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Evaluating an interpolation approach for modelling spatial variability in pest development

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Abstract

Air temperatures estimated by partial thin plate spline interpolation, or from the 'nearest station' (Voronoi polygon method), were used to model the phenology of three pests of horticultural crops throughout England and Wales. Temperatures for a particularly hot (1976) and a particularly cold (1986) year were interpolated to a grid resolution of 1 km. Estimates were made of the timing of spring emergence (*Cecidophyopsis ribis* (Westwood)), the maximum number of generations completed during the summer (*Plutella xylostella* (Linnaeus)) and the numbers of days when mating was possible (*Merodon equestris* (Fabricius)). The relative accuracy of the two temperature estimation methods was compared using jack-knife cross-validation. For *C. ribis* and *P. xylostella*, modelling with interpolated temperature input data was more accurate than using data from the 'nearest station'. Of the three phenology models used, the one that relied on an activity threshold (*M. equestris*) was the most sensitive to both types of input data. Spatial variability in the activity of *M. equestris* adults was investigated in the two main areas (south-west peninsula and Lincolnshire) where its host crop (*Narcissus*) is grown. Modelling at cruder scales (up to 25*25 km) masked local variation, but the degree to which this was important varied from region to region and over time, as did the geography of the variability itself. The results indicate that interpolated data, computed to a resolution of 1 km using the UK synoptic network, have the potential for wider use within agricultural decision support systems for horticultural crops.

Introduction

The strong relationship between insect development and temperature is well established (Sharpe & deMichele, 1977) and the use of biological models of varying sophistication to make temperature-based forecasts of insect phenology and activity is reported widely (e.g. Welch *et al.*, 1978; Baker & Cohen, 1985; Morgan, 1992; Collier *et al.*, 1999). However, such forecasts are limited spatially by the availability of meteorological data from national networks. Indeed it has been suggested that the use of data from the 'nearest station' in a national synoptic network is a major contribution to the error obtained when applying phenology models in the field (Higley *et al.*, 1986). Although the network of meteorological stations is particularly well established in England and Wales, there are still only approximately 175 synoptic temperature data stations from which to draw records.

Interest in modelling the spatial aspects of insect ecology has increased steadily over the past few years, both over the broader landscape (e.g. Tiilikkala & Ojanen, 1999) and at the scale of an individual forest (e.g. Downing & Bartos, 1991; Loh *et al.*, 1991) or field (e.g. Weisz *et al.*, 1995b). Much of this previous work has focused on geographical modelling using trap records (e.g. Weisz *et al.*, 1995a,b). More rare are examples linking phenological models and interpolation methods.

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Two approaches to the linking of biological temporal models and input data over space can be identified; (i) those that interpolate the times to events from phenology models (e.g. Schaub *et al.*, 1995); and (ii) those that model phenologies over the landscape using interpolated temperature input (e.g. Russo *et al.*, 1993). While the first of these options is computationally efficient, interpolation of times can lead to biologically implausible discrepancies in insect development sequences at certain locations. Predicted dates for the emergence of larvae have for example been found to pre-date those of eggs (Jarvis *et al.*, 1999). Additionally, when interpolating the times to events rather than the underlying temperatures, the resulting interpolated surfaces can be over-smoothed (Jarvis & Stuart, 2001c).

For these reasons, the interpolation of daily maximum and minimum air temperatures is used as a basis for modelling insect phenology in this paper. The paper explores whether geographically continuous temperature data, constructed through modelling the spatial correlation between points, together with topographical information, could be used to improve local phenology estimates, which are often based on the nearest weather station in the UK synoptic network. Much of the previous work that has used interpolation methods to model the spatial distribution of pest phenology and population at a landscape-wide level has been with forest pests, particularly in northern America (e.g. Régnière, 1996; Weseloh, 1996; Liebhold *et al.*, 1998; Yang *et al.*, 1998). In contrast, this paper focuses on three pests that threaten horticultural crops and compares phenological estimates for these pests modelled using either temperatures from the 'nearest station' (Voronoi polygon method) or temperatures estimated using partial thin plate spline interpolation methods (Hutchinson, 1991). The relative accuracy of the two methods is compared using jack-knife cross-validation (leave-one-out) techniques employed commonly where data are sparse (e.g. Cressie, 1991; Vanclay & Skovsgaard, 1997; Beard & Buttenfield, 1999). In this way, it is possible to investigate: (i) how good the 'nearest station' method is; (ii) whether interpolation is better; and (iii) whether interpolated data, computed to a resolution of 1 km using the UK synoptic network, have the potential for wider use within entomological modelling and agricultural decision support systems.

Methods

An integrated FORTRAN framework, designed using GIScience principles, and comprising data management, interpolation and modelling components (Jarvis, 2001), was used to undertake the integrated modelling reported in this paper. The framework allows point models to be run over space using time sequences of interpolated, continuous daily maximum and minimum temperatures. In this paper, the point model used is a simple accumulated temperature model, but more complex phenology and population models may similarly be integrated. From a user perspective, the start and end date for a model run may be specified, along with any model related parameters such as base threshold temperature and the spatial area over which model results are required. The software is described in more detail elsewhere (Jarvis, 2001).

Insect pests and models

Phenological outputs were computed for three pest insects of horticultural crops in the UK. The timings of events critical to the successful management of these pests were modelled to assess the potential for the practical application of temperature interpolation methods within decision support systems. The models chosen are based on air temperatures and the pest insects and their respective model parameters are presented in table 1.

The blackcurrant gall mite *Cecidophyopsis ribis* (Westwood) (Acari: Eriophyidae) is a major pest of blackcurrant crops. It is also a vector of blackcurrant reversion associated virus (BRAV). Together, these are the principal factors limiting the life of blackcurrant plantations. A day-degree forecast has been developed to predict the spring emergence of mites that have overwintered in galls on blackcurrant plants (Cross & Ridout, 2001). Once they have emerged, the mites migrate to colonize new buds. Control with acaricides is aimed at preventing migration and subsequent bud infestation. In this paper, the day-degree forecast is used to predict the timing of first, 5% and 50% emergence of the blackcurrant gall mite throughout England and Wales.

