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Ref No	Details of the Published Work
1	**Sparks, T.H.** & Carey, P.D. (1995). The responses of species to climate over two centuries: An analysis of the Marsham phenological record, 1736-1947. *Journal of Ecology*, **83**, 321-329.
2	**Sparks, T.H.** & Yates, T.J. (1997). The effect of spring temperature on the appearance dates of British butterflies 1883-1993. *Ecography*, **20**, 368-374.
3	**Sparks, T.H.,** Jeffree, E.P. & Jeffree, C.E (2000). An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Biometeorology*, **44**, 82-87.
4	Huin, N. & **Sparks, T.H.** (1998). Arrival and progression of the Swallow *Hirundo rustica* through Britain. *Bird Study*, **45**, 361-370.
5	Huin, N. & **Sparks, T.H.** (2000). Spring arrival patterns of the Cuckoo *Cuculus canorus*, Nightingale *Luscinia megarhynchos* and Spotted Flycatcher *Musciapa striata* in Britain. *Bird Study*, **47**, 22-31.
6	**Sparks, T.H.** (1999). Phenology and the changing pattern of bird migration in Britain. *International Journal of Biometeorology*, **42**, 134-138.
7	**Sparks, T.,** Heyen, H, Braslavska, O., & Lehikoinen, E. (1999). Are European birds migrating earlier? *BTO News*, **223**, 8-9.
8	Crick, H.Q.P, & **Sparks, T.H.** (1999). Climate change related to egg-laying trends. *Nature*, **399**, 423-424.
9	Loxton, R.G., **Sparks, T.H.** & Newnham, J.A. (1998). Spring arrival dates of migrants in Sussex and Leicestershire (1966-1996). *The Sussex Bird Report*, **50**,182-196.
10	**Sparks, T.H.,** Carey, P.D., & Combes, J. (1997). First leafing dates of trees in Surrey between 1947 and 1996. *The London Naturalist*, **76**, 15-20.
11	**Sparks, T.** & Manning, M. (2000). Recent phenological changes in Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **33**, 105-110.
12	Roy, D.B. & **Sparks, T.H.** (2000). Phenology of British butterflies and climate change. *Global Change Biology*, **6**, 407-416.
13	**Sparks, T.H.** & Crick, H.Q.P. (1999). The times they are a-changing? *Bird Conservation International*, **9**, 1-7.
14	**Sparks, T.H.,** Roy, D.B. & Mason, C.F. (2000). Phenology in Essex: lessons from the past and examples of recent trends. *Essex Naturalist*, **17**, 31-37.
15	**Sparks, T.** (2000). The long-term phenology of woodland species in Britain. In K.J. Kirby & M.D. Morecroft (eds) *Long-term studies in British woodland. English Nature Science series* **34**, 98-105.
16	Cannell, M.G.R., Palutikof, J.P. & **Sparks, T.H.** (eds) (1999). *Indicators of Climate Change in the UK.* DETR, London, 87 pages.
17	Harrington, R. Woiwod, I.P., & **Sparks, T.H.** (1999). Climate change and trophic interactions. *Trends in Ecology and Evolution*, **14**, 146-150.

Abstract

Phenology, the study of timings of natural events, is the longest written biological record in the UK. It has thus proved invaluable in revealing how species have responded to recent climate warming. I have played a major role in achieving scientific 'legitimacy' for the subject and there is a growing urgency to demonstrate climate induced effects to both a scientific and a general audience. My phenological publications fall into four broad areas.

1. Utilising historic data. Many historic data sets have languished in obscurity for ≥50 years. Identification and examination of some of these data has revealed how biological events responded to past fluctuations in temperature. The typical response of c.6 days earlier for each 1°C warming has enabled a prediction of response to future climate. National data sets have given greater confidence in these results.

2. Bird phenology. Bird data, particularly that on migration timing, forms a huge resource of phenological material. I have examined the role of temperature in bird phenology and on migration patterns from various sources of data and have begun to extend these studies through international collaboration (two further papers 'in press'). In general, the response of birds is more variable and not as great as that of plants and invertebrates.

