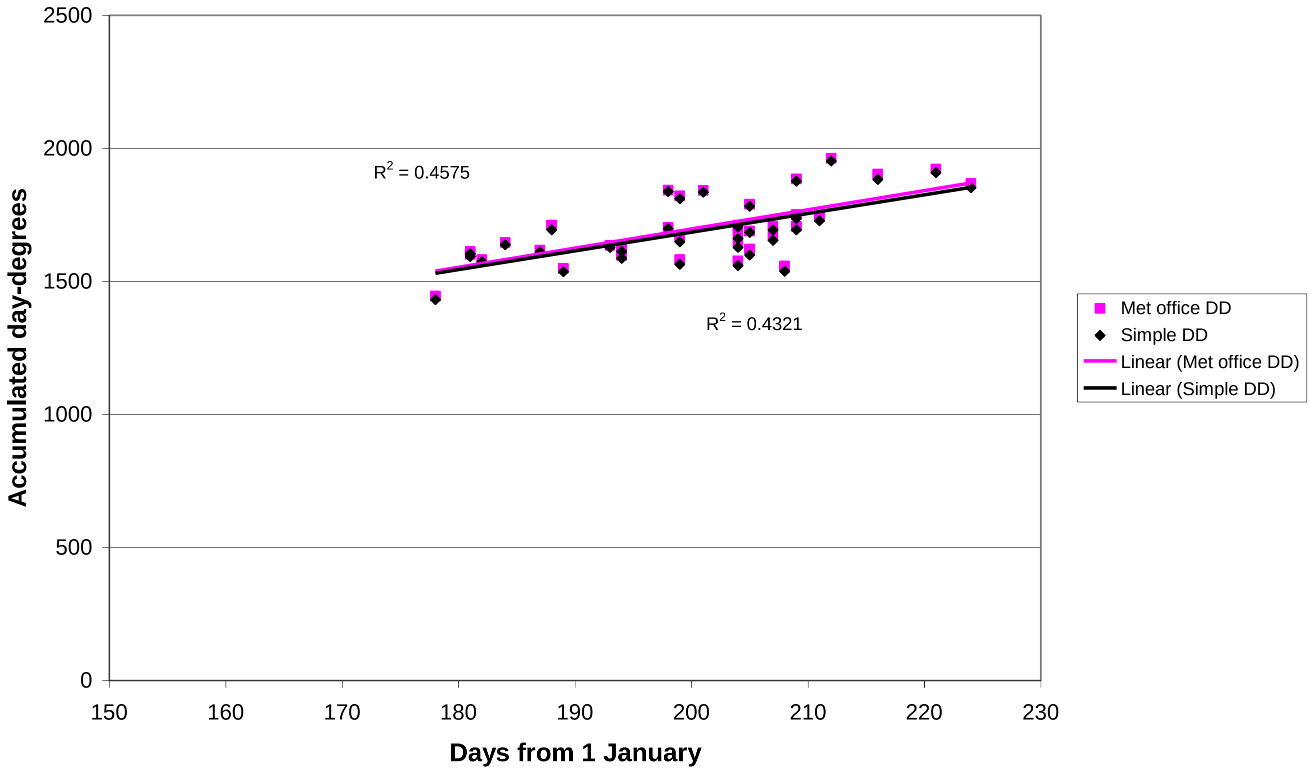

Figure 2.19. The numbers of day-degrees (base 0^{o}C) accumulated to dates of 50% capture.

Figures 2.20-2.22 show the numbers of day-degrees (base 0°C) accumulated from 1 January, 1 February and 1 March to dates of first, 10% and 50% capture. There were linear correlations in all three cases.

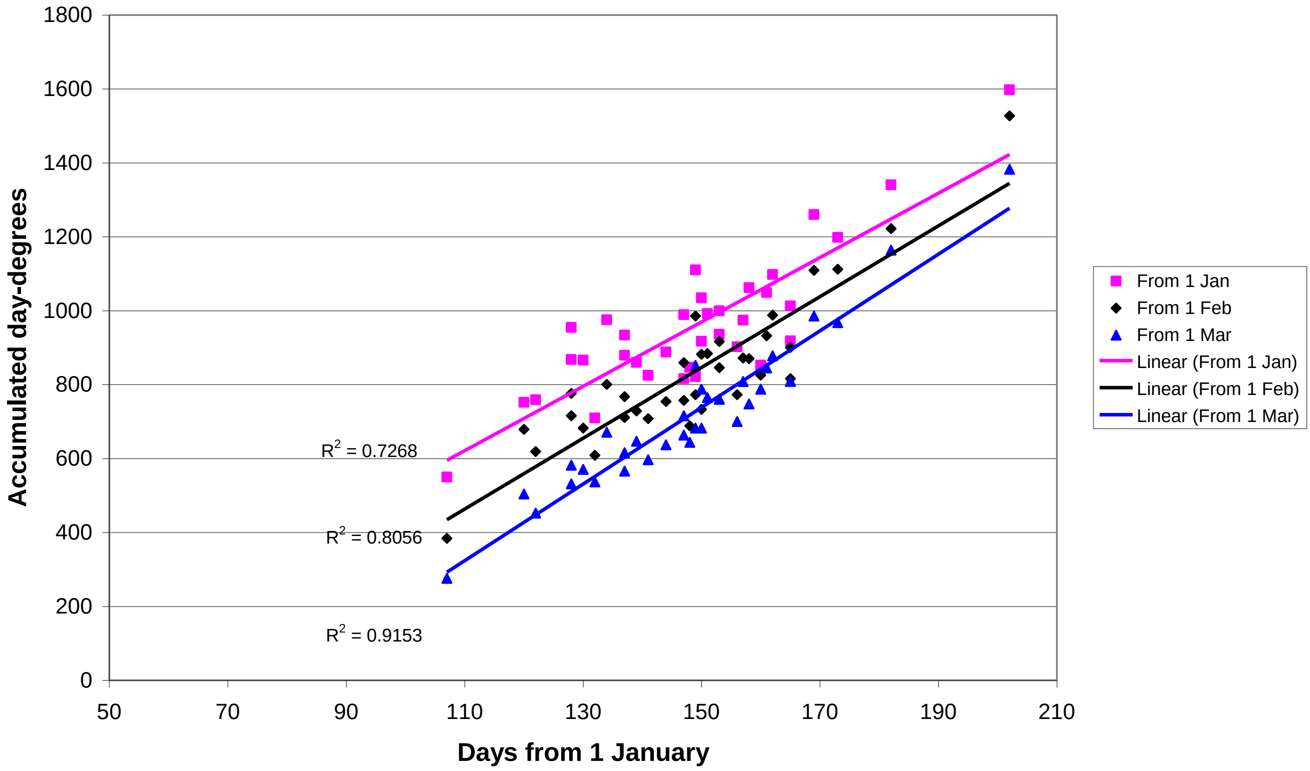

Figure 2.20 . The numbers of day-degrees (base 0°C) accumulated from 1 January, 1 February and 1 March to dates of first capture.

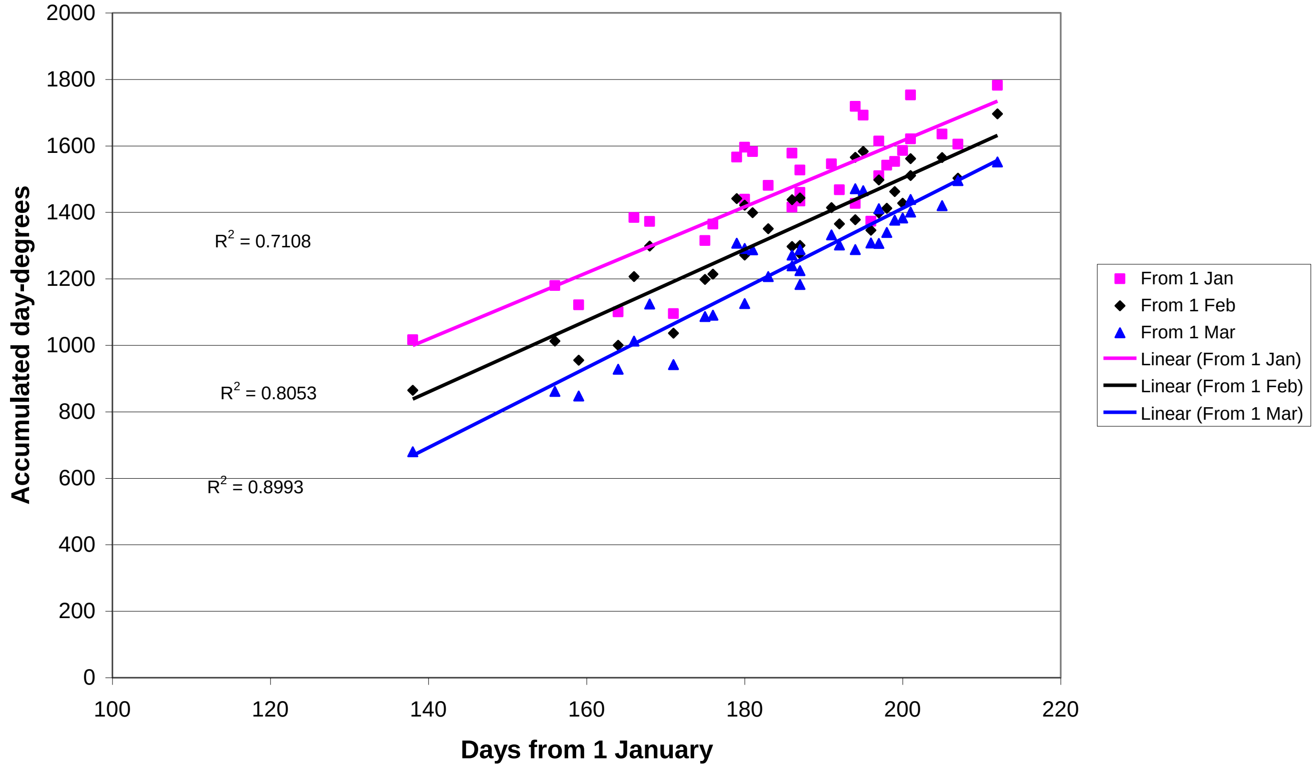

Figure 2.21. The numbers of day-degrees (base 0°C) accumulated from 1 January, 1 February and 1 March to dates of 10% capture.

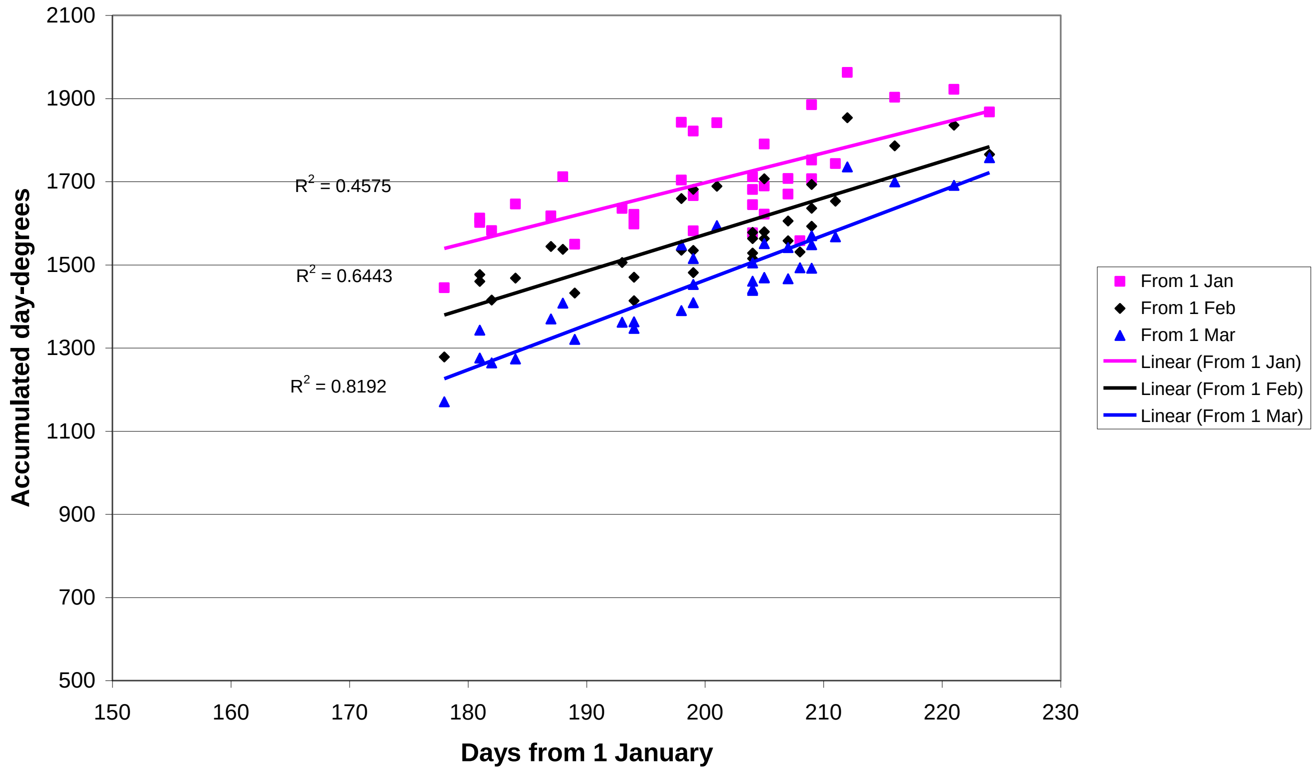

Figure 2.22. The numbers of day-degrees (base 0°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

In all cases there were linear relationships between accumulated day-degrees and the date of capture, indicating that the day-degree sum to a particular event would be dependent on the warmth of the spring/summer and would not be constant.

Further base temperatures and in some cases a later start date of 15 March were tested (Figures 2.23 – 2.27), but in all cases a strong linear relationship prevailed.

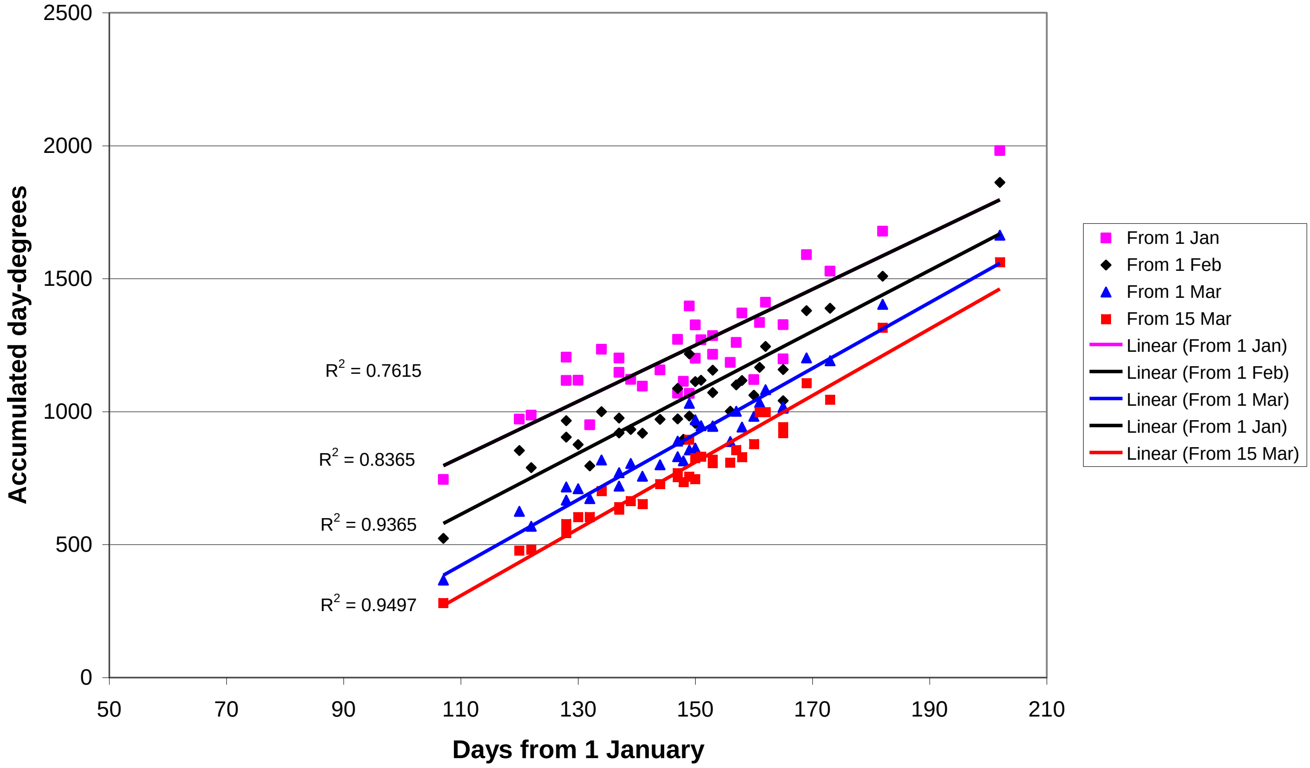

Figure 2.23. The numbers of day-degrees (base -2^{o}C) accumulated from 1 January, 1 February and 1 & 15 March to dates of 50% capture.