The larva of diamondback moth *Plutella xylostella* (Linnaeus) (Lepidoptera: Yponomeutidae) is a pest of brassica crops (cabbage, cauliflower, calabrese, Brussels sprouts). In contrast to the blackcurrant gall mite, few diamondback moths overwinter successfully in the UK and infestations occur usually as a result of mass migrations of moths from continental Europe. This can occur at any time during the summer and is dependent on weather conditions. The diamondback moth completes its life cycle rapidly when temperatures are high, and the extent and duration of infestations are determined by the number of generations that the moth can complete. Day-degree sums derived in North America (Harcourt, 1954; Butts & McEwen, 1981) are used in this paper to estimate the numbers of generations that might occur at different locations in England and Wales. It is assumed that the initial infestation began on 12 June, which was the date of a particularly devastating migration in 1996 (R.H. Collier, unpublished data).

Finally, the larva of *Merodon equestris* (Fabricius) (Diptera: Syrphidae) is a pest of narcissus bulbs. The fly completes one generation each year and adult flies emerge during May–June to mate and lay their eggs. The adults are active only when the weather is hot and sunny, typically when the air temperature is above 20°C (Collier & Finch, 1992). If the weather is cool, then mating, and subsequent oviposition, are delayed. A delay in oviposition provides the opportunity for growers to reduce the risk of infestation, by using cultural control methods such as early harvesting. Phelps *et al.* (1993) developed a simulation model of large narcissus fly phenology that predicts the times of adult fly emergence, oviposition and egg hatch in relation to temperature. At present, the output from this model is provided to growers as a forecasting service (R.H. Collier, unpublished). However, there are only a few meteorological stations in the two main areas (south-west England and Lincolnshire) where narcissus crops are grown and it is possible that, because the forecasts are dependent on an 'activity threshold', that 'nearest station' data may not be appropriate for certain localities.

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Table 1. Phenology models used in the paper.

Pest insect	Target event	Period model run	Low temperature threshold for development/activity (°C)	Degree-days required (°C)	Reference
Cecidophyopsis ribis	First emergence 5% emergence 50% emergence	From 15 February	4.0	122 199 316	Cross & Ridout (2001)
Plutella xylostella	Generation time (egg to adult)	From 12 June	7.3	283–293	Harcourt (1954) Butts & McEwen (1981)
Merodon equestris	Egg hatch to start of migration	From 1 May	20.0	–	Collier & Finch (1992)
		May–June	20.0	–	

Temperature modelling

Modelling runs and analyses were carried out for 1976 and 1986, using data from 175 UK Meteorological Office (UKMO) stations. The partial thin plate spline technique was chosen for interpolating daily maximum and minimum temperatures between these 175 locations, following a series of comparative experiments (Jarvis & Stuart, 2001a,b). Annual average root mean square (r.m.s.) accuracies for these interpolated data are 0.8°C for maximum and 1.14°C for minimum temperatures (Jarvis & Stuart, 2001b).

The interpolation process took account of elevation and distance from the sea and was constructed using a proprietary geographical information system (GIS) and digital topographic and land-cover data. Data were interpolated to a grid resolution of 1 km. In addition, temperatures over the landscape were computed using 'nearest neighbour' (Voronoi) interpolation to a nominal resolution of 1 km. An area of approximately 50 km^2 is covered by each station.

Integrated bio-geographical modelling

For the two day-degree models, time series of interpolated and 'nearest station' temperature data were used to accumulate temperatures using the UK Meteorological Office method (Anon., 1969), for a 1 km grid over England and Wales (fig. 1). For *C. ribis*, the grid of dates by which the specified day-degree sums were reached was imported to a proprietary geographical information system (GIS) for visualization and further analyses. In the case of *P. xylostella*, the day-degree sum accumulated from 12 June until the end of the year was divided by the total day-degrees required per generation, to estimate the number of complete generations achievable in any one 1 km cell within the landscape.

To estimate the error, jack-knife cross-validation (Efron, 1982) was used to construct estimated temperatures and, from these, estimated phenologies at the known points, in a process where each point was withheld in turn (see Jarvis & Stuart (2001c) for further details). This method was used because the fixed sampling network limits the numbers of records available for modelling, and early trials showed that extracting a sizeable, representative data set for independent testing would affect the statistical validity of the interpolated spline surfaces. Jack-knifing provided a set of semi-independent residuals in units relating to the phenological target event (e.g. generations, Julian days) from which bias and root mean square (r.m.s.) metrics were computed (equation 1).

$$\text{Annual r.m.s. error} = \frac{\sum_{day=1}^{365}\left(\sqrt{\sum_{i=1}^{n}\left(t_a - t_e\right)^2 / n}\right)}{365} \quad (1)$$

where t_a is the actual temperature at a point, t_e the estimated temperature and n the number of sample points

The summers of 1976 and 1986 were chosen because they were, respectively, appreciably warmer and cooler than average. Firstly, the relative ability of temperature data computed using partial thin plate spline interpolation versus that taken from the 'nearest station' to predict phenology was assessed. Secondly, the ability of interpolated versus point source data to describe the underlying spatial variability in pest development across the surface of the landscape was investigated. To achieve this, grids and cross-validated statistics of predicted timing of emergence were

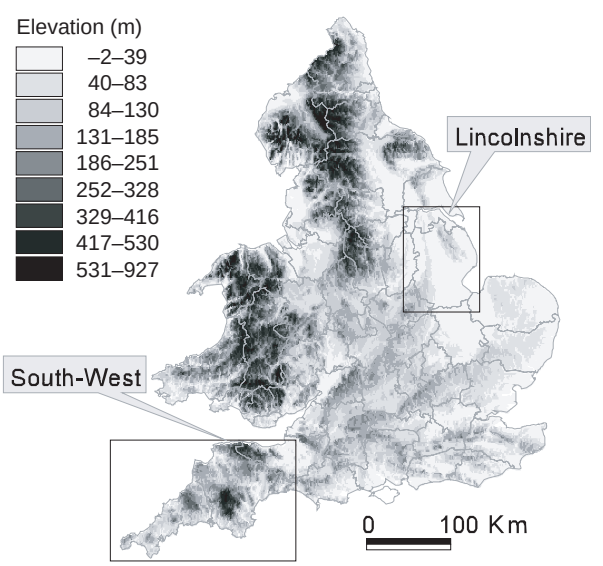


Fig. 1. Study areas, with location and elevation of extracted regions.

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modelled on the basis of temperatures constructed using Voronoi and spline interpolation methods. This modelling process was carried out for key management events in the life-cycle of each pest.