3. Other taxa. Post-war changes have already taken place in the timing of a wide range of taxa. In some instances events are at least three weeks earlier. These results have encouraged me to resurrect a phenology network after a 50-year break (www.phenology.org.uk).

4. Increasing awareness. Changes in phenology are readily understood by various sectors of the public and are a good vehicle with which to demonstrate climate change. The UK Government has now accepted phenological events as Climate Change Indicators.

Introduction

My introduction to phenology was a chance event. At my research station were several scientists with interests in hedgerow ecology. One of these, Max Hooper, knew of my emerging interests in hedgerows, and when he retired he gave me a box of files covering much of his early work from the 1960s and 1970s. One of these contained an intriguing hand-drawn graph displaying a histogram of over 100 years of tree leafing dates. I had no idea that data over such a long period existed and enquiries led to a forgotten 1926 paper (published oddly enough by an expert on Roman roads) which listed the Marsham family phenological records from 1736 to 1925. Subsequent work extended the record to 1947 and again more recently to 1958. My passion for phenology had been kindled.

It became apparent that there was an extensive resource of phenological data whose value had not been acknowledged. This failure had been recognised as long ago as 1936 when J.E. Clark wrote "Taken as a whole, however, it may be said that the present labourers have been builders up of statistics, looking for the coming of other labourers into the field to reap a bounteous reward". Even 25 years later those labourers had not appeared "In fact, its very valuable work has gone on so long that biologists have enough material for years of statistical work" (R.M. Savage 1961). I remain uncertain about the true extent of phenological data. I continue to acquire data sets to add to a database and as yet there doesn't seem to be a reduction in the number coming forward.

Whilst tree rings, ice cores or lake sediments can be used to construct long time series, phenological data provide the longest *written* biological record we have (some far eastern records extend back to the eighth century). Undoubtedly these simple phenological measures have a high public resonance, i.e. are very easy to understand. The longevity of these records makes them of particular value in comparing the long-term response of species to climate. Furthermore the extent of data is particularly useful, as "it is certain that observations, apparently trivial when viewed alone, will fall into their proper places when considered in connection with others, and go to the building up of an orderly and substantial structure." (Charles Oldham, 1937).

My research program has examined phenological data from a wide range of historical and contemporary sources. It covers a range of taxa in order to understand how different species have responded to past changes in temperature and allow predictions following climate change. Forecasts for climate change have recently been re-assessed and changes as great as 5°C are anticipated in the current century. Man's past activities (including land use change and chemical pollution), have affected the sustainability of many species' populations, but anthropogenically enhanced climate warming may be the most serious threat to wildlife in the future. Climate change may occur at a rate faster than experienced at any time in the past and it is essential to know if species can adapt at the rate that is likely to be demanded of them. Phenology is the first stage in examining how climate change may affect the life cycles of species and provides clues as to how biodiversity may be affected. The following description of my phenological research is divided into four broad themes in which references to published works are given in square brackets, e.g. [1].

Theme 1. Utilising historical data.

The forgotten paper from 1926 listed the phenological record of the Marsham family from 1736-1925. Subsequent data were extracted from individual volumes of the *Quarterly Journal of the Royal Meteorological Society* up to 1947 when the Royal Meteorological Society's interest waned. After publication of [1] I managed to obtain further data up to 1958 from the current members of the Marsham family. The data themselves, and the story of the Marsham family, are both fascinating. The observations were begun by Robert Marsham, an early scientist and correspondent of Gilbert White, in 1736 and were continued after his death by subsequent generations of his family. Early records were published by Robert Marsham himself in 1789 and led to his election as a FRS. The data were subsequently "rediscovered" in 1875 and in 1926 and by myself in 1995.

What struck me immediately was the longevity of the record. As with all "real" data there are gaps in the time series but of the 27 "Indications of Spring" there were between 68 and 180 years of records for each. For 24 of the series at least 130 years of data existed. Equally obvious was the realisation that here was a goldmine of data, probably the longest written biological record in the UK and no one had yet examined the timing of these events in relation to temperature. Whilst it was, and remains, difficult and expensive to obtain temperature data from individual locations the Central England Temperature series is freely available and broadly indicative of the climate of the UK as a whole and was thus used in this and subsequent investigations.