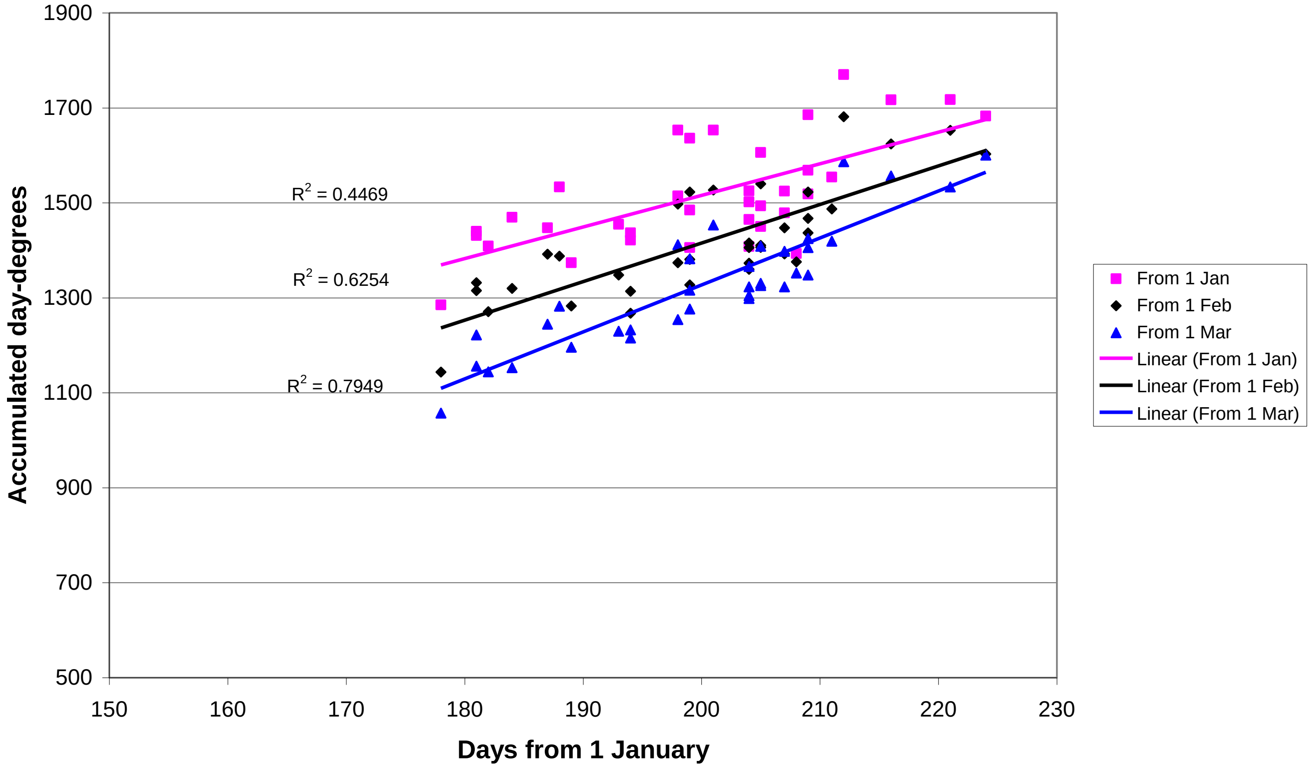

Figure 2.24. The numbers of day-degrees (base 1°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

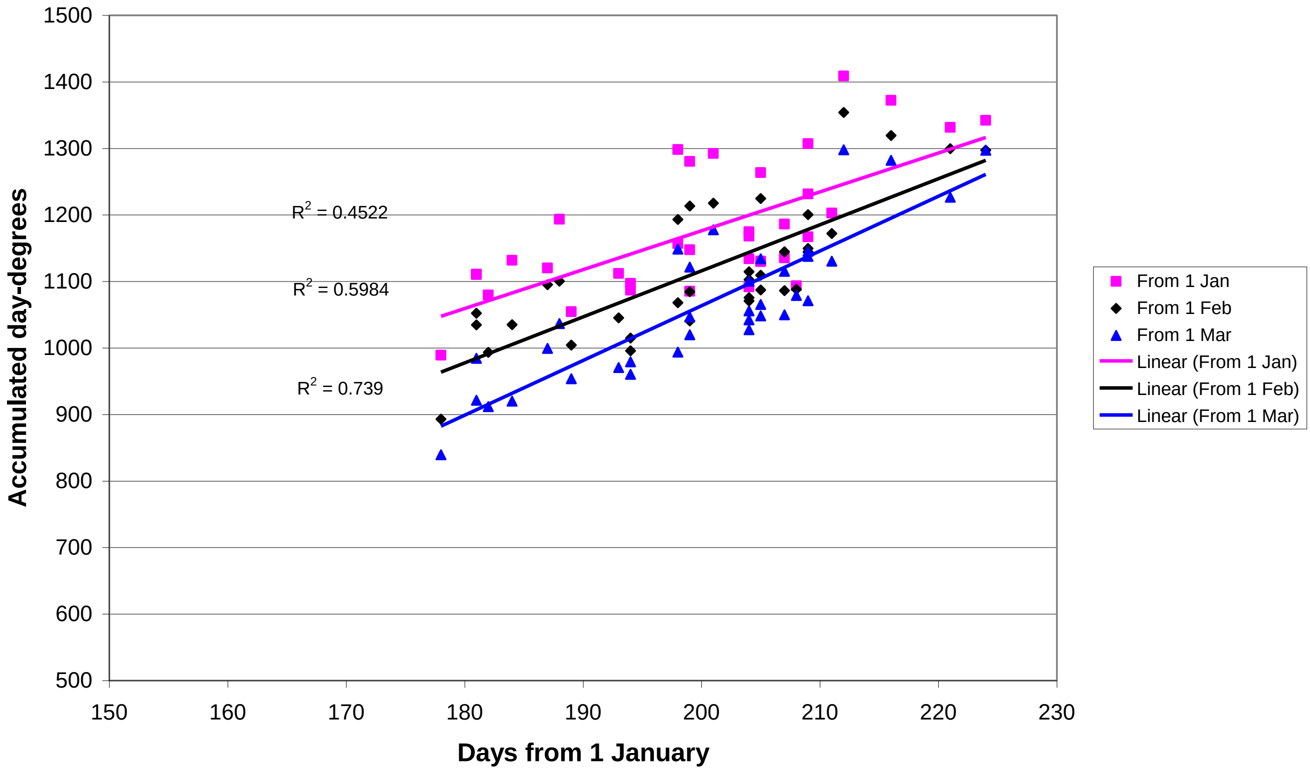

Figure 2.25. The numbers of day-degrees (base 3°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

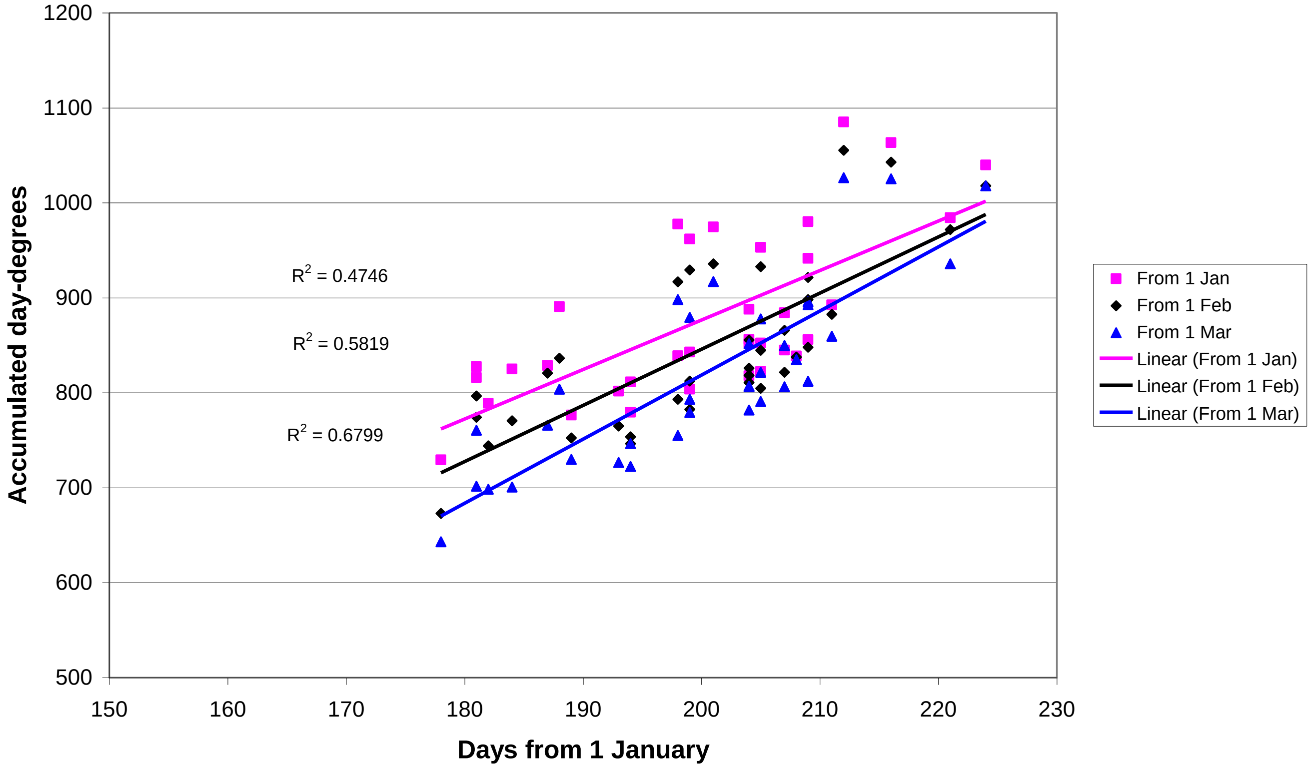

Figure 2.26. The numbers of day-degrees (base 5°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

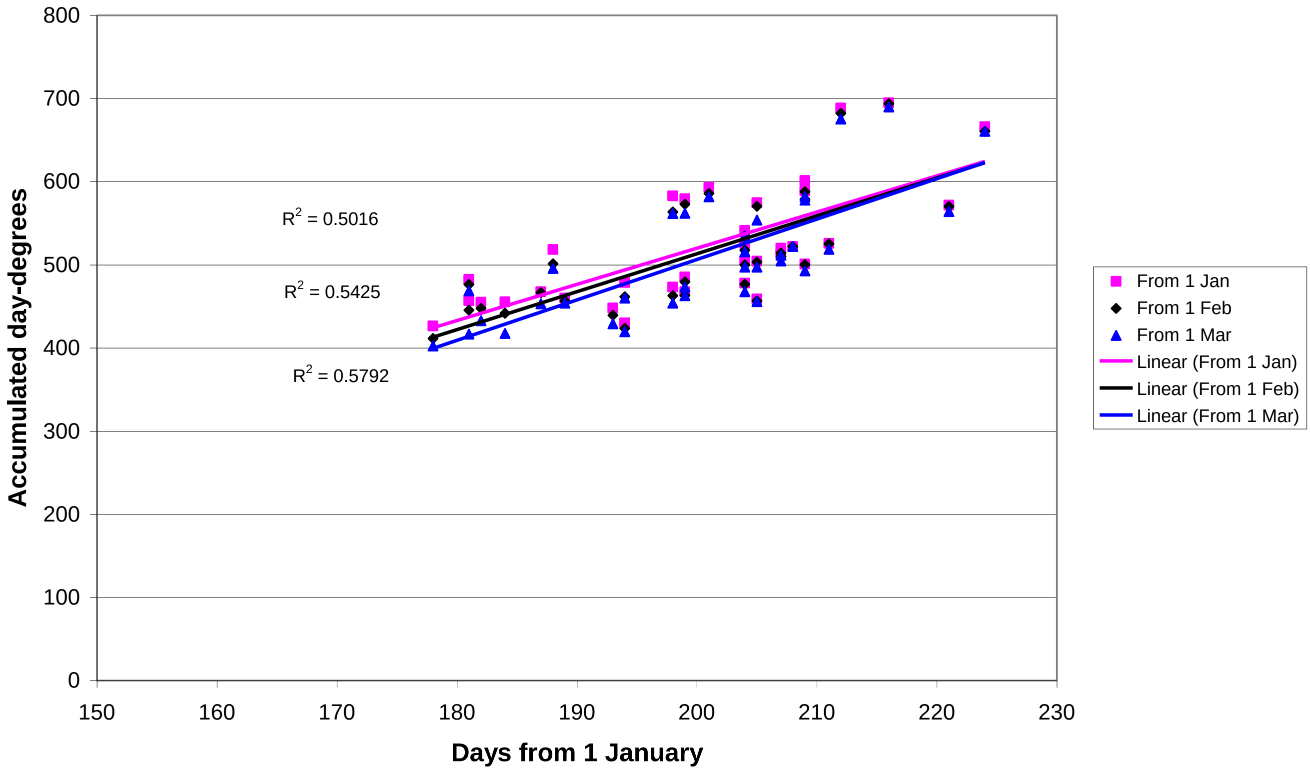

Figure 2.27. The numbers of day-degrees (base 8°C) accumulated from 1 January, 1 February and 1 March to dates of 50% capture.

Data set – several sites 1981-88

This data set consists of capture dates for a range of sites, all in the period 1981-88 (Table 3.1). This was to determine whether the relationships identified for one site over a number of years were consistent with those from other sites.

Table 3.1. Capture dates for a range of sites, all in the period 1981-88.

Location of trap	Year	Total number in year	No. of days after 1 January: First aphid	10% aphids	50% aphids	Aphids to 15 June	Aphids to 31 August
Ayr	1981	160	193	212	223	0	93
Ayr	1982	133	152	202	215	1	100
Ayr	1983	140	187	218	226	0	139
Ayr	1984	62	206	229	234	0	61
Ayr	1985	33	211	216	228	0	18
Ayr	1986	107	194	223	225	0	24
Ayr	1987	44	155	201	220	1	42
Ayr	1988	13	202	204	213	0	10
Brooms Barn	1981	624	151	194	207	5	562
Brooms Barn	1982	221	167	190	206	0	140
Brooms Barn	1983	389	150	189	197	5	353
Brooms Barn	1984	386	157	207	211	4	362
Brooms Barn	1985	1250	146	203	211	7	1173
Brooms Barn	1986	2141	181	216	228	0	2119
Brooms Barn	1987	320	143	195	205	1	244
Brooms Barn	1988	434	147	199	217	3	378
Dundee	1981	184	200	220	234	0	99
Dundee	1982	485	187	216	225	0	269
Dundee	1983	28	222	222	230	0	27
Dundee	1984	16	221	223	230	0	15
Dundee	1985	13	231	231	237	0	3
Dundee	1986	1261	192	226	233	0	264
Dundee	1987	143	152	230	238	1	123
Dundee	1988	16	217	221	228	0	11
Hereford	1981	764	151	191	210	3	764
Hereford	1982	213	152	189	225	2	65
Hereford	1983	155	155	187	194	8	154

Hereford	1984	48	167	181	227	0	42
Hereford	1985	158	145	203	205	2	118
Hereford	1986	396	152	195	220	2	357
Hereford	1987	143	179	194	231	0	118
Hereford	1988	162	142	181	201	4	112
Kirton	1981	1714	142	206	221	4	1440
Kirton	1982	215	176	191	213	0	138
Kirton	1983	248	157	193	209	2	144
Kirton	1984	258	201	206	211	0	140
Kirton	1985	452	180	203	210	0	282
Kirton	1986	1014	182	205	225	0	954
Kirton	1987	504	172	218	229	0	270
Kirton	1988	226	146	200	227	1	162
Starcross	1981	377	173	196	210	0	373
Starcross	1982	39	136	136	190	3	8
Starcross	1983	252	149	185	193	11	249
Starcross	1984	30	159	190	198	2	24
Starcross	1985	28	154	182	203	1	17
Starcross	1986	114	162	191	202	1	95
Starcross	1987	201	139	187	197	6	199
Starcross	1988	41	165	172	186	2	27
Writtle	1981	833	133	192	208	22	815
Writtle	1982	556	151	195	212	1	505
Writtle	1983	1116	150	187	192	8	1100
Writtle	1984	169	168	194	203	0	158
Writtle	1985	176	147	193	206	4	170
Writtle	1986	421	153	200	216	1	412
Writtle	1987	111	148	195	201	2	97
Writtle	1988	114	128	170	201	6	71
Wye	1981	353	139	191	201	12	345
Wye	1982	54	146	171	211	2	48
Wye	1983	189	142	185	192	9	183
Wye	1984	119	155	186	204	4	112
Wye	1985	246	161	196	204	3	224
Wye	1986	298	158	191	201	8	293
Wye	1987	55	186	189	193	0	47

Wye	1988	56	147	174	192	1	51

Firstly, the 1981-88 data set was used to investigate the relationship between latitude and the timing of capture, and latitude and the total number of aphids captured.