To estimate local variability in mating activity of *M. equestris*, south-west England and Lincolnshire were chosen for more detailed analyses (fig. 1). As part of this process, the local range in gridded phenologies within a 5 km and 10 km square of each grid cell was computed within a proprietary GIS (Geographical Information System). The range, computed using gridded results at 1 km, is the maximum minus the minimum value over the specified local area. Two measures were determined: (i) the first date in May–June when the maximum temperature reached 20°C; and (ii) the numbers of days in May–June when this occurred. These gave an indication of the opportunities for mating and subsequent oviposition.

Results

Day-degree forecasts

Cecidophyopsis ribis

The variability in the estimated emergence dates of *C. ribis* is shown in fig. 2. Three measures of emergence (first, 5% and 50%) are plotted, using an identical date scale, for 1976 and 1986. While spatial variation in emergence date is discernible within the individual maps, the use of identical shading deliberately emphasizes the predominantly temporal differences between years and stages across the country. The results indicate that first generation mites may emerge as early as mid-March (first emergence, 1976), but could still be emerging in August (50% emergence, 1986) on higher ground across all regions. The range of dates for first emergence in 1986 (Julian dates 94–172, mean 122) corresponds with those for 5% emergence in 1976 (Julian dates 99–176, mean 122). Similarly, the dates for 5% emergence in 1986 (Julian dates 121–184, mean 135) are close to those for 50% emergence in 1976 (Julian dates 121–187, mean 140). However, the underlying variability in the surfaces for 1976 is greater than that for 1986, in all cases. This reflects the wider range of high-pressure weather conditions, with their greater spatial variability in temperatures, which occurred in 1976.

The residual errors attributable to the remote location of stations relative to the target location are shown in figs 3 and 4. For 1976 (fig. 3), at first emergence, residuals ranged from –5 to 10 days for splines and –41 to 47 days when 'nearest station' method (Voronoi) was used. For 1986 (fig. 4), less extreme errors occurred when Voronoi interpolation was used; residuals ranged between ± 8 days for splines and –24 to +18 days for Voronoi. In all cases, bias (or average residual) was minimal (< 0.25). As figs 3 and 4 indicate, similar results occurred at 5% and 50% emergence times. Comparison between plots (a) to (c) for both 1976 (fig. 3) and 1986 (fig. 4) showed no discernible spreading of residual range as the modelling run progressed. Higher residual values for 1976 than for 1986 were expected, given the wider range and higher variance of the underlying temperature data in the warmer year. The corresponding r.m.s. errors, summarized in table 2, show significant differences when computed using temperatures constructed using Voronoi polygons versus partial thin plate splines.

Plutella xylostella

The potential number of generations of *P. xylostella* in 1976 and 1986 are shown in fig. 5. Up to six generations may be feasible in the warmest areas of England and Wales, particularly in urban areas and on the south-west coastal fringes. Even within the highest regions of northern England and Wales, the pest could complete a single generation. In southern agricultural areas, three full generations were possible, even in 1986, despite that year's particularly cool summer. The r.m.s. errors for the numbers of generations were higher when using the Voronoi method for estimating development (0.63 and 0.60 respectively in 1976 and 1986, compared with 0.44 and 0.32 for splines) (table 2).

Regional variability in an activity threshold

Merodon equestris

The overall benefits of using data interpolated by splines to construct indices of activity of *M. equestris*, in comparison with Voronoi polygons were studied. Looking, firstly, at predictions of the first date in May–June when the maximum temperature exceeded 20°C, r.m.s. errors for 1976 were 9.54 for splines, and 11.8 for Voronoi polygons (table 2). Respective r.m.s. figures for 1986 were 13.1 and 20.0. In contrast, the numbers of days on which maximum temperatures exceeded 20°C within the May–June period are estimated more easily using both methods, but again splines outperform estimates computed using 'nearest neighbour' station data (Voronoi polygons), by factors greater than 80%.

Estimates of the opportunities for *M. equestris* to mate (at a resolution of 1 km) are plotted for south-west England (fig. 6a) and Lincolnshire (fig. 7a). In the case of the south-west, dates for first mating activity in 1986 (Julian days 152–167) fall within the much broader range indicated for 1976 (Julian days 127–177). This highlights the local spatial variability in the distribution of maximum temperatures from year to year. Highest temperatures are not offset solely in time, but also geographically, particularly at the coastal margins. Overall, however, the mean first date on which a maximum temperature of 20°C was reached in the south-west was 8 May in 1976 and 3 July in 1986. This contrasts with the flatter, easterly aspect of Lincolnshire, where differences between years were considerably less pronounced, albeit over a smaller geographical area. In 1976, temperatures first exceeded 20°C in Lincolnshire between Julian dates 128–158, with a mean value of 130 (30 May), while in 1986 the mean date was estimated to be only 5 days later. The variability over the landscape was considerably higher for 1986 than 1976 for Lincolnshire (stdev. 19.59: 4.57) but the reverse was true for the south-west (stdev. 2.1: 6.8 respectively). This may reflect differences in predominant weather patterns between the two years. Additionally, geographical differences in phenology-related phenomena become more pronounced where conditions are marginal, either through the effects of elevation or the underlying weather conditions.

Turning to the numbers of days in May and June on which mating may have been feasible, values are higher for 1976 than 1986 in both regions, as expected (figs 6b and 7b). In the south-west, the mean for 1976 is 17 days, in contrast to the higher value of 25 in Lincolnshire. For 1986, this difference is less marked with means of 10 and 11 for the south-west and Lincolnshire respectively. The effect of high elevations over wider areas in the south-west, together with