What the examination revealed was the strength of the correlation between, particularly, tree leafing dates and temperature with precipitation variables appearing much less important. Correlations with early spring temperatures were strongly negative (warmer springs leading to earlier leafing) and, where included, correlations with previous autumn temperatures were less important and tended to be positive (warm autumns delaying subsequent leafing). All leafing models were highly significant ($p<0.001$) with R^2 ranging from 34% to 73%. As a rule of thumb a response of 6-8 days per °C appeared to be the response of vegetation to warming.

When extracting the Marsham data from the *Quarterly Journal of the Royal Meteorological Society* it was apparent that there was a multitude of other data lying unused in paper form. For each of the years 1883-1947 I extracted the appearance dates of three common butterfly species and for the period 1937-47, a further nine species. To these data were added current data recorded by the Butterfly Monitoring Scheme for the 1976-1993 period. A comparison with Central England Temperatures revealed the strength of the correlation between emergence times and temperature [2]. All species appeared to respond to warming. The response would appear to be the same as the rule of thumb suggested in the previous paragraph for tree leafing. Butterfly response historically appeared to be similar to current response. This is a very important result as it suggests that the wealth of historic data can provide temperature relationships where current data do not exist. Strong correlations existed between first appearance and mean dates suggesting, at least at the national level as examined here, that first appearance dates are representative of the butterfly's flight period. A further important result was that two of the larval foodplants of the orange tip butterfly seemed to be responding to temperature in a similar way to the butterfly suggesting that synchrony could be maintained under a warming climate.

In 1960 Edward Jeffree reported weighted means over 58 years of 24 plant phenological events from the *Quarterly Journal of the Royal Meteorological Society* reports. However, at that time a lack of computing power meant that little else was undertaken. It was apparent that these would benefit from a comparison with temperature [3]. All but one of the events was significantly related to temperature at the $p<0.001$ level with R^2 ranging from 36% to 95%. The response to temperature was in the same ball park as identified above. The importance of this work is that it represents national mean data rather than the longer, but single location, Marsham data. The data also revealed the skew nature of flowering dates and how this switched between early and late species. Edward Jeffree had the possibly unique experience of being involved with a follow up paper exactly 40 years after his initial paper. Those reading this summary may already have commented that the relationships with temperature outlined so far are correlative and cannot be assumed to be causative. However I have seen so many of these strong correlations, supported by reported responses in controlled experiments, that I have very little doubt that these observations are true responses to changing temperatures and I hope the reader will understand my continued use of the phrase "temperature response".

The enormous quantity of historical phenological data has been shown to be of great value. I managed to obtain a NERC competitive grant to produce a database of these records for wider use and this task will be complete over the next year, although there will always be more records to add to this. Prior to this I managed to attract a York MSc student to extract national data for a sample of years on bird migration timing. We selected 20 years to cover a wide range of weather conditions. The subsequent investigation led to two papers [4,5]. These showed, despite the greater noise in zoological data, that arrival timing was affected by temperatures, both along migration routes and within the UK. But the investigation also produced extra information about the pattern of bird arrival, for instance the swallow arrival was along a SW-NE axis in early years shifting to a S-N axis in later years. It was also apparent that migration was accelerated when arrival was later and this finding has recently been confirmed by an examination of swallow arrival in Slovakia (currently in press).

Theme 2. Bird phenology.