Figures 3.1-3.3 show the relationships between the date of capture of the first, 10% and 50% aphids and latitude of the suction trap site. All were strongly correlated, the further north the trap, the later the aphids were captured.

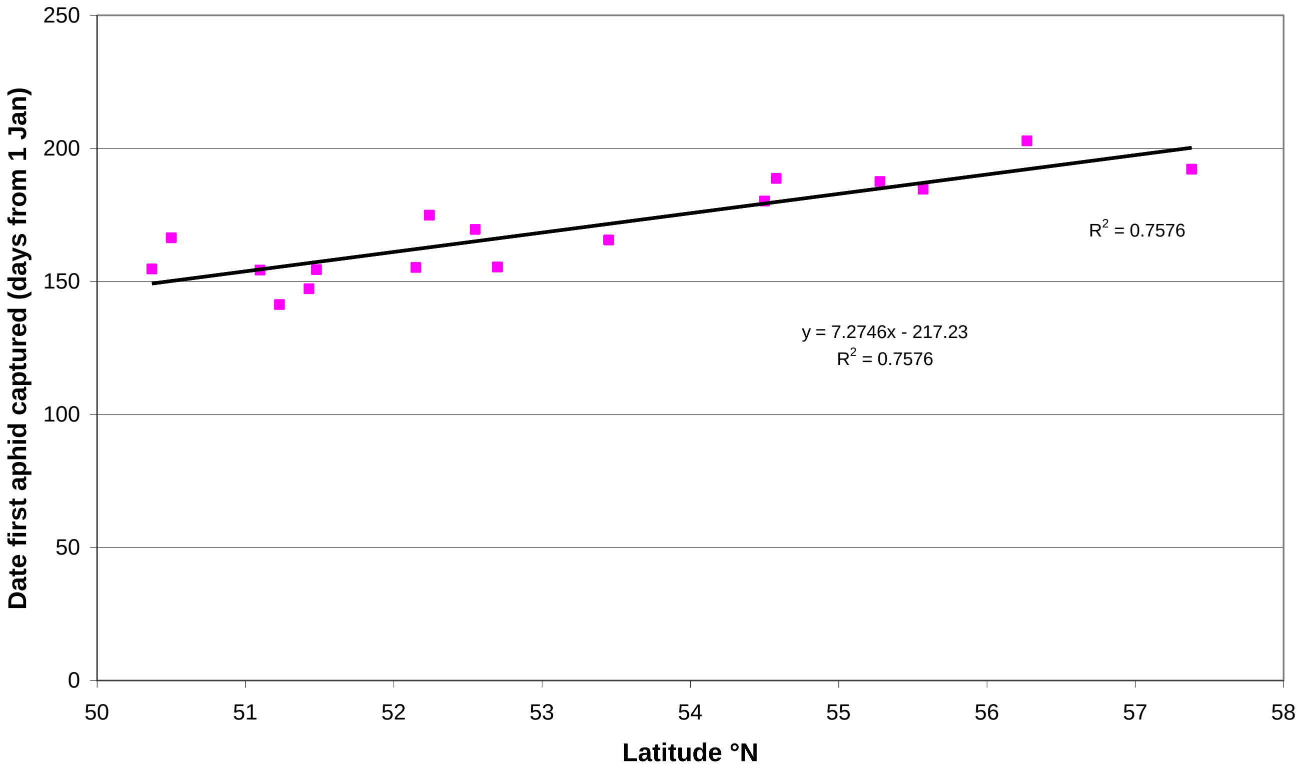

Figure 3.1. Relationships between the date of capture of the first aphid and latitude of the suction trap site.

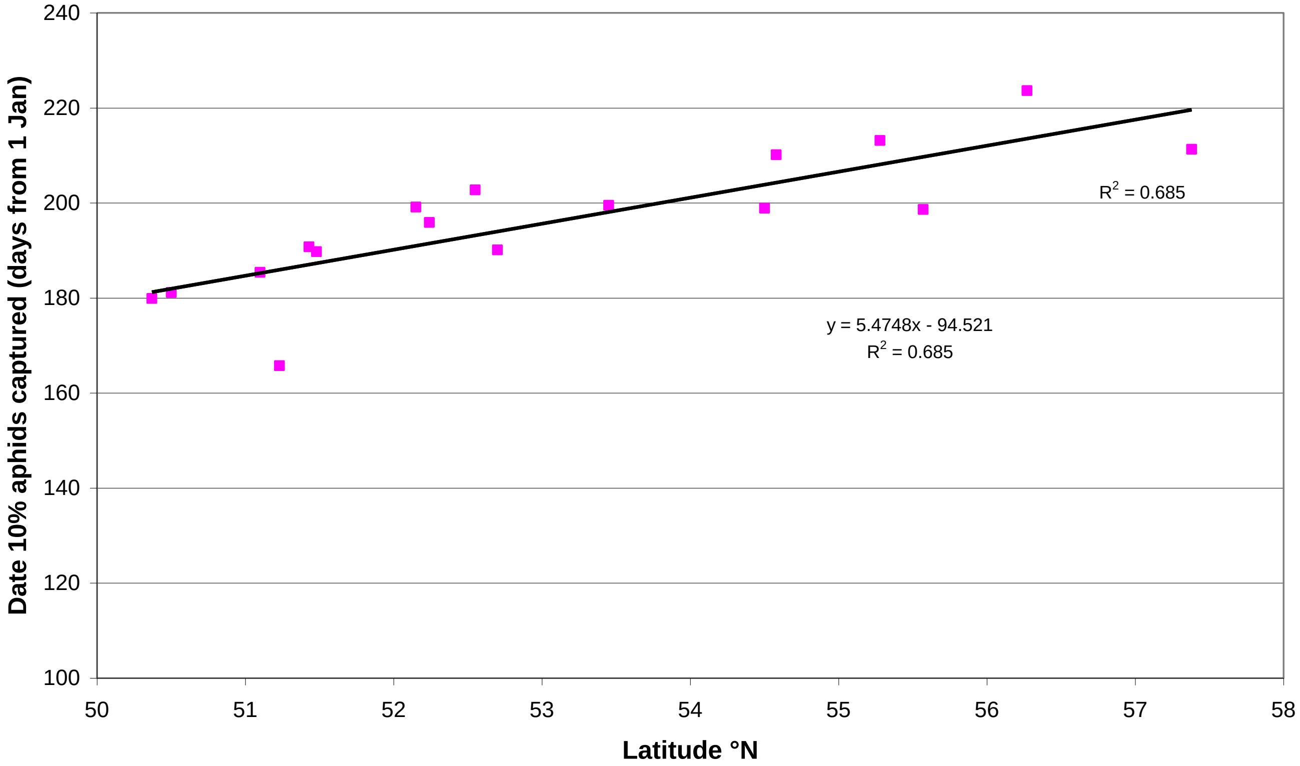

Figure 3.2. Relationships between the date of capture of 10% aphids and latitude of the suction trap site.

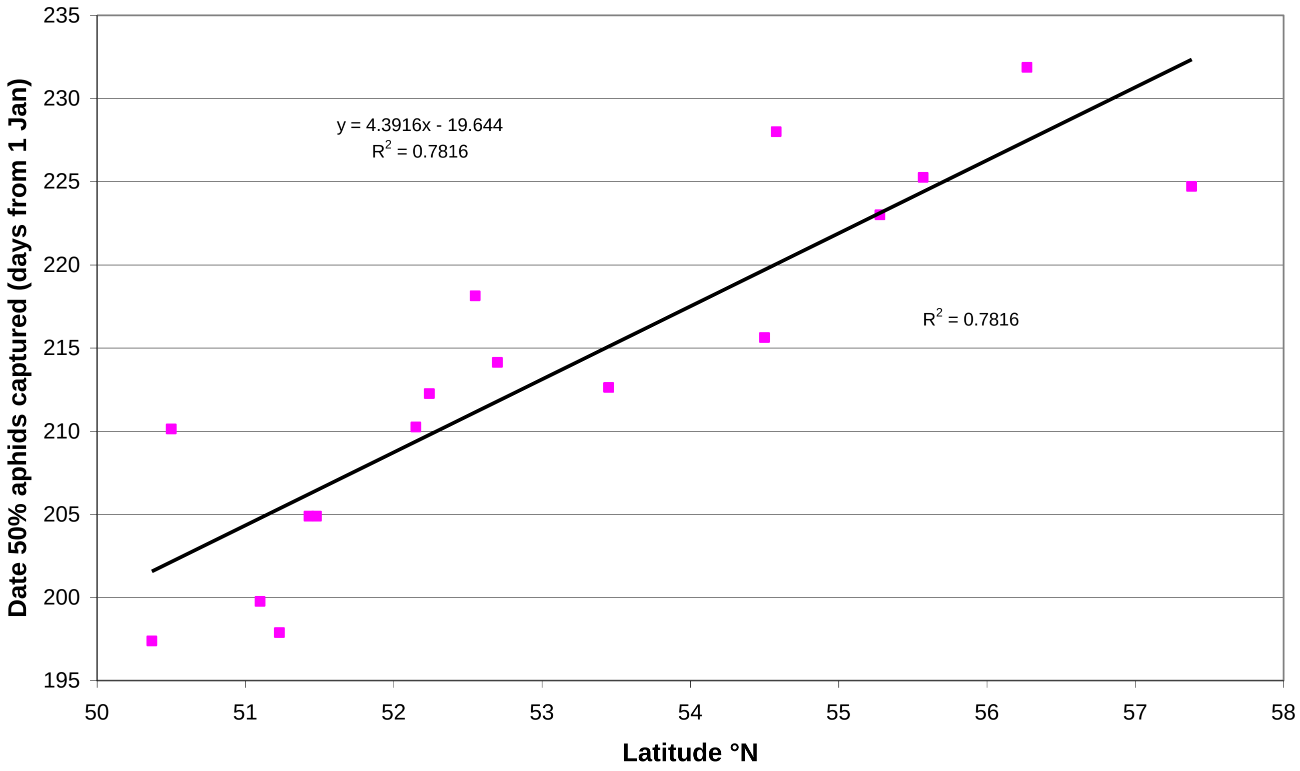

Figure 3.3. Relationships between the date of capture of 50% aphids and latitude of the suction trap site.

Investigating relationships with temperature and the possible use of day-degree sums

The comparisons were undertaken using a base temperature of 2°C.

Figures 3.4-3.6 show the relationships between the first, 10% and 50% capture dates and the mean temperature from January-May inclusive for the 1981-88 and Rothamsted data sets. There was a considerable amount of scatter and whilst the fitted lines (Rothamsted and 1981-88 data sets) appeared to have the same slope the intercepts were different.

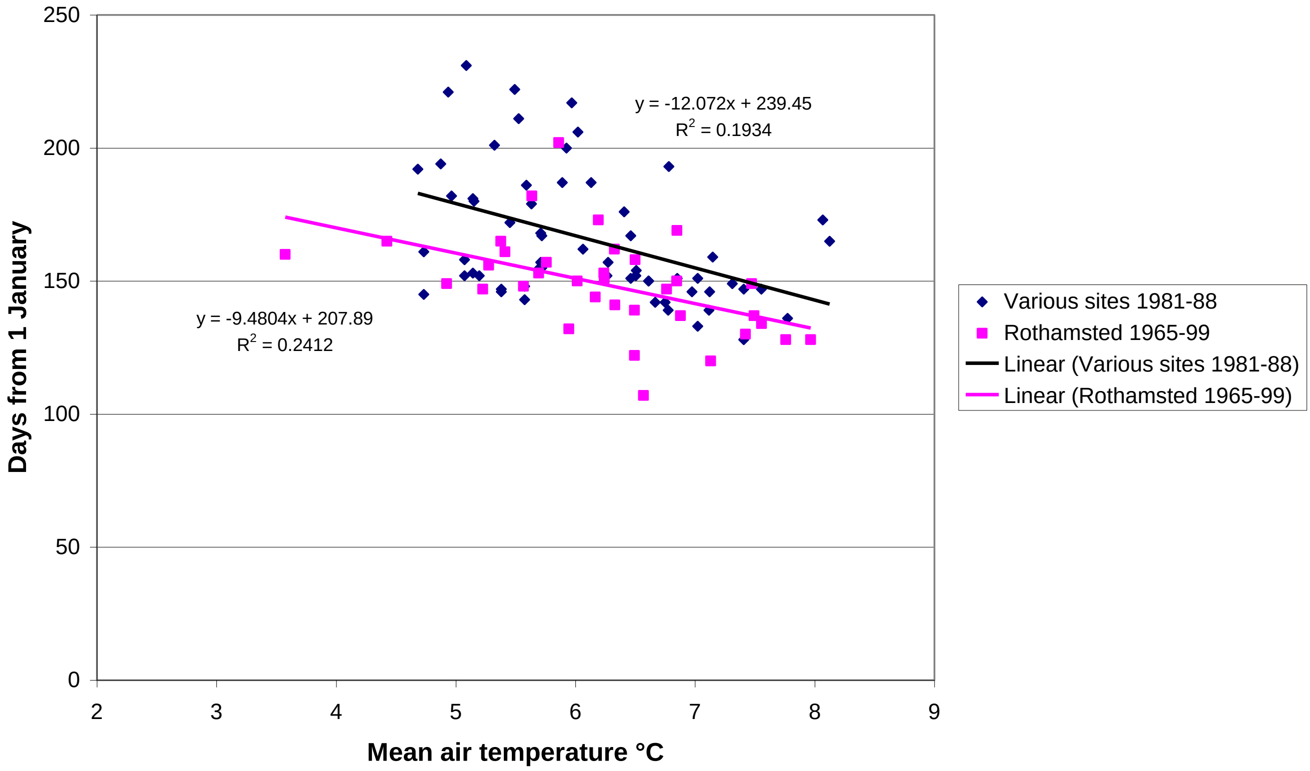

Figure 3.4. Relationship between date first aphid captured each year and mean temperature from January-May inclusive for the 1981-88 and Rothamsted data sets.