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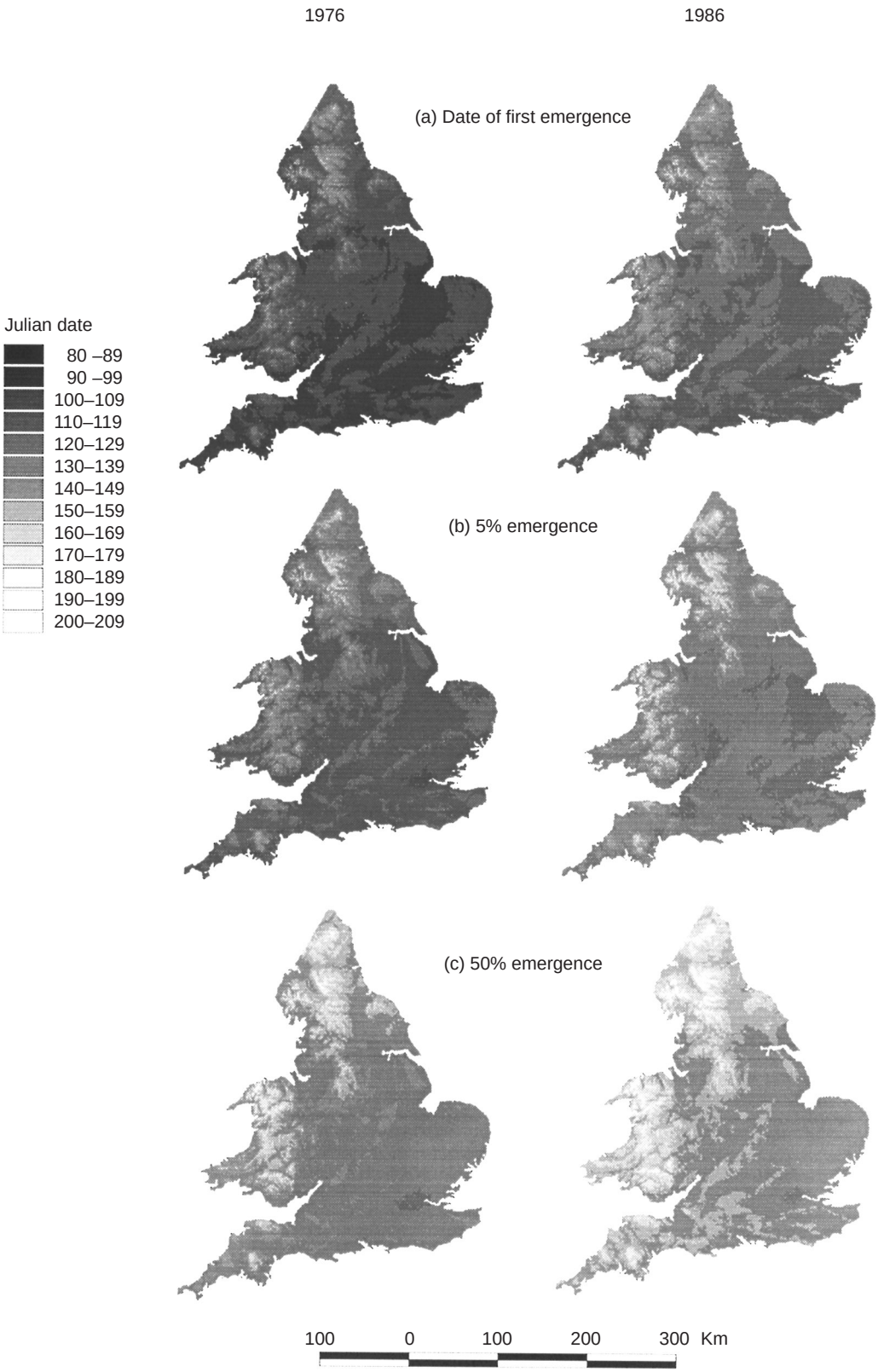


Fig. 2. Date of first, 5% and 50% emergence of *Cecidophyopsis ribis* across England and Wales, 1976 and 1986.

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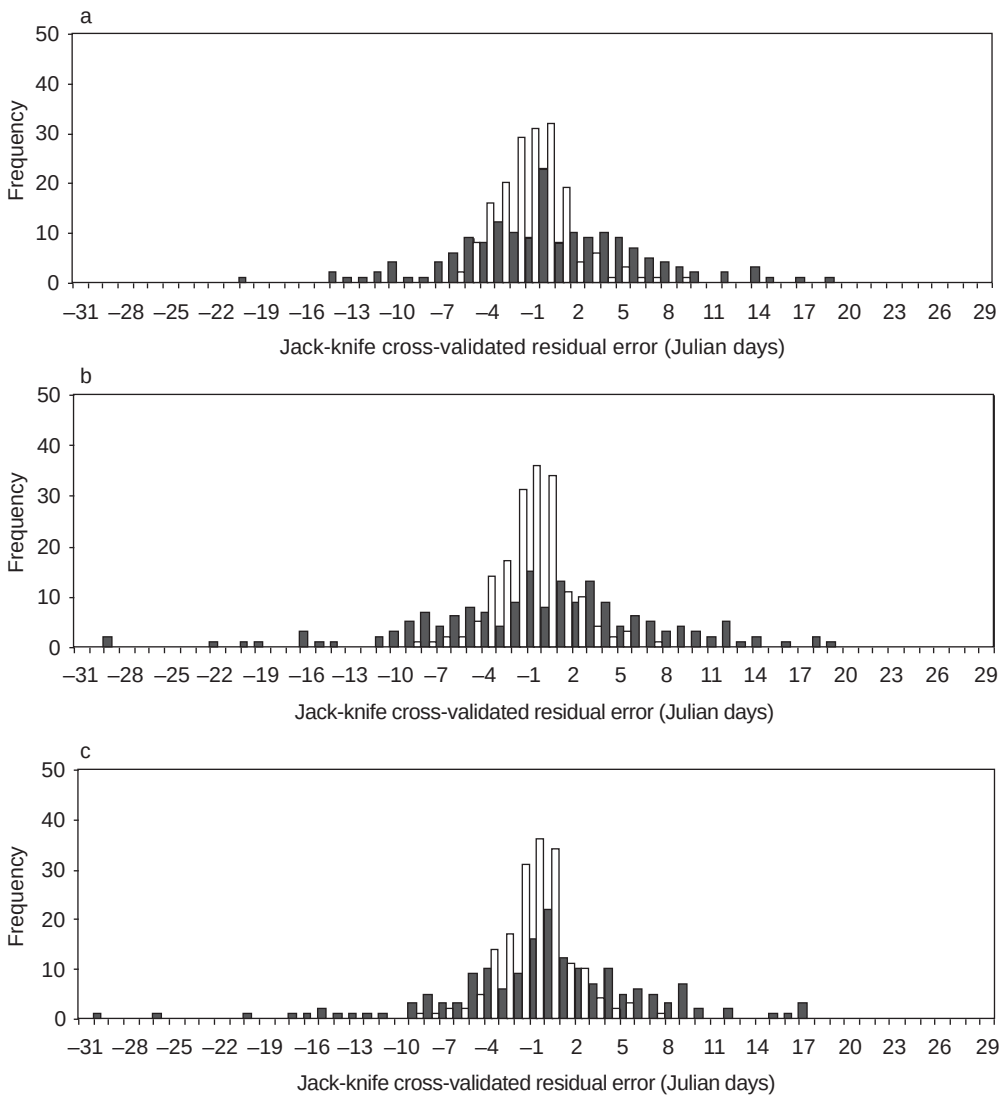


Fig. 3. Jack-knife cross-validated residuals using 'nearest station' data (■) (Voronoi polygons) and interpolated data (□) for *Cecidophyopsis ribis*: distribution for England and Wales, (a) first emergence, (b) 5% emergence, (c) 50% emergence, 1976.