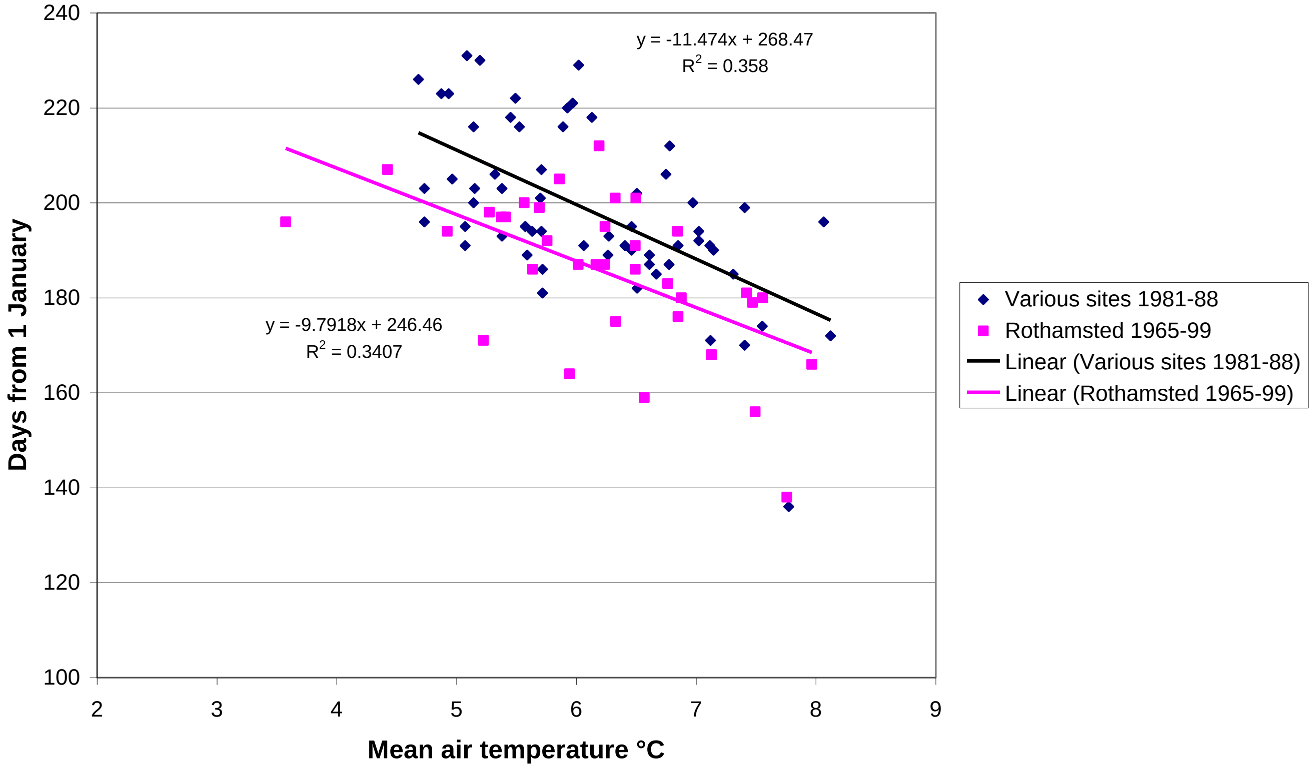

Figure 3.5. Relationship between date 10% aphids captured each year and mean temperature from January-May inclusive for the 1981-88 and Rothamsted data sets.

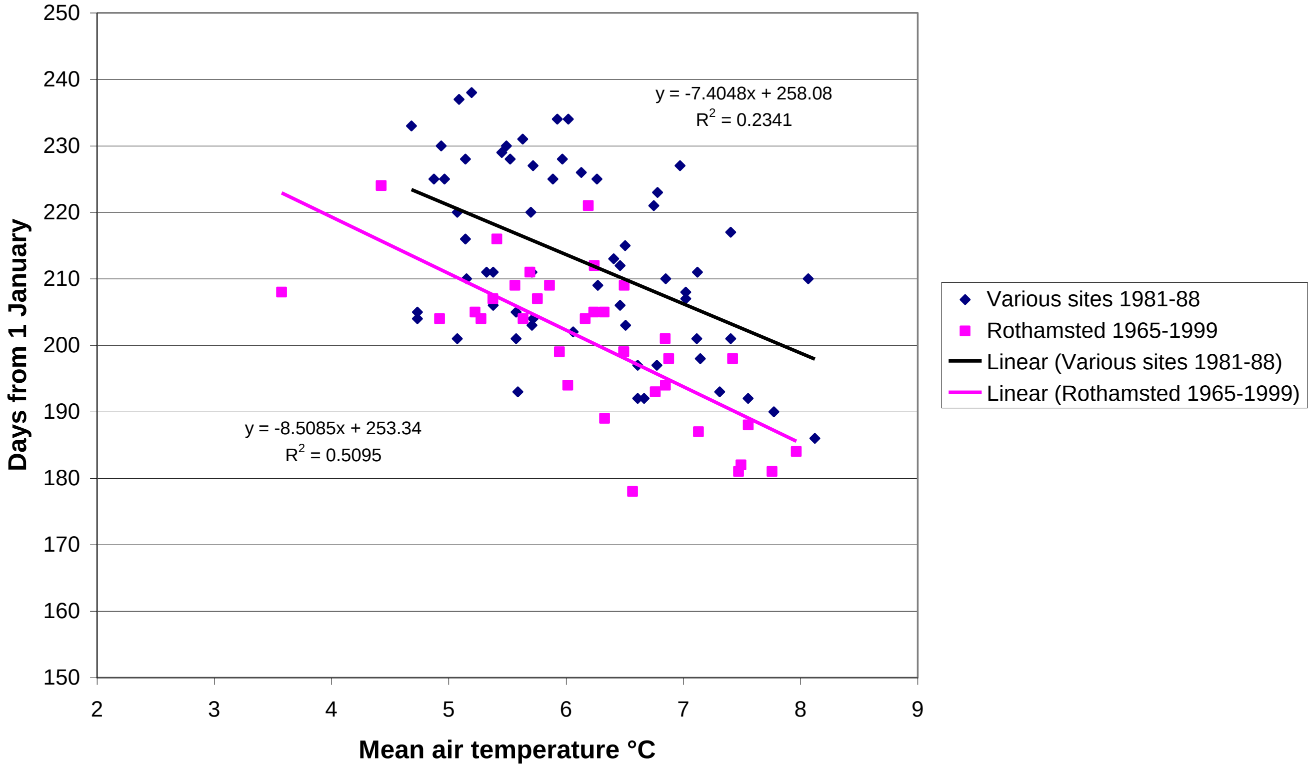

Figure 3.6. Relationship between date 50% aphids captured each year and mean temperature from January-May inclusive for the 1981-88 and Rothamsted data sets.

Figures 3.7-3.9 show the accumulated day-degrees above 2°C from 1 January to first capture and the dates of 10% and 50% capture of aphids for the 1981-88 and Rothamsted data sets. Here, the two sets of data are quite similar with the strong relationship between accumulated day-degrees and day number being very evident.

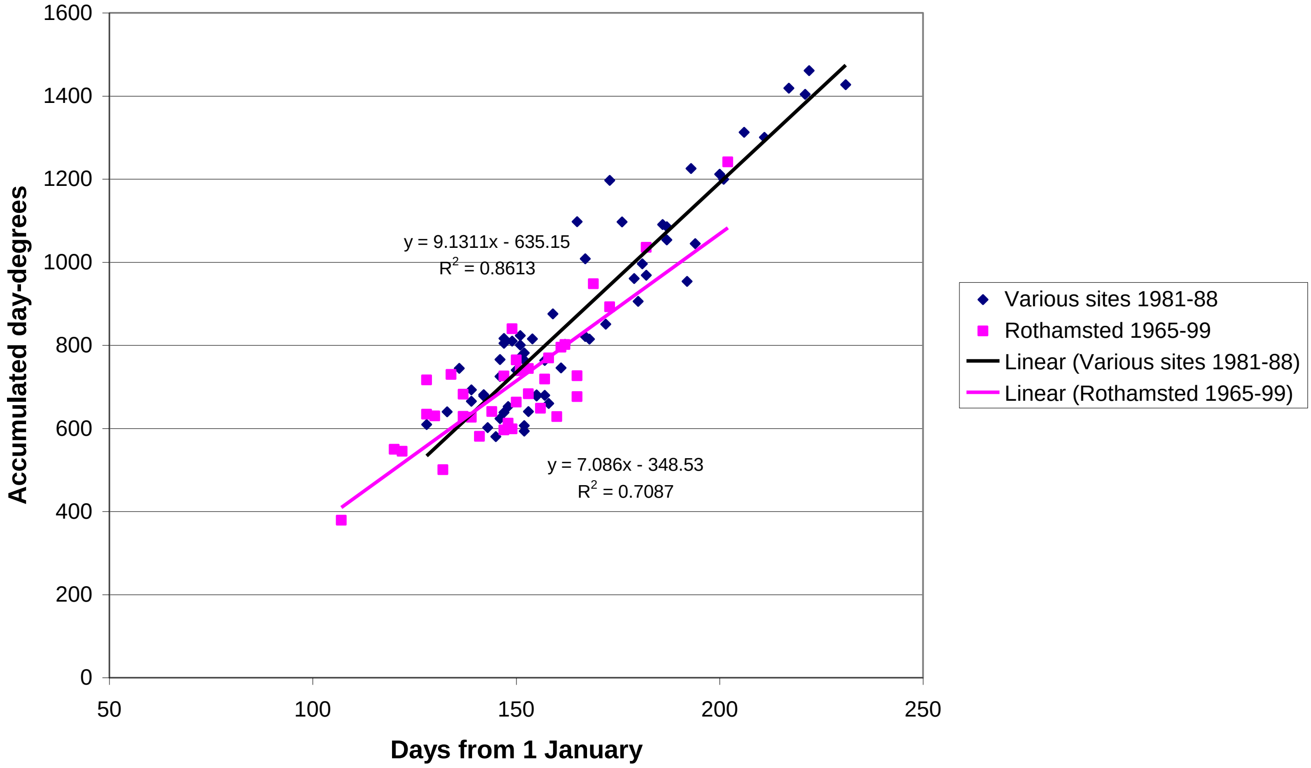

Figure 3.7. The accumulated day-degrees above 2°C from 1 January to first capture of aphids for the 1981-88 and Rothamsted data sets.

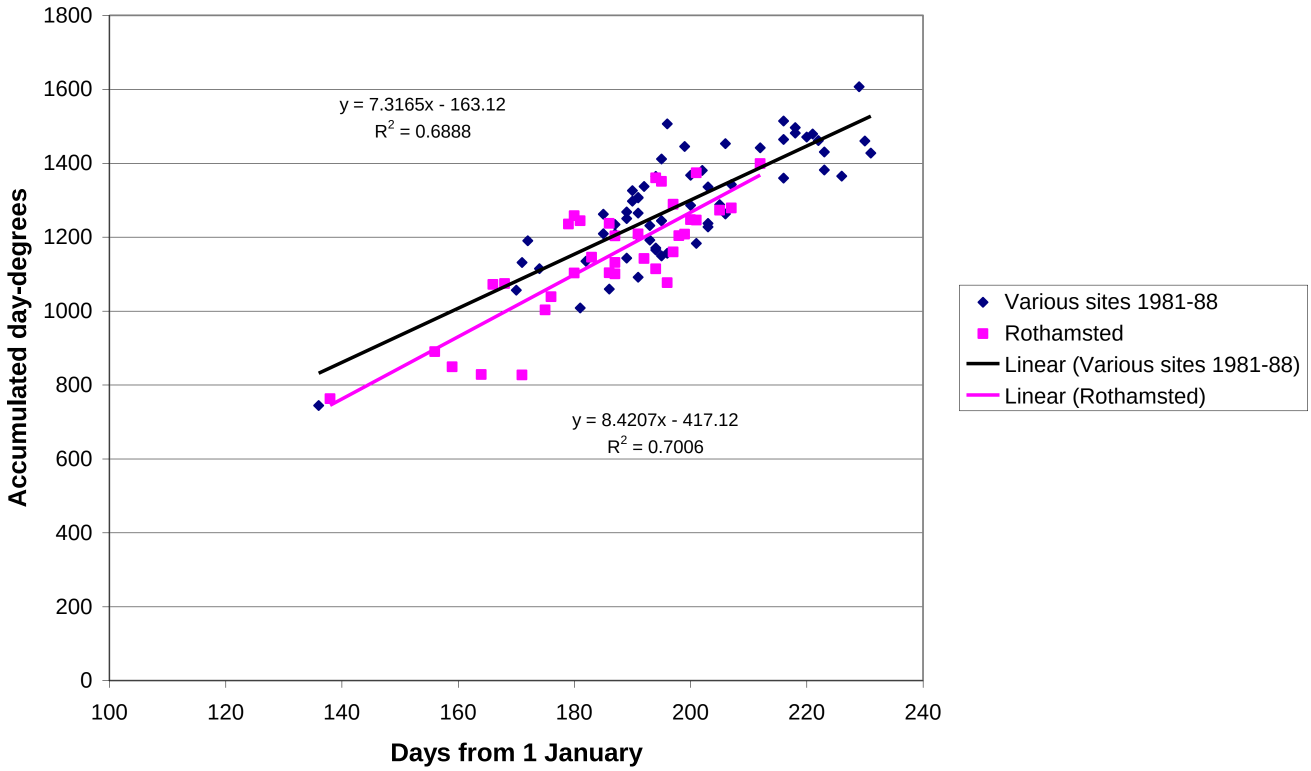

Figure 3.8. The accumulated day-degrees above 2°C from 1 January to the date of 10% capture of aphids for the 1981-88 and Rothamsted data sets.

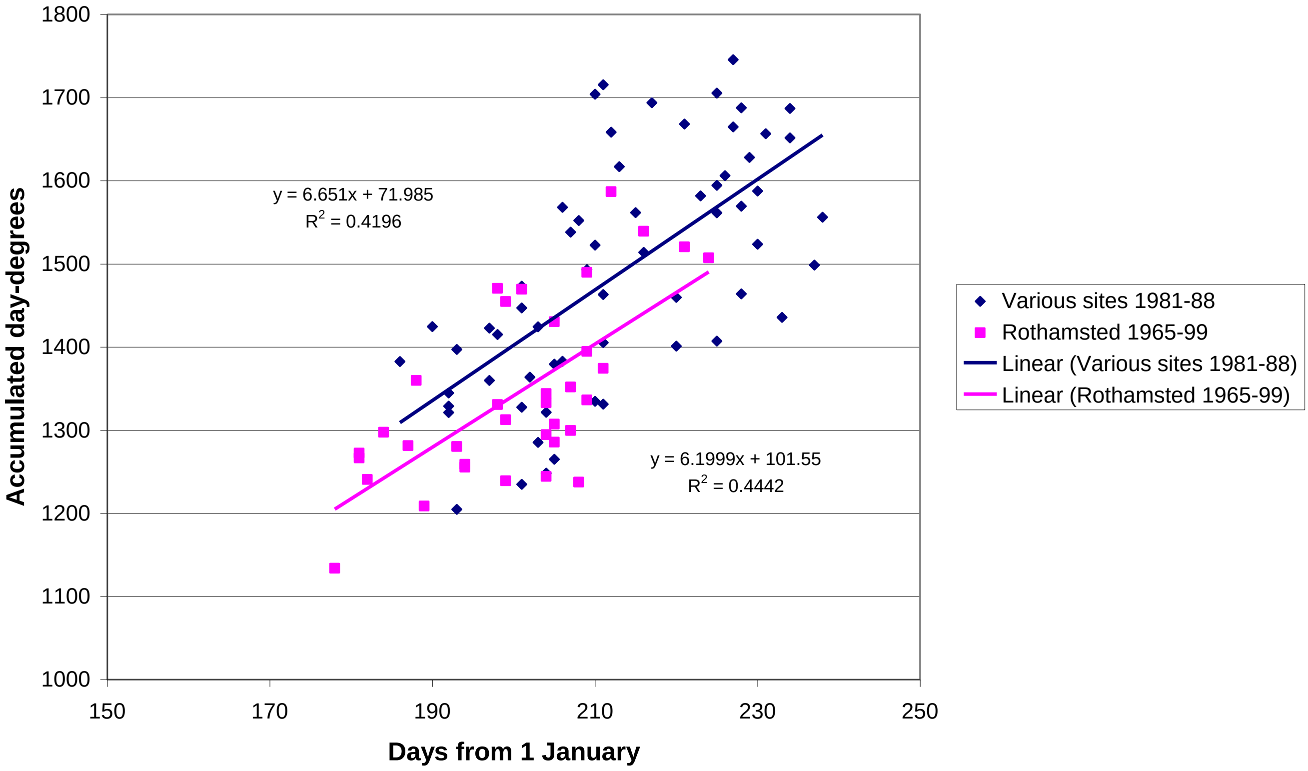

Figure 3.9. The accumulated day-degrees above 2°C from 1 January to the date of 50% capture of aphids for the 1981-88 and Rothamsted data sets.

Developing a forecast for Aphis fabae

The further calculations undertaken in this project confirmed the initial findings of Project FV 407, which were that the dates of first and 50% capture were highly negatively correlated with measures of mean temperature; the warmer the spring, the earlier the first aphid and 50% aphids were captured. In FV 407, the relationship was very similar for the two sites evaluated. In addition, in this study, the date of 10% capture was also negatively correlated with all of the measures of mean temperature so that, as with the date of first capture and 50% capture, the warmer the spring, the earlier the date when 10% of aphids were captured.

What was 'unexpected' in the current project is that this relationship did not translate into a relatively constant number of day-degrees from a fixed start date (e.g. 1 January, 1 February or 1 March) to a particular event e.g. first capture, 10% capture or 50% capture. Whilst a certain amount of variability would be expected, because the capture of aphids in suction traps is essentially a random process, the strong positive linear relationships between the date of the event and accumulated day-degrees to that event indicate the influence of other factors apart from random variation.

Potential factors that might account for an absence of a constant day-degree sum are a lack of linearity in the relationship between the rate of insect development and temperature and/or the choice of an inappropriate base temperature for the day-degree calculation. A study by Tsitsipis and Mittler (1976) indicated that the base temperature for the development of *A. fabae* nymphs was 5.5^{o}C, although the plotted relationship between rate of development and temperature was slightly curvilinear.

In principle, if the relationship between the rate of insect development and temperature is linear, then providing the appropriate base temperature is used, the day-degree sum to complete that particular stage of development should be constant regardless of the temperature of the environment. Figure 4.1 illustrates the effect of using inappropriate base temperatures for a hypothetical insect with a true threshold temperature of 6^{o}C and a day-degree requirement of 100 day-degrees above a base of 6^{o}C. This might suggest that the base temperatures estimated for *A. fabae* were too high. Consequently, a threshold as low as -2^{o}C was tested. However, this still produced a strong linear relationship with day number. In fact, the lines shown in Figure 4.1 are not straight lines, but curves, this provides additional 'evidence' that the linear relation is probably not due to the choice of an inappropriate threshold temperature. This suggests therefore that the possible reason why the day-degree sum is not constant is because the relationship between development of *A. fabae* between the end of overwintering and 'peak' appearance in the summer and temperature is non-linear.

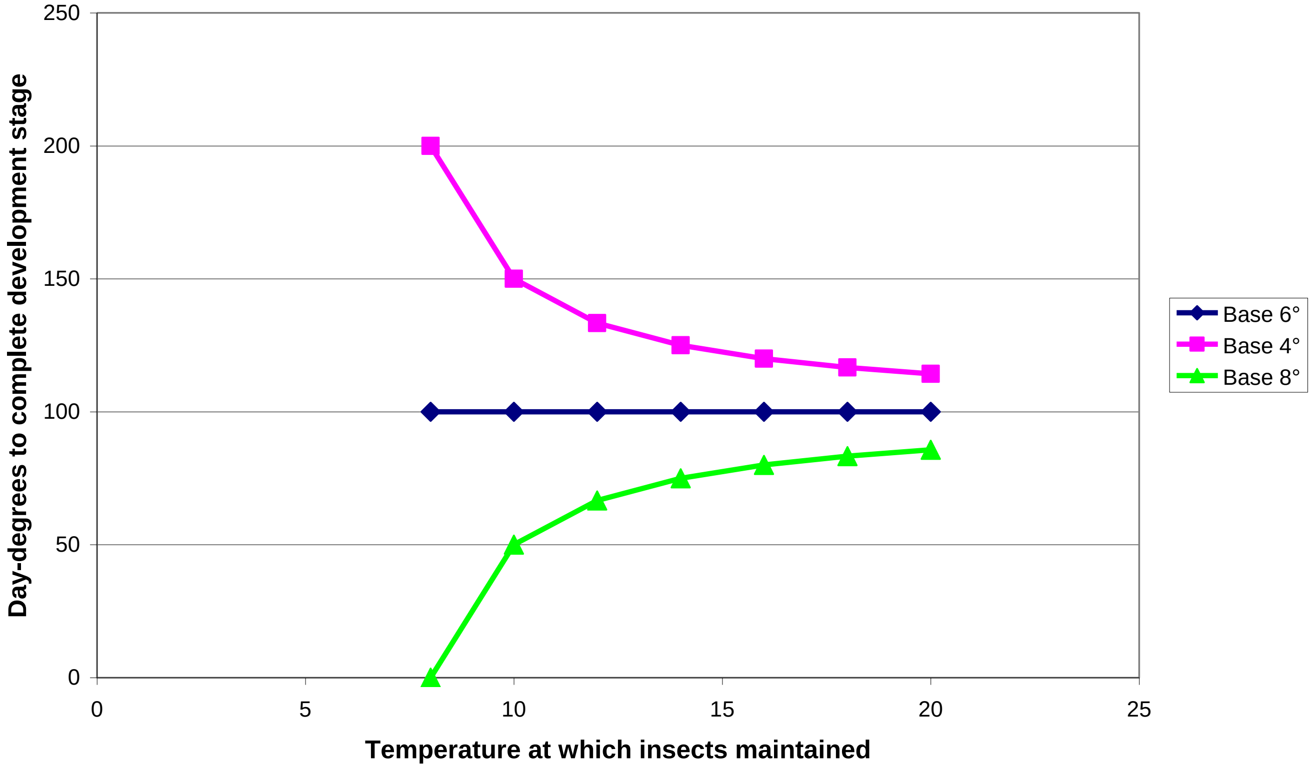

Figure 4.1. Calculated day-degrees above base temperatures of 4, 6 and 8°C for a hypothetical insect with a base temperature of 6°C.

Other studies

The present study is not the only example of variable day-degree sums estimated from field data. In a study on common green capsid (*Lygocoris pabulinus)* in the Netherlands, earlier sightings of the pest appeared to occur at higher temperature sums (Blommers *et al*., 1997), the converse of the present study. In addition, examination of some of the day-degree sums provided on the University of California web site (http://www.ipm.ucdavis.edu/MODELS/index.html) indicate a wide range of variation and it is unclear whether the researchers developing these forecasts have plotted them in such a way as to identify trends, as in the present study, and as done by Blommers *et al*..

The way forward

Blommers *et al.* (1977) dealt with their variable day-degree relationship by applying a 'fix' based on the average temperature sum in the set of data used – which was a relatively small data set, and from one location. It is probably more appropriate in the case of *A. fabae* to use the clear relationship with mean temperature rather than develop a similar fix.

The relationship between the dates of capture of first, 10% and 50% aphids and mean temperature was investigated in more detail for all the sites x occasions where there were reliable weather records. Over all sites x occasions, the first aphid was captured on Day 97 (7 April) and there were 8 sites x occasions where the first aphid was captured before 30 April. Similarly, the earliest capture of 10% aphids was on Day 135 (15 May) and there were 12 sites x occasions when 10% aphids were captured before 31 May. Finally, the earliest capture of 50% aphids was on Day 147 (27 April) and there were 15 sites x occasions were 50% aphids were captured before 30 June. Therefore it seems reasonable, as a starting point, to use mean temperatures between January-April, January-May and January-June as possible predictors of the timing of colonisation.

Figures 4.2 – 4.7 show relationships for the whole data set versus the mean temperature over defined periods (Jan-Apr, Jan-May and Jan-Jun). These graphs show a good deal of scatter but a clear negative relationship between mean temperature and the timing of aphid capture.

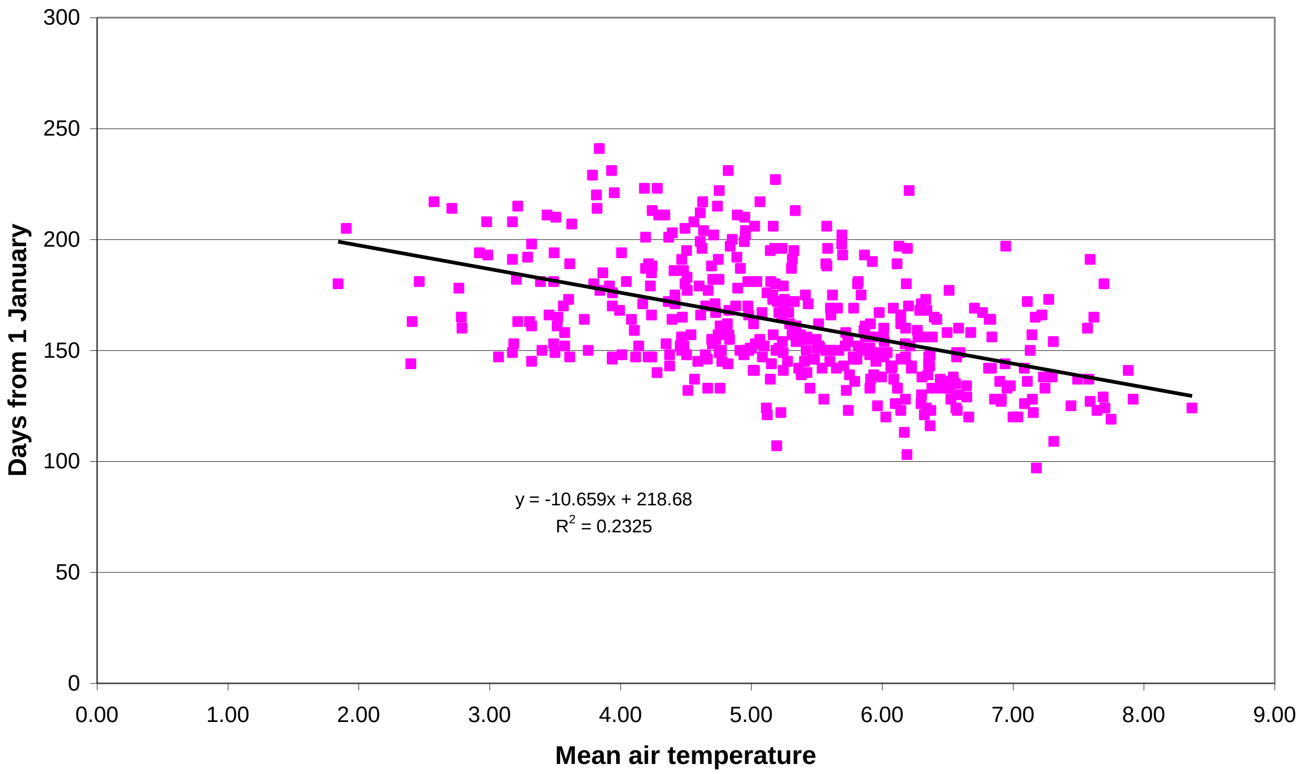

Figure 4.2. Relationship between date the first aphid was captured and mean air temperature (January-April inclusive).

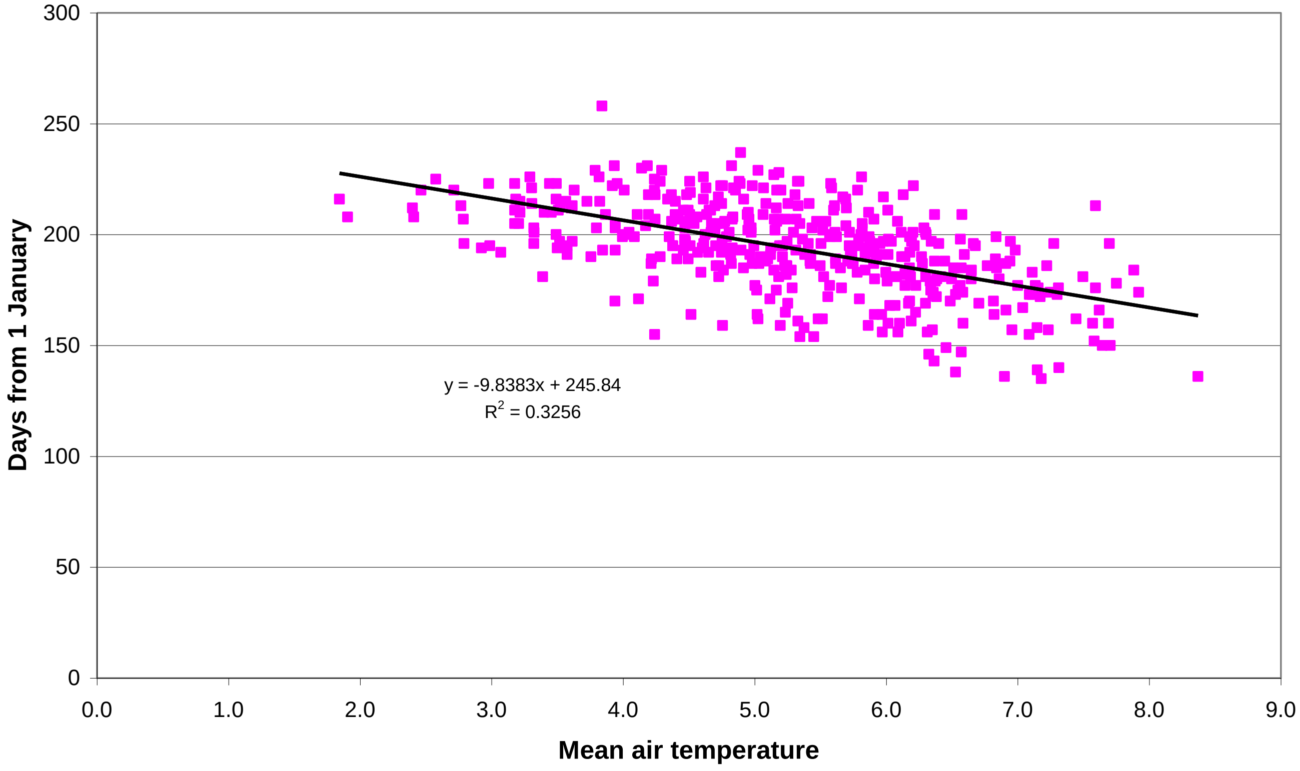

Figure 4.3. Relationship between date 10% aphids were captured and mean air temperature (January-April inclusive).

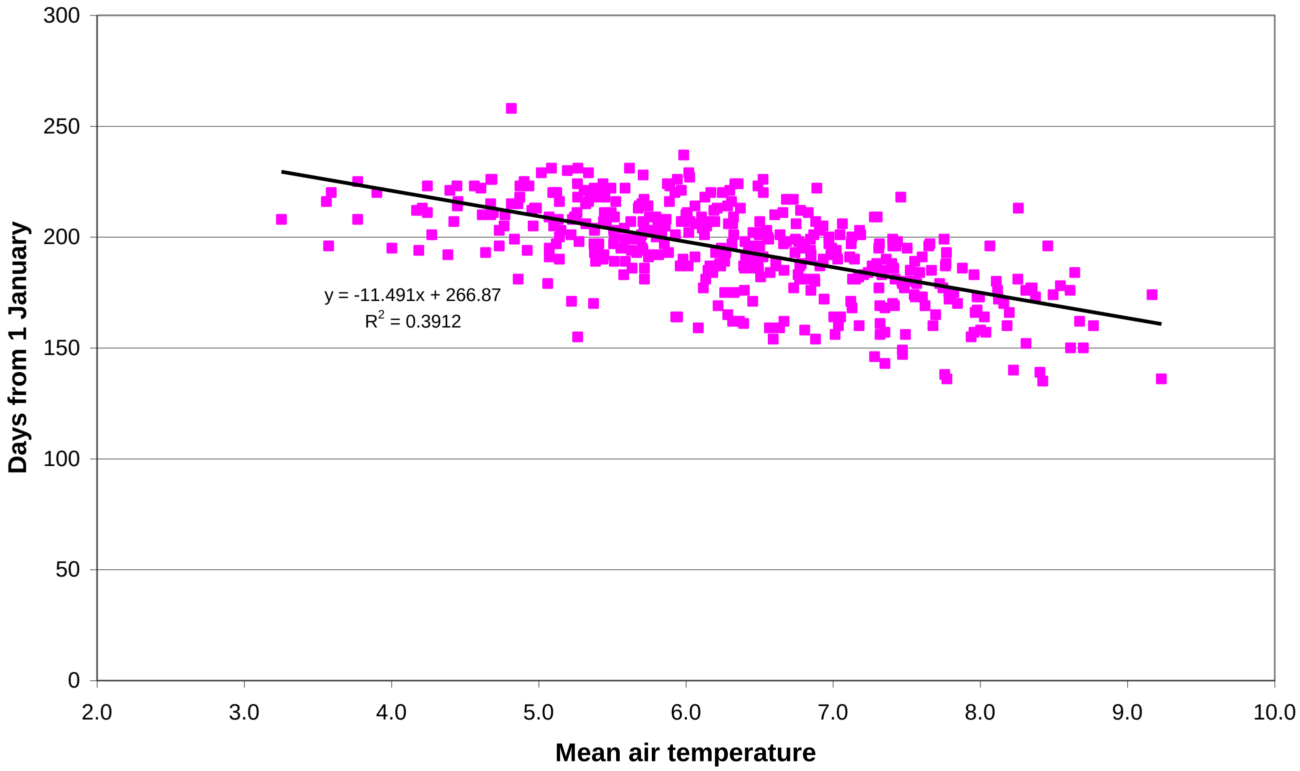

Figure 4.4. Relationship between date 10% aphids were captured and mean air temperature (January-May inclusive).