Table 2. Summary root mean square (r.m.s.) errors, by pest and target event, 1976 and 1986.

Pest	Target event	1976		1986	
		r.m.s. error (spline interpolation)	r.m.s. error (nearest station)	r.m.s. error (spline interpolation)	r.m.s. error (nearest station)
Plutella xylostella	No. of complete generations	0.44	0.63	0.32	0.60
Cecidophyopsis ribis	1% emergence	2.14	9.28	2.30	6.39
	5% emergence	2.86	10.02	2.14	5.90
	50% emergence	2.36	9.07	2.33	6.52
Merodon equestris	1st day over 20°C (May/June)	9.54	11.82	13.07	20.00
	No. of days > 20°C, (May/June)	2.41	5.45	1.92	3.44

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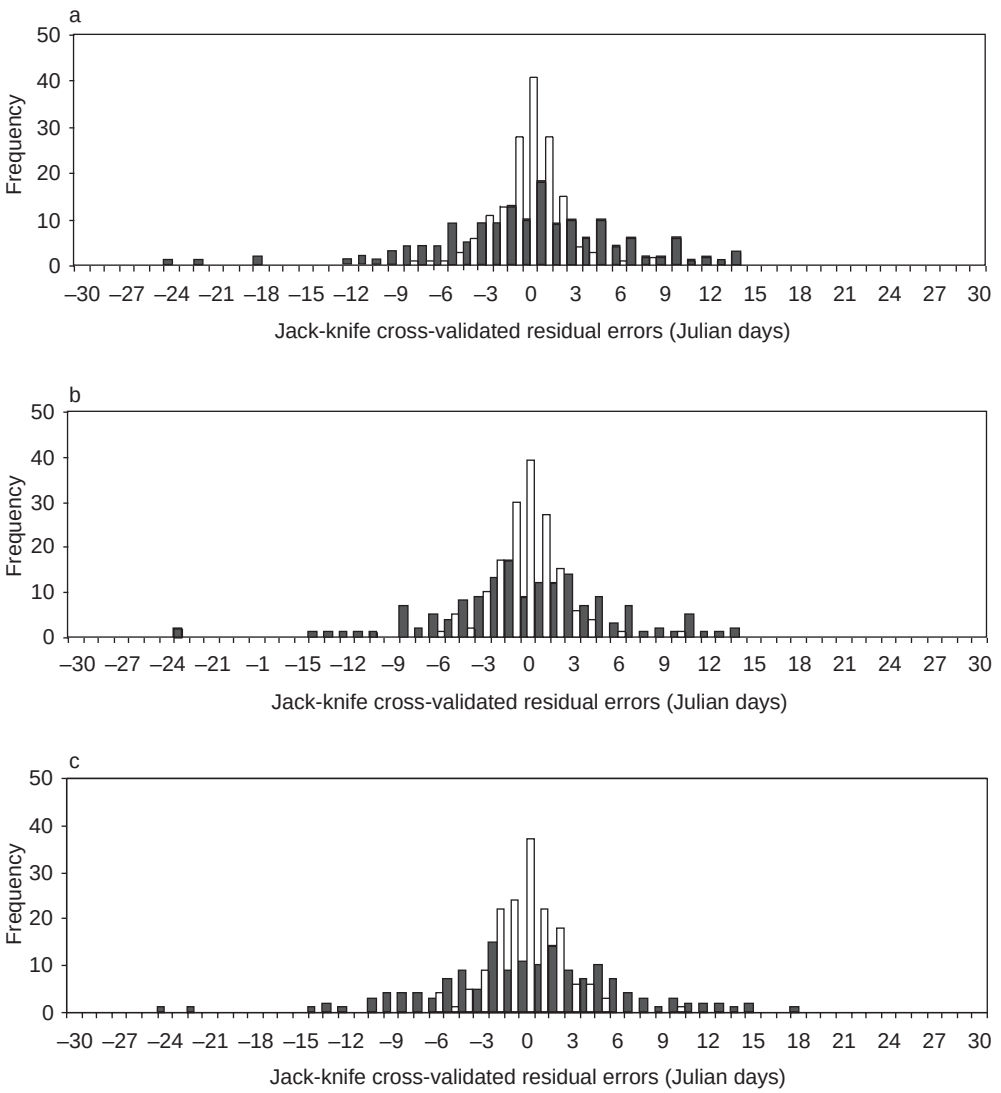


Fig. 4. Jack-knife cross-validated residuals using 'nearest station' data (■) (Voronoi polygons) and interpolated data (□) for *Cecidophyopsis ribis*: distribution for England and Wales, (a) first emergence, (b) 5% emergence, (c) 50% emergence, 1986.

the attenuating effect of local cooling summer breezes, particularly during hot summers in the English south-west, are probably contributory factors. With a range of 18–31 days in 1976 and 3–16 days in 1986 for Lincolnshire, these results suggest that the opportunities for mating might be expected to be greater in the east than in the south-west.

Figures 6c–d and 7c–d illustrate the local range in the numbers of days suitable for mating over 5*5 km and 10*10 km blocks of interpolated cells respectively. For both neighbourhoods, considerable local variation in the patterns of spatial association may be identified, both within the regions and between them, in any one year. In Lincolnshire, for example, and focusing on the plots for 1976, the average range in the number of days suitable for mating over a 10*10 km neighbourhood is 9 days, while in the south-west this reaches 13 days. That is, higher levels of spatial fragmentation are apparent in surfaces for the south-west, as might be expected, given the greater variation in the underlying topography. Similarly, fragmentation levels are higher on average in the south-west than in Lincolnshire over a 5*5 km neighbourhood, with average ranges of 8 and 4 days respectively. Turning to 1986, this difference between the two regions remains, but is less marked. Additionally, little temporal consistency in the spatial patterns of local association between individual years is apparent within the plots, although certain islands of spatial heterogeneity may be identified.

Analysis of average spatial association for mating activity across the two regions, at neighbourhood areas from 3*3 to 10*10 km (figs 8 and 9) provides a graphical summary of average local variability. For the south-west, the average local range in both 1976 and 1986 exceeds that of Lincolnshire in either year. More importantly however,

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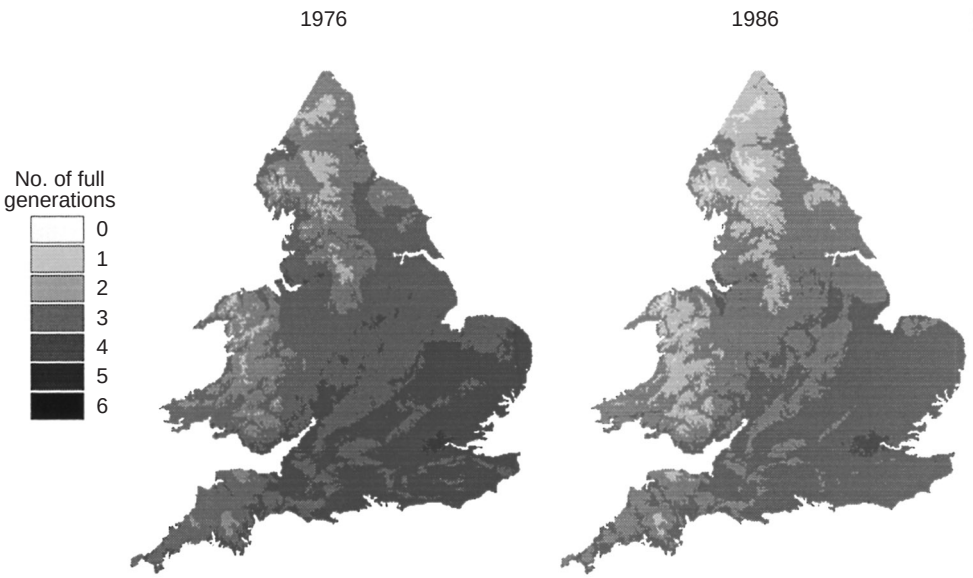


Fig. 5. Expected number of generations of *Plutella xylostella*, assuming arrival of migrants on 12 June.

where the slope for range, and its mean and standard deviation, remain static from one local neighbourhood area to the next, this suggests that modelling results at coarser grid resolutions could provide equally valid results. Consider for example the situation where there is a high proportion of the regional landscape over which the predicted activity does not alter over a 5*5 km square, where the original model ran at a resolution of 1 km. This would suggest that there is little to be gained by running the model at 1 km, and a 5 km resolution would in most places be expected to provide adequate results. In fact, in all cases (figs 8 and 9) the rate of change of range in activity level curves increases most sharply in regions up to 5*5 km in size, indicating that modelling at resolutions of 1 km or below is appropriate. Additionally, an analysis of the slope between area and local range (maximum–minimum activity within the local neighbourhood area) also reveals differences in spatial regimes within and between the regions. The steep slopes of fig. 8 for the south-west in comparison with those of Lincolnshire suggest that the choice of optimal resolution is more sensitive in the south-west than Lincolnshire.

Discussion

For all three pests investigated, the use of interpolated data improved significantly the accuracy of predicted phenological events when compared with the use of data from the nearest meteorological station, which is the commonly adopted approach. The low level of bias in the results, across all pests and target stages, also provides verification of the interpolation procedure and supports the results of previous work, which used temperature data, interpolated using partial thin plate splines, to estimate the development of *Cydia pomonella* (Linnaeus) (Lepidoptera: Tortricidae) (Jarvis, 1999). Importantly, this work extends the knowledge gained from previous studies and shows that the results are consistent across a variety of species.

The r.m.s. figures relating to the large narcissus fly mating threshold were high compared with those forecast for *Cecidophyopsis ribis*. This is thought to reflect the use of a single threshold temperature, rather than a heat sum accumulated over time, where daily bias and problems with estimating particular weather types have a tendency to average out. Since, irrespective of interpolation method, the threshold type of forecast (e.g. first day at 20°C) is very sensitive, it may be preferable to use an alternative model, if one exists. A model describing the life-cycle of *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae) (Baker & Cohen, 1985) also showed the greatest error at points in the cycle where thresholds were applied (Jarvis & Stuart, 2001c).

This paper raises questions about the 'most appropriate' scale for interpolation and modelling, and begins to work towards a solution, through an examination of variability over different neighbourhood areas. Examination of local variation in the threshold temperature for the mating of *M. equestris* suggests that the 'optimal' scale may be regionally dependent. Resolution will certainly be pest dependent, since the amount of variation depends on the sensitivity of a pest to local fluctuations in temperature at critical stages of development. Moreover, the degree of local movement of different types of pests in the field will also impact upon optimal resolution, since it is unrealistic to restrict a highly mobile pest to an artificially high resolution cell to model development throughout its life-cycle. Such issues will form the basis of further modelling experiments, in combination with field research, to explore local variability. It may transpire that modelling at lower resolutions, but perturbing input temperatures stochastically according to the local variance in conditions, may be advantageous for migratory pests.

The use of jack-knife cross validation provided a way of assessing the errors arising in phenology model outputs as a result of using remote temperature data. Previous work has validated surfaces of interpolated phenologies using field