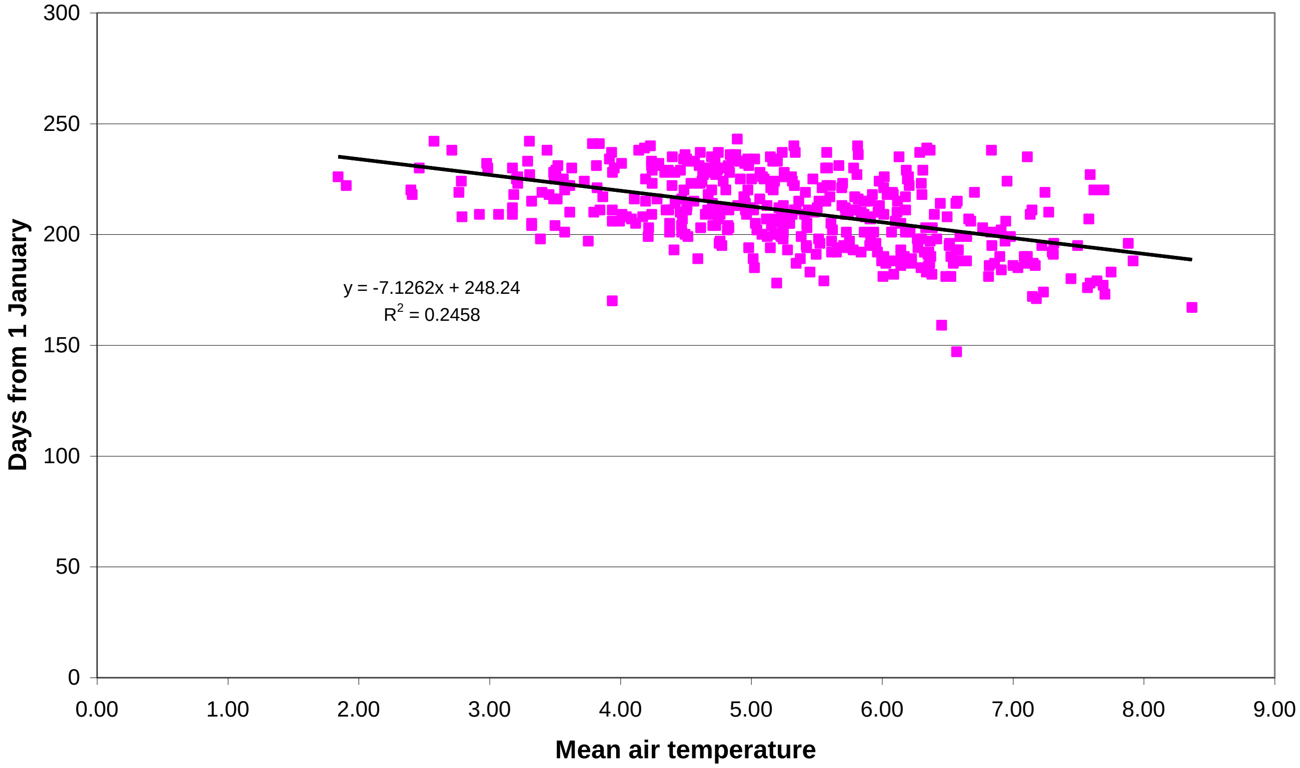

Figure 4.5. Relationship between date 50% aphids were captured and mean air temperature (January-April inclusive).

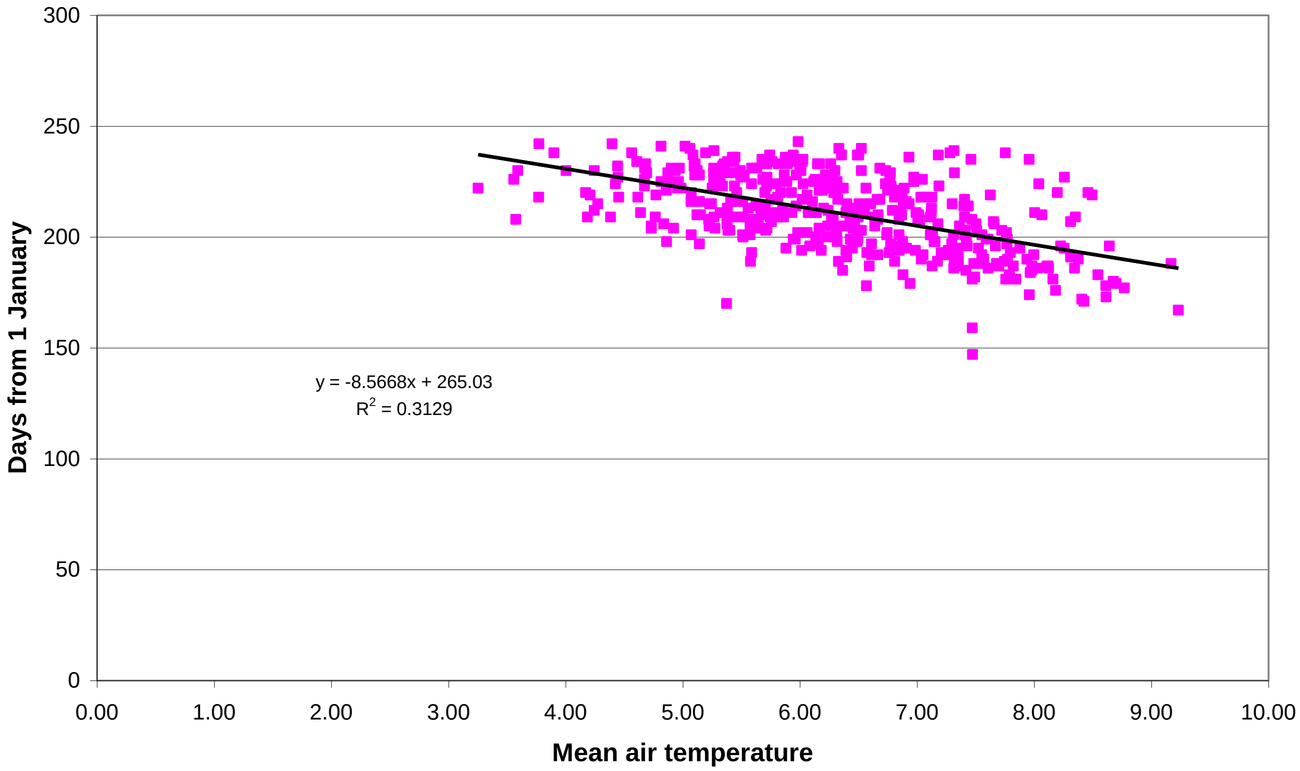

Figure 4.6. Relationship between date 50% aphids were captured and mean air temperature (January-May inclusive).

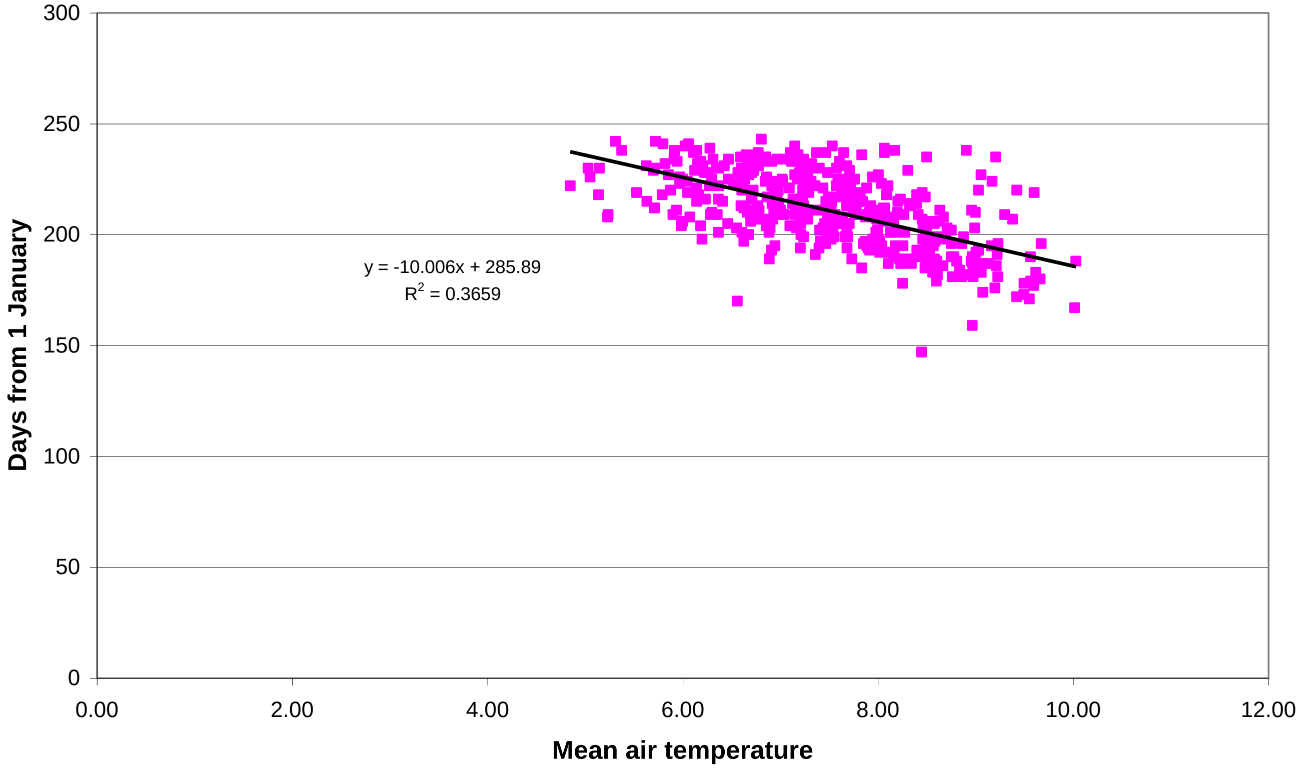

Figure 4.7. Relationship between date 50% aphids were captured and mean air temperature (January-June inclusive).

In order to identify possible additional effects of latitude or longitude, the data for the individual sites were also plotted. Some examples are shown in Figure 4.8, indicating an effect of latitude. There is also possibly an additional effect of longitude.

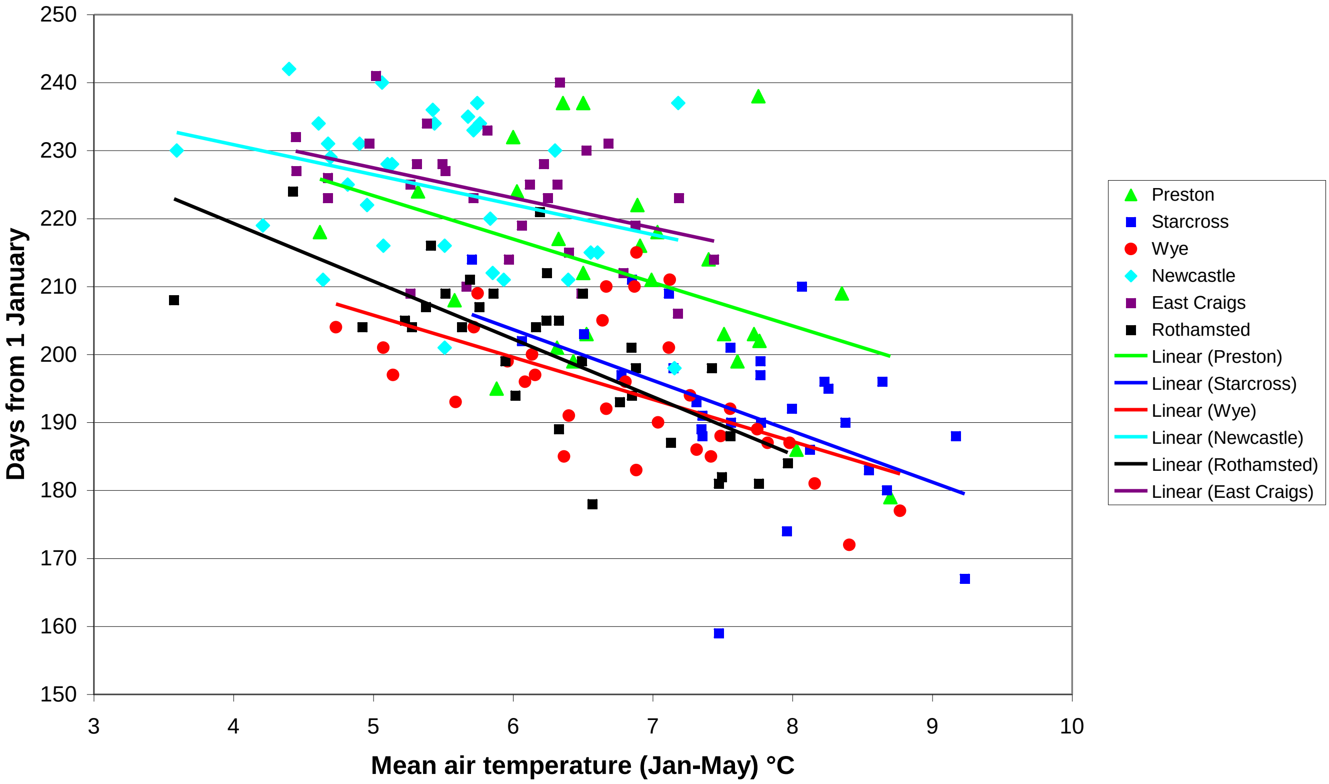

Figure 4.8. Relationship between date 50% aphids were captured and mean air temperature (January-May inclusive). All were statistically significant ($p<0.001$).

To investigate the nature of the relationships with mean temperature, latitude and longitude a series of regression analyses were run on the full data set. These were:

- First aphid against Mean Temperature Jan-Apr
- 10% aphids against Mean Temperature Jan-Apr
- 10% aphids against Mean Temperature Jan-May
- 50% aphids against Mean Temperature Jan-Apr
- 50% aphids against Mean Temperature Jan-May
- 50% aphids against Mean Temperature Jan-Jun

For each of these the analysis started with a simple linear regression for the whole data set. For the analyses of 10% aphids and 50% aphids against different explanatory variables, the 'percentage variance accounted for' provides an informal comparison of the different models, in both cases suggesting that using the mean temperature over a longer period provides a better fitting model (Table 4.1).

Table 4.1. Fitted equations for linear regressions between dates of first, 10% and 50% capture and mean air temperature over different periods. All were statistically significant ($p<0.001$).

Measure of timing of aphid activity	Mean temperature during	Fitted equation	Percent variance accounted for
First	Jan-Apr	Time=219-10.66*mean temp	23.1
10%	Jan-Apr	Time=246-9.84*mean temp	32.4
10%	Jan-May	Time=267-11.49*mean temp	39.0
50%	Jan-Apr	Time= 248-7.13*mean temp	24.4
50%	Jan-May	Time=265-8.57*mean temp	31.1
50%	Jan-Jun	Time= 286-10.01*mean temp	36.4

A simple linear regression 'with groups' analysis was then applied, allowing both the intercept and slope of the fitted relationship to change between locations. In every case, there was evidence for differences in the intercepts between locations, but not for differences in the slopes, therefore indicating a series of parallel lines. For each of the parallel line models, the intercept parameters for the 15 locations were extracted (Table 4.2), and a multiple linear regression was applied for these against both latitude and longitude. All showed evidence for the intercepts varying with both latitude and longitude.

Table 4.2. Fitted lines for time of capture of 50% aphids against mean temperature (Jan-Jun). Lines are parallel (same slope) but with different intercepts. Data are sorted by 'Intercept' with 'earliest' location at the top.

Equations	Time to 50% aphids = Intercept - 7.575*temperature		
Location	**Intercept (days from 1 January)**	**Latitude**	**Longitude**
Wye	255.44	51.10	-0.56
Rothamsted	257.12	51.48	0.21
Starcross	257.47	50.37	3.27
Writtle	258.32	51.43	-0.25
High Mowthorpe	260.30	54.50	0.39
Brooms Barn	262.84	52.15	-0.33
Hereford	265.47	52.70	2.39
Kirton	268.20	52.55	0.30
Preston	272.20	53.45	2.42
Rosewarne	272.32	50.50	5.19
Newcastle	273.96	54.58	1.37
Ayr	275.29	55.28	4.33

Dundee	276.02	56.27	3.30
East Craigs	276.78	55.57	3.18
Elgin	282.45	57.38	3.19

The final output in each set of analyses was for a multiple linear regression model including the appropriate mean temperature variable and both latitude and longitude. These again all showed significant effects of both latitude and longitude (effectively influencing the intercept of the fitted line for each location) as well as of mean temperature (Table 4.3). So this overall fitted model could be used to predict the timing of aphid activity at any location (in the UK) for the temperature data in any particular year.