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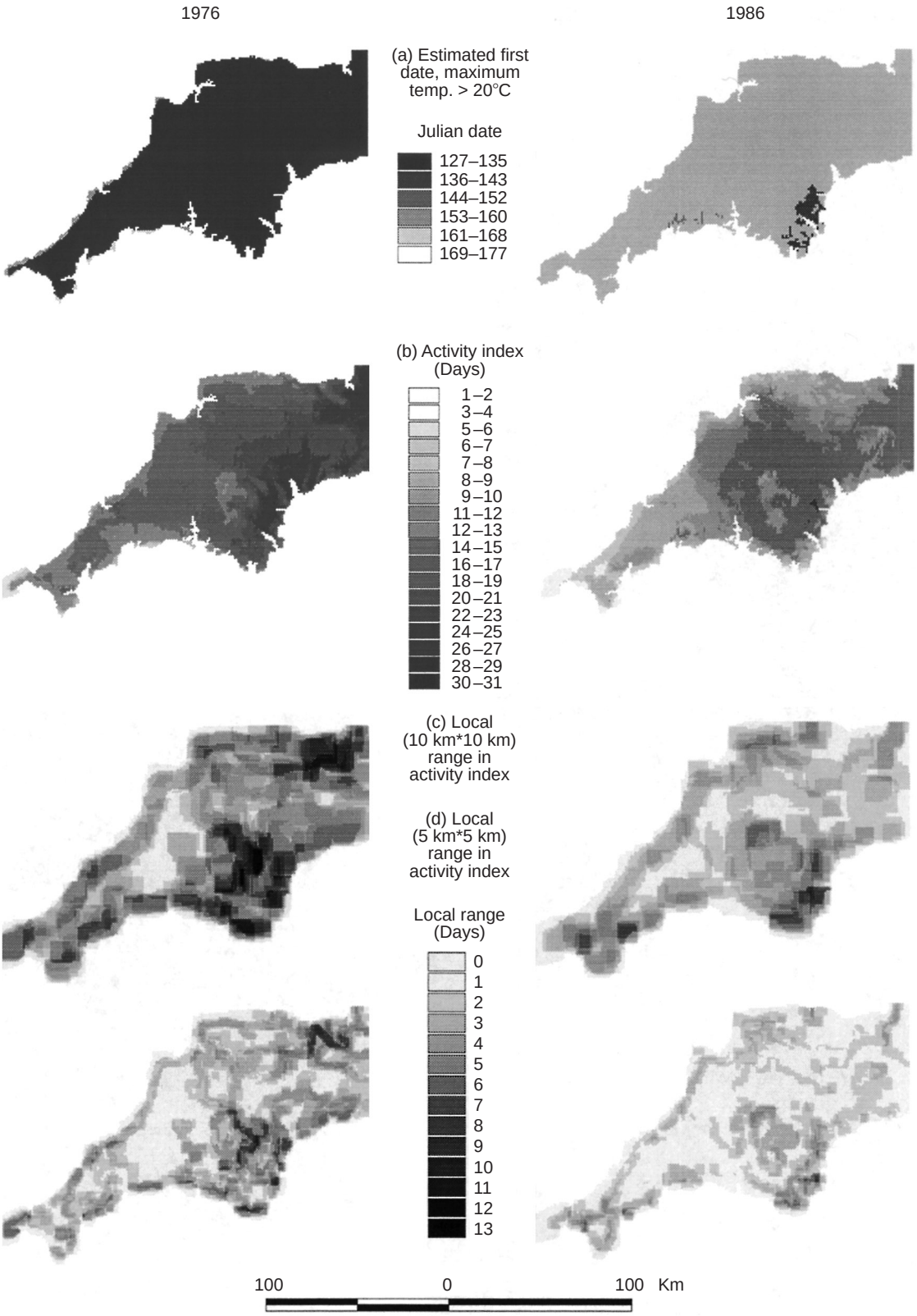


Fig. 6. Date on which the threshold temperature (20°C) for *Merodon equestris* mating activity was first exceeded in Lincolnshire, 1976 and 1986.

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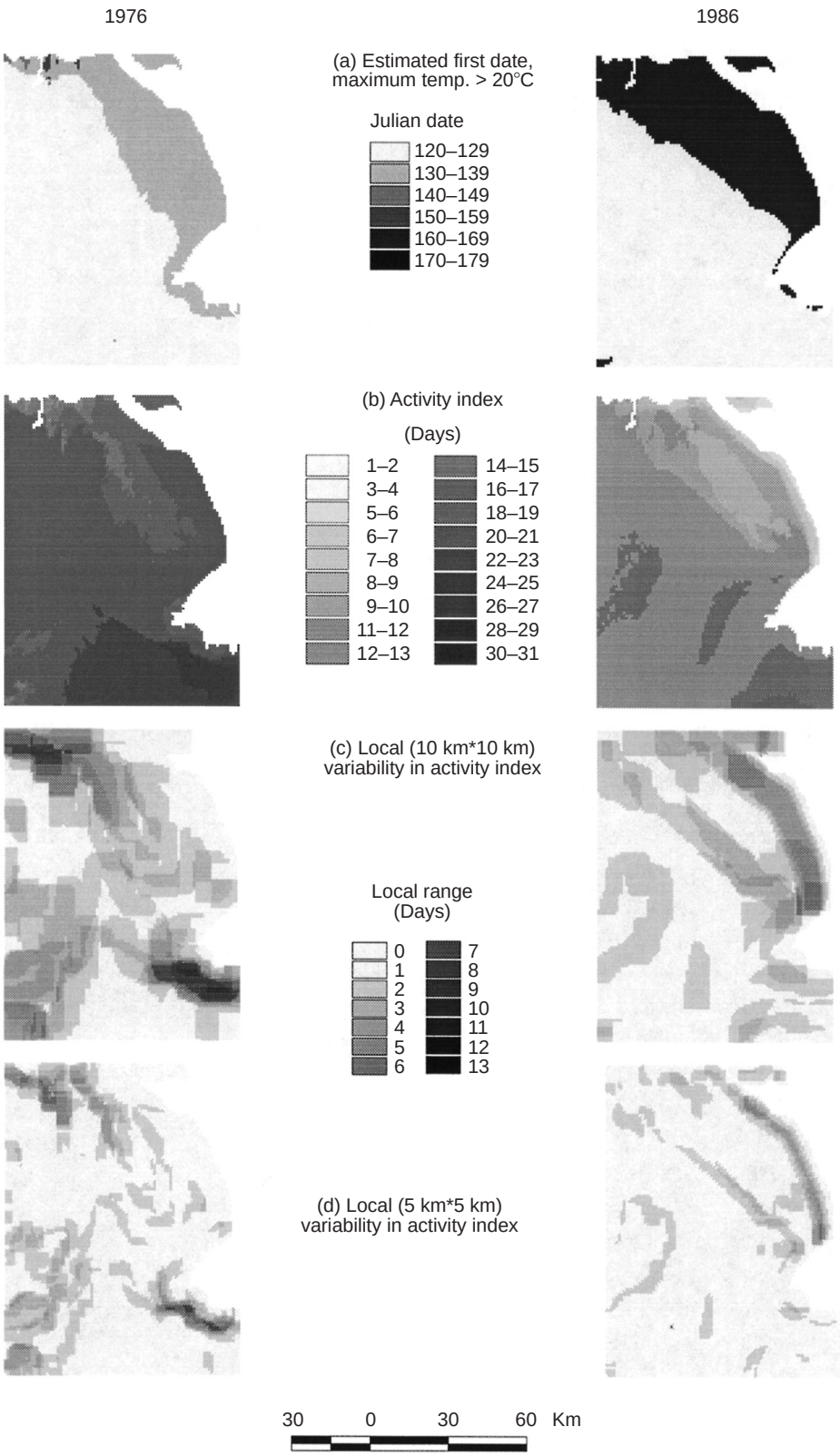


Fig. 7. Date on which the threshold temperature (20°C) for *Merodon equestris* mating activity was first exceeded in south-west England, 1976 and 1986.