Table 4.3. Fitted equations for multiple linear regression models between dates of first, 10% and 50% capture and mean air temperature over different periods and latitude and longitude. All were statistically significant ($p<0.001$). The simple linear regression models (from Table 4.1) are shown for comparison.

Measure of timing of aphid activity	**Mean temperature during**	**Fitted equation**	**Percent variance accounted for**
First	Jan-Apr	Time=219-10.66*mean temp	23.1
First	Jan-Apr	Time=64-9.70*mean temp+2.67*latitude+4.19*longitude	40.1
10%	Jan-Apr	Time=246-9.84*mean temp	32.4
10%	Jan-Apr	Time=60-7.78*mean temp+3.24*latitude+1.21*longitude	46.4
10%	Jan-May	Time=267-11.49*mean temp	39.0
10%	Jan-May	Time=96-9.11*mean temp+2.88*latitude+1.04*longitude	49.3
50%	Jan-Apr	Time= 248-7.13*mean temp	24.4
50%	Jan-Apr	Time=57-5.23*mean temp+3.32*latitude+2.15*longitude	52.5
50%	Jan-May	Time=265-8.57*mean temp	31.1
50%	Jan-May	Time=82-6.15*mean temp+3.07*latitude+2.04*longitude	54.4
50%	Jan-Jun	Time= 286-10.01*mean temp	36.4
50%	Jan-Jun	Time=110-7.07*mean temp+2.81*latitude+1.93*longitude	55.3

Objective 2.Validate day-degree forecast and method of predicting abundance using any available historical crop monitoring data.

The predicted dates for first, 10% and 50% emergence were calculated using the equations in Table 5.1. The differences between observed and predicted dates were then calculated and the absolute difference was used to calculate the mean deviation between observed and predicted dates, which are shown in Table 5.1. The predictions for the capture of first aphid were the least consistent (January-April temperatures) and those for capture of 50% aphids were most consistent. Consistency was improved by using weather data over a longer period of time. The predictions appeared to be least accurate for Rosewarne, followed by Preston. However, it is important to bear in mind that the trap records were from different runs of years for each site.

Table 5.1. Mean absolute difference between observed and predicted dates of activity for all site x year combinations.

	Latitude	Longitude	First (Jan-Apr)	10% (Jan-Apr)	10% (Jan-May)	50% (Jan-Apr)	50% (Jan-May)	50% (Jan-Jun)
Starcross	50.37	3.27	10	13	13	10	9	9
Rosewarne	50.50	5.19	16	17	16	14	14	14
Wye	51.10	-0.56	11	10	9	7	7	7
Writtle	51.43	-0.25	13	10	9	8	8	8
Rothamsted	51.48	0.21	13	10	9	7	7	7
Brooms Barn	52.15	-0.33	10	9	9	8	8	8
Kirton	52.55	0.30	13	9	9	10	10	10
Hereford	52.70	2.39	18	11	11	11	10	10
Preston	53.45	2.42	19	9	8	11	11	11
High Mowthorpe	54.50	0.39	22	12	12	9	9	9
Newcastle	54.58	1.37	15	12	11	11	10	10
Ayr	55.28	4.33	19	12	12	8	9	8
East Craigs	55.57	3.18	24	13	12	7	7	6
Dundee	56.27	3.30	20	10	10	8	8	7
Elgin	57.38	3.19	19	13	12	8	8	8
Mean			16.07	11.25	10.93	9.09	8.88	8.82
Max			24	17	16	14	14	14
Min			10	9	8	7	7	6

Another way of predicting the timing of activity might be to use the mean date for a particular site (if this information is available). Table 5.2 compares mean absolute difference between observed and predicted dates for the use of the mean date with the predictions based on the regression models for Rothamsted and Broom's Barn which are the two largest data sets. In most cases, the regression model is more accurate.

Table 5.2. Comparison of the mean absolute difference between observed and predicted dates using predictions based on regression models or on the mean date of capture for that location.

	Rothamsted	Broom's Barn
First (Jan-Apr) + latitude and longitude	13	10
10% (Jan-Apr) + latitude and longitude	10	9
10% (Jan-May) + latitude and longitude	9	9
50% (Jan-Apr) + latitude and longitude	7	8
50% (Jan-May) + latitude and longitude	7	8
50% (Jan-Jun) + latitude and longitude	7	8
First – mean date for location	12	14
10% - mean date for location	11	13
50% - mean date for location	11	9

Objective 3. Analyse these data for relationships that might help to predict abundance.

Using the 1981-88 data set, Figures 6.1 and 6.2 show the mean numbers of aphids captured to 31 August and the total numbers captured respectively versus latitude. There was no relationship between the numbers of aphids captured and latitude of the suction trap location.

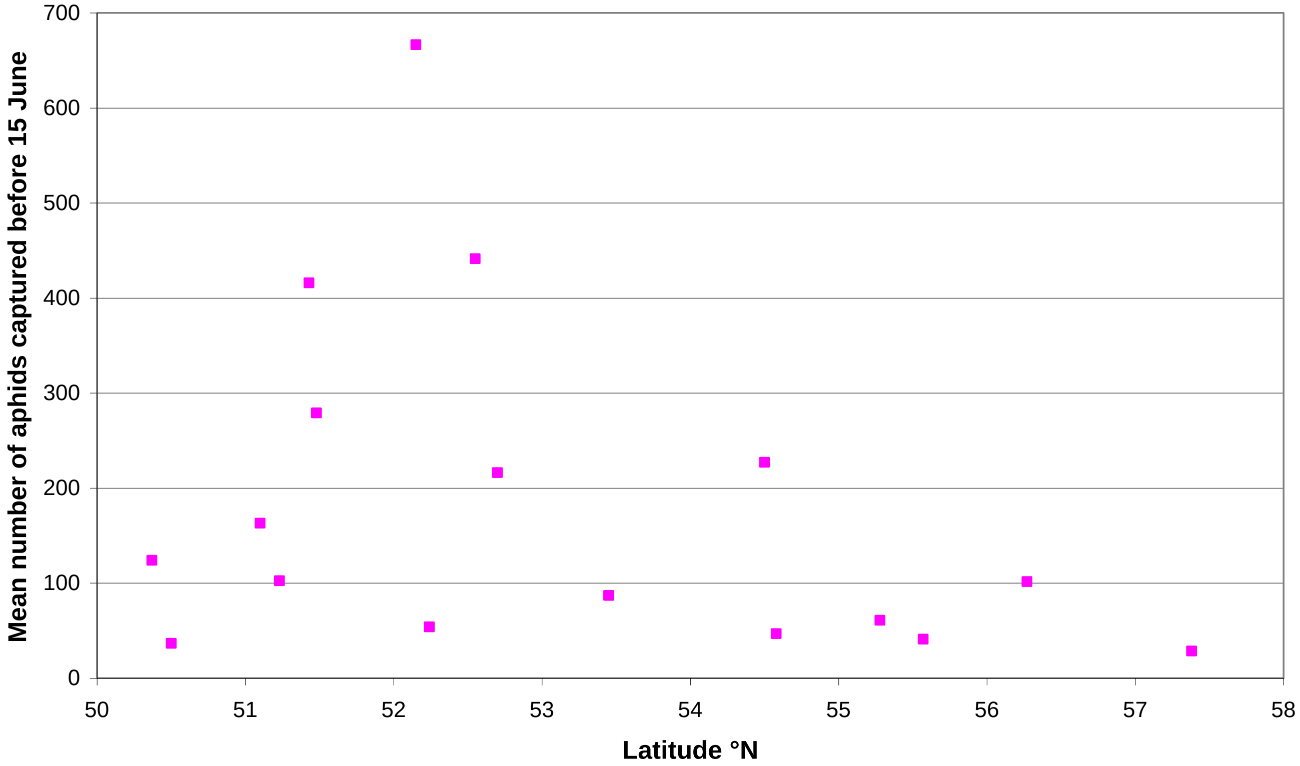

Figure 6.1 Mean numbers of aphids captured to 31 August versus latitude.

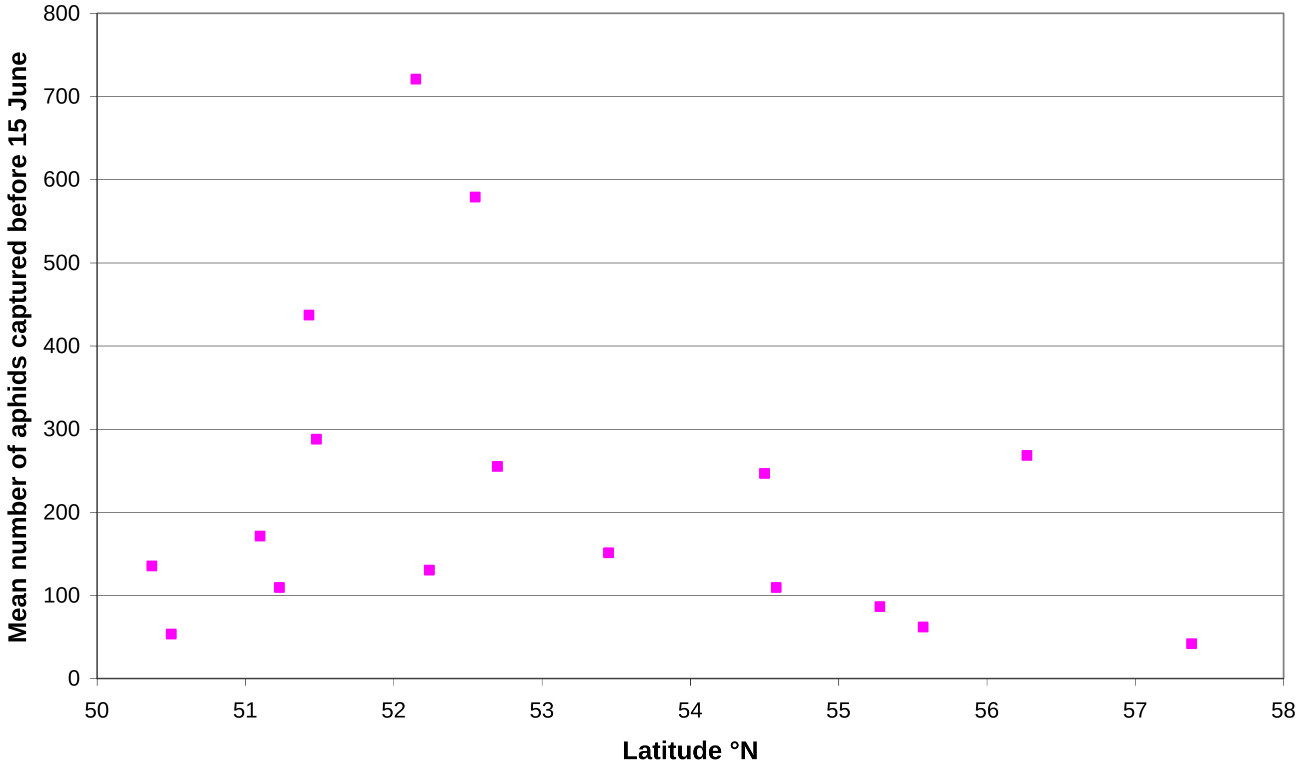

Figure 6.2 Mean total numbers of aphids captured versus latitude.

The data were assessed for relationships that might help to predict abundance in any one year. One possibility might be that the numbers caught are influenced by the size of the autumn migration in the previous year. Examples of the data are shown in Figures 6.3-6.5. There was no evidence of useful relationships.

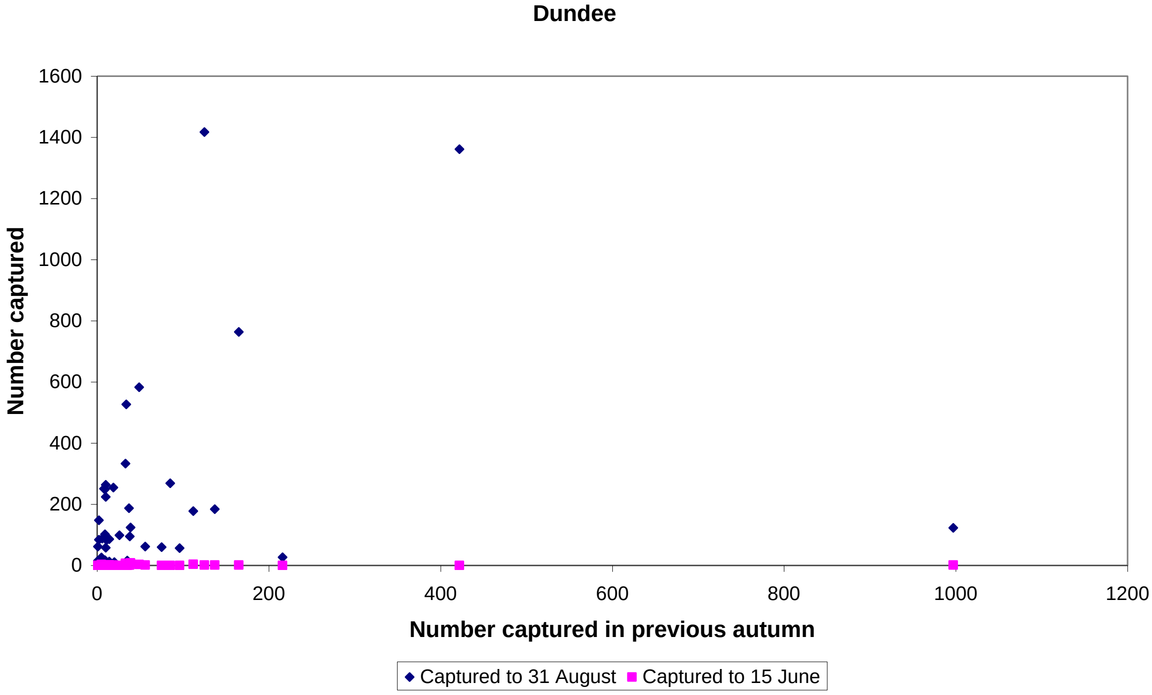

Figure 6.3 Relationship between the numbers of aphids caught to 15 June and 31 August and the numbers caught during the autumn migration in the previous year (Dundee).

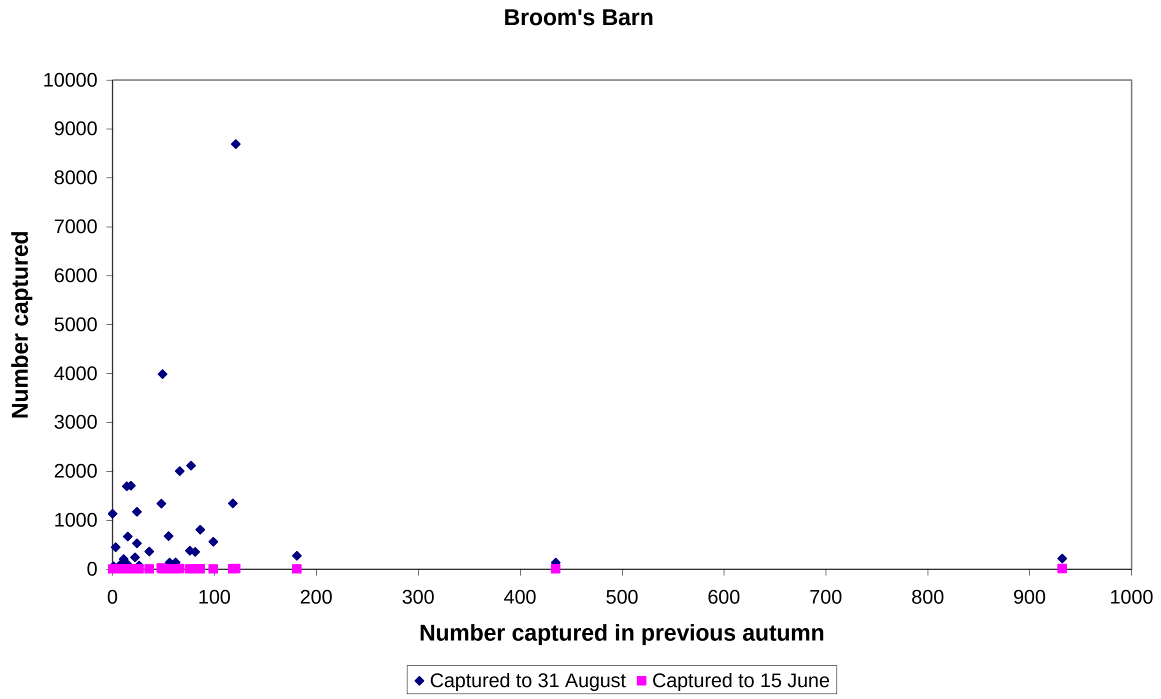

Figure 6.4 Relationship between the numbers of aphids caught to 15 June and 31 August and the numbers caught during the autumn migration in the previous year (Broom's Barn).