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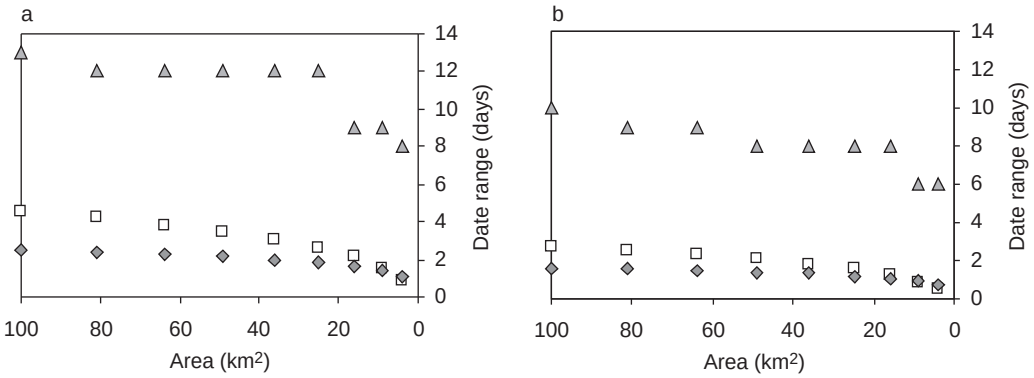


Fig. 8. Local range (latest – earliest date within neighbourhood area) in number of days when the mating of *Merodon equestris* was feasible over the south-west region: overall range (▲), mean range (□) and standard deviation of range by size of neighbourhood area (♦), for 1976 (a) and 1986 (b).

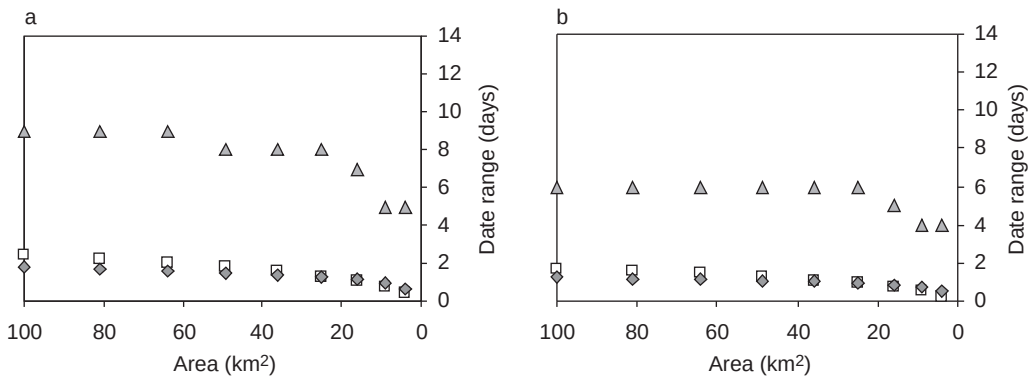


Fig. 9. Local range (latest – earliest date within neighbourhood area) in number of days when the mating of *Merodon equestris* was feasible over the Lincolnshire region: overall range (▲), mean range (□) and standard deviation of range by size of neighbourhood area (♦), for 1976 (a) and 1986 (b).

data (Régnière & Bolstad, 1994; Schaub *et al.*, 1995), a valuable practice but one which relies on the availability of significant sample volumes which are often unavailable. Field validation includes errors in the interpolation process, the model, and the sampling procedure. The use of cross-validation, however, provides a greater degree of assurance than assessing error using a small data set, where the partitioning of independent data would in itself compromise the underlying modelling approach.

The method also incorporates implicitly the notion that errors are likely to be spatially variable. Previous studies have shown that temperatures in coastal areas can be more difficult to interpolate compared with those further inland (Jarvis & Stuart, 2001b). Moreover, the interpolation errors related to maximum temperatures in Cornwall have a higher day-to-day variability than those for Lincolnshire. There is further scope for modelling the errors in phenologies throughout the landscape, rather than at a limited number of locations, using current methods in GIScience (e.g. Heuvelink, 1998), in association with stochastic biological models (e.g. Phelps *et al.*, 1993). It is the case, however, that current error propagation strategies across both space and time are computationally intensive, and may require high performance computing strategies in the short term (Mineter *et al.*, 2000).

The focus within this paper on events of particular relevance to practical pest management strategies, rather than a more theoretical investigation across all stages of development, suggests that there may be a role for interpolated meteorological data in tactical agricultural decision support systems. While in-field sensors are becoming increasingly popular, data supplied by the UK Meteorological Office, as used here, are quality assured and are obtained from locations which have consistent exposure to the elements. This means that, if such data are available, model performance can be assessed using standardized, quality assured data, available across the country. In contrast, field sensors may be placed within a crop, at different heights or with different exposure to wind. It is also possible that a user could be asked to position their sensors differently on a model by model basis. These possibilities are discussed more widely elsewhere (Jarvis *et al.*, in press).

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Given the likelihood that errors arising as part of the interpolation procedure could become compounded within the subsequent modelling process (Jarvis & Stuart, 2001c), it is also important that the best possible interpolation techniques are used for agricultural support.

Whilst the results look promising, certain caveats must be applied. Firstly, the accuracies achieved relate to a particular amount, and distribution, of underlying temperature data. In this case, the temperature data are from the UK Meteorological Office synoptic weather records, which are those that can be used without a significant delay in transmission to the user. This corresponds to the minimum amount of data that might be available to an operational decision support system in Britain. Secondly, and ideally, the modelling of geographical phenologies should link with significant national and regional field sampling programmes to allow the errors in input temperature data, phenology models and trapping effort to be assessed together. In combination, such work would allow the partitioning of error and would allow research effort to be targeted more closely to the 'weakest link' in the overall prediction system.

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