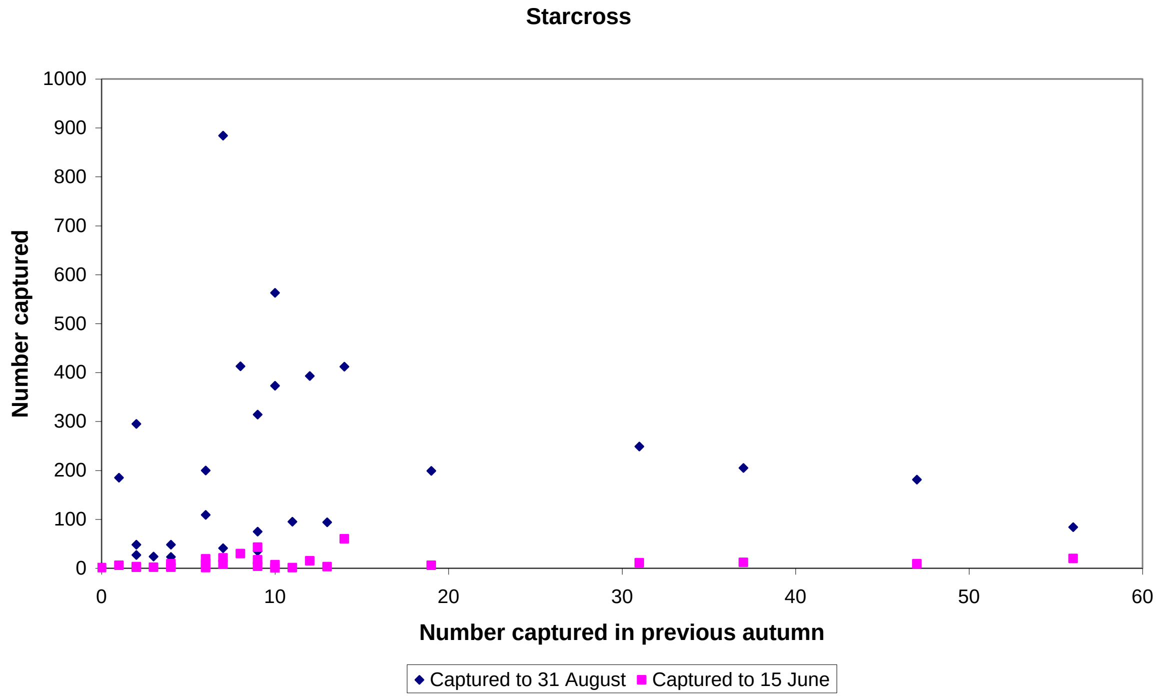

Figure 6.5 Relationship between the numbers of aphids caught to 15 June and 31 August and the numbers caught during the autumn migration in the previous year (Starcross).

Another approach was to look for relationships between the warmth of the spring and the numbers of aphids captured. Examples for 3 locations are shown in Figures 6.6-6.8. Again there was no evidence of useful relationships.

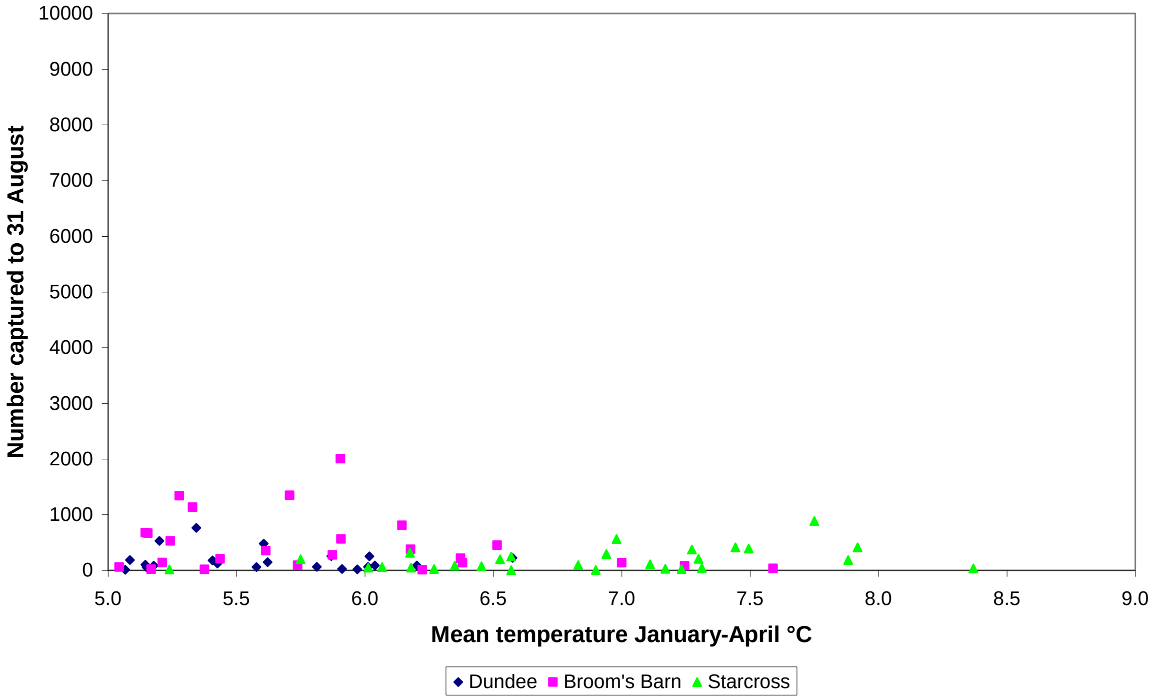

Figure 6.6 Relationship between the numbers of aphids caught to 31 August and the mean air temperature (January-April).

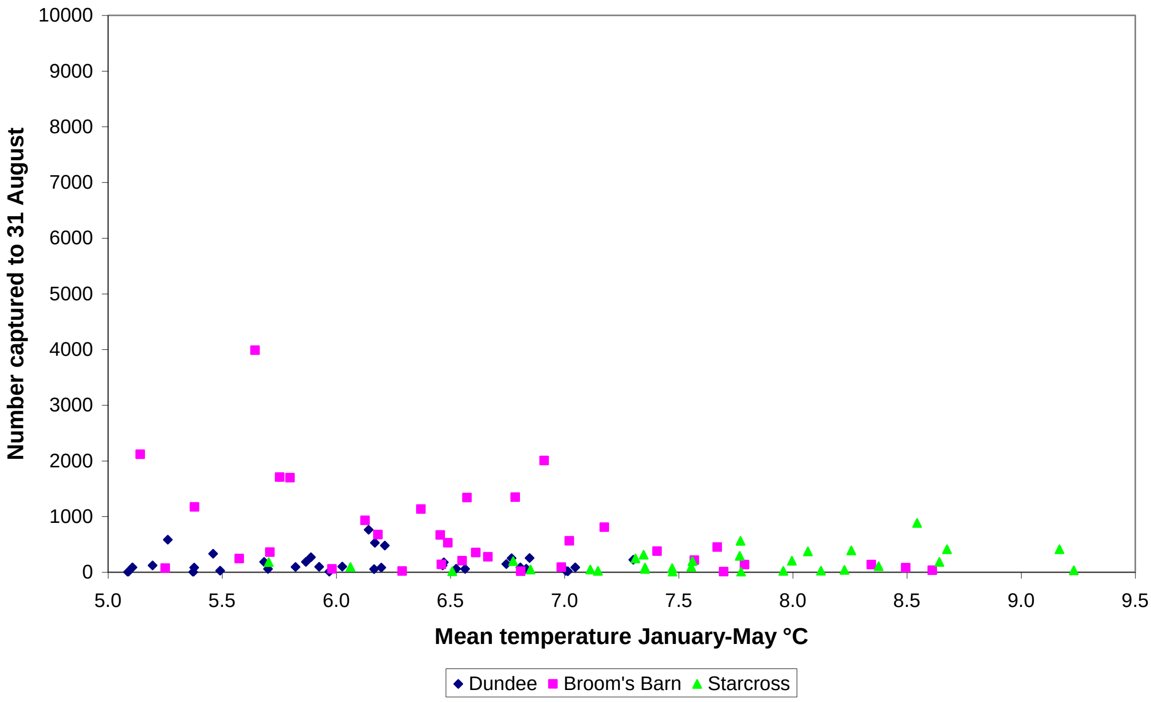

Figure 6.7 Relationship between the numbers of aphids caught to 31 August and the mean air temperature (January-May).

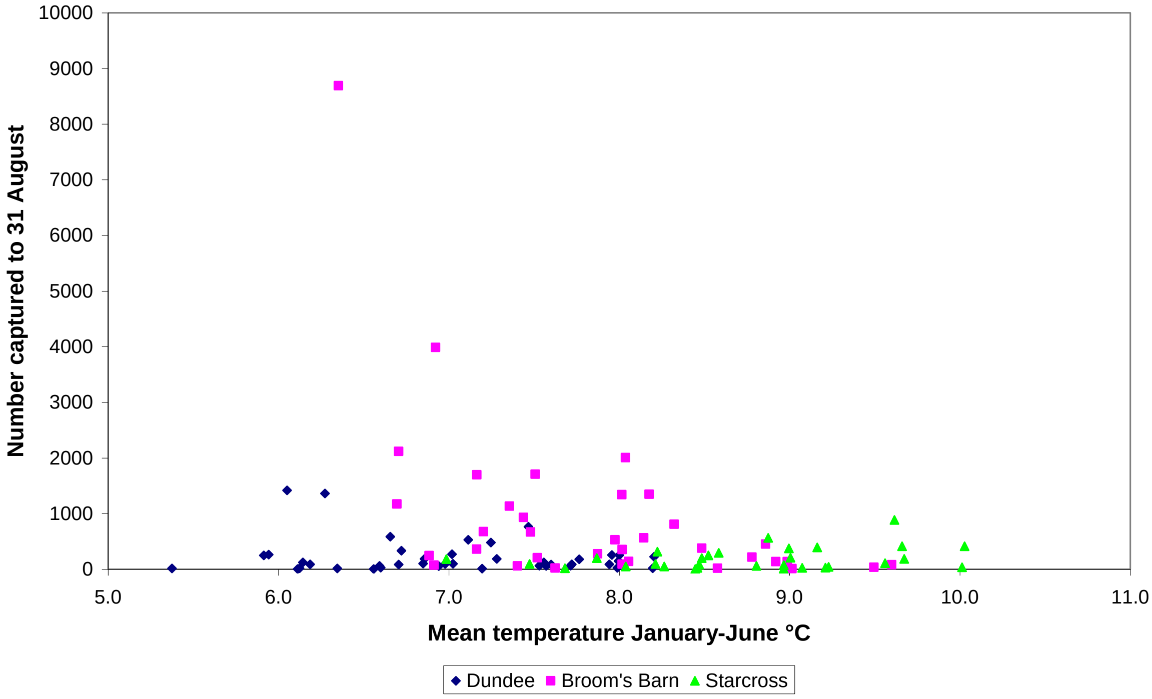

Figure 6.8 Relationship between the numbers of aphids caught to 31 August and the mean air temperature (January-June).

Objective 4. Develop a method of predicting relative abundance in the summer as early as possible from real-time suction trap data.

By predicting the date of 10% activity it might be possible to use the numbers captured by that predicted date to predict the total number of aphids captured during the summer (up to 31 August). Figure 7.1 shows three examples of the relationship between the actual captures up to 31 August and the predicted capture up to 31 August, based on the numbers captured at the predicted date of 10% activity. These are plotted on a log scale and show a large amount of scatter, indicating that this might provide an estimate of the final capture, but would not completely reliable.

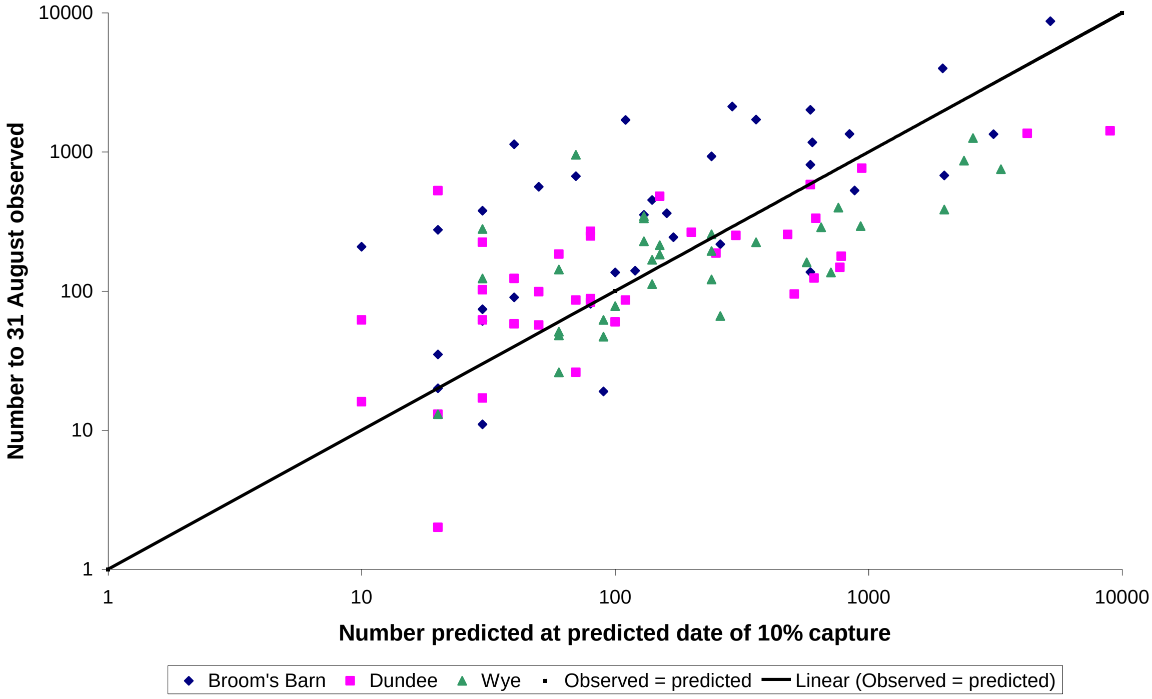

Figure 7.1. Three examples of the relationship between the actual captures up to 31 August and the predicted capture up to 31 August based on the numbers captured at the predicted date of 10% activity.

Discussion

The original 'hypothesis' was that because FV 407 had shown a clear relationship between aphid activity and the mean air temperature over different periods this would 'translate' into a simple day-degree relationship. There was also a biological basis for thinking that this would be the case as *A. fabae* overwinters as an egg in diapause and once diapause is complete, it might be expected that the relationship between development rate and temperature could be described using day-degrees. However, it was not possible to obtain a constant day-degree sum across years. This leads to a whole range of questions, firstly about the detail of the summer life-cycle of *A. fabae* and the influence of temperature, secondly, about the 'mathematics' of the day-degree approach and thirdly, about the consistency of sum of the published day-degree sums for other species that have been developed from field data – and especially of those developed from much smaller sets of data than used here (e.g. some of the models described on the University of California web site http://www.ipm.ucdavis.edu/MODELS/index.html).

As an alternative approach, the relationship with mean temperature was explored in more depth, with the initial aim of producing a simple relationship based on temperature alone.

However, it became clear that although the slope of this relationship appeared to be the same for different locations, the intercepts were not, and the intercepts appeared to be heavily influenced by latitude, and also by longitude. Thus equations were produced using temperature, latitude and longitude and these appeared to produce relationships that could be used to forecast the timing of aphid activity. Exactly why latitude and longitude are explanatory factors in the regressions is not clear – and again relates to the need for a greater understanding of the biology of *A. fabae*. Similar effects of latitude and longitude on long range forecasts based on winter temperature have been identified for species of aphid that overwinter in the mobile stages, such as *Myzus persicae,* and again, the explanation is unclear (HDC Project FV 162e - Collier & Harrington, 2001).

The models developed could be refined, and for example, altitude might be another factor that could be included in the models. In addition, the models have been developed using air temperatures averaged over periods of 4, 5 and 6 whole months and obviously it would be possible to average them over periods of different durations, and maybe to develop 'bespoke' models for particular regions. One piece of evidence that suggests that this might not make a very great difference is the similarity of the mean absolute differences for predictions of 50% activity using mean air temperatures for January- April, January-May or January-June (Table 5.1).

Acknowledgements

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