The publication of [1] had a great impact and captured the imagination of many. It encouraged others to identify data sets containing phenological data and brought forth data from a wide range of sources. It became obvious that a huge amount of information existed on the arrival times of migrant birds. The majority of these species are insectivorous so a linkage with insect emergence times might be expected and there would be advantages for a species to return to the UK as soon as food supplies were adequate in spring in order to resume breeding. The main sources of data are i) coastal bird observatories, ii) county bird records and iii) individual recorders. A combination of data from these sources led to the publication of [6]. The majority of species were showing some tendency to get earlier in recent years (negative correlations between arrival date and year) and an encouraging number of these were statistically significant despite the greater variability in these data series compared to those of plants. Most series suggested earlier arrival in warmer years. Notable among the species was sand martin which showed a strong trend towards earlier arrival and a remarkable synchrony between records from the counties of Leicestershire and Sussex. This work identified two potential problems with bird migration data. The first was the presence of a greater recording effort at weekends in county records and the second the possibility of arrival dates affected by population size, albeit only likely to be a problem amongst species at low population density. One feature of bird migration phenology is that the response to temperature seems to be of the order of 2 days per °C, much lower than that apparent in plants and invertebrates. It is not known why migrating species are not taking more advantage of earlier springs. If they are being conservative, because of the danger when arriving too early for food supplies to be available, we might expect a lag in their response to earlier springs before they take advantage of the opportunities for earlier breeding.

Publication of these results led to a growing number of contacts at home and abroad and allowed a preliminary examination of arrival time data from several European counties [7] with arrival timing revealed as temperature responsive over a wide geographic area. Subsequently I have had two papers accepted for publication covering arrival times in Poland and in Slovakia and have started further studies of data from Finland, Estonia and within the Arctic Circle in Russia.

Recognition of these works by others led to two important collaborations. Humphrey Crick of the British Trust for Ornithology spent a short sabbatical with me and we undertook an analysis of a vast amount of information on nest timing [8]. Most of these species showed a strong relationship between their nest timing and temperature and, to help justify the word "response", could be seen to get later in a cooler period of years and earlier in a warmer period of years. The disappointing feature of a *Nature* article is its brevity, but we intend to rectify that as we continue collaborative work. The second of the important collaborations was, and remains, Dick Loxton who has done a huge amount of work in unearthing data on bird migration timing. One result of this was an examination of data from Sussex and Leicestershire [9] which emphasises the trend towards earliness and relationship with temperature. As expected most species arrived later in Leicestershire. A feature of the data which has been confirmed in subsequent data sets is that early arriving species had higher inter-annual variability than later arriving species, almost certainly linked with higher inter-annual variability in temperatures earlier in the year.

Theme 3. Other taxa.

Soon it became apparent that the trickle of data was growing and that many more data existed than had been anticipated. This trickle continues to the current time as a steady flow. Of great importance amongst these sources of data is a group of people whom I respectfully call "closet phenologists". These are individuals working in isolation on a hobby, not realising that others were doing similar recording, unaware of the value of their data, and slightly embarrassed by their efforts over timescales often stretching into decades. As publicity grew over changes to spring events offers of data came in that would help to fill the gap following the end of the Royal Meteorological Society scheme in 1947.

One such person was Jean Combes who had recorded leafing dates of four tree species since 1947. These data resulted in [10] which examined her data up to 1996. The data has since been extended to 2001 and Jean promises me she will continue to record for as long as she can (her pre-war records were unfortunately destroyed). All four species showed a trend towards earliness in the 1990s, apparently associated with a run of warmer springs. There is some suggestion that not all tree species may respond in the same way to temperature, for example oak appearing to be more responsive than ash and this has been confirmed from other data sources. The Combes record has proved to be a very valuable post war record and has been used by other researchers to validate the Forestry Commission budburst models, to compare with some dendrochronological (tree ring) records and as a climate change indicator (see later). The oak data, in particular, provide an approximate extension to the Marsham record. One feature of the data is that change in recent years has sometimes been greater than would be expected by the changes to mean monthly air (shade) temperatures.

Another useful contact was Mary Manning whose 36 year record on flowering dates from her garden showed some enormous shifts over time [11]. Foremost amongst these was the way that aconite had advanced from being a late January species to a late December species. A documented record is necessary in order to believe that such shifts have taken place. Some of this change may have resulted from urbanisation and the "heat island" effect resulting from increased energy usage in cities. However, the relationship between flowering time and temperature must have been a major influence on these changes. The Manning data on snowdrop agree very well with the Marsham historical data, once more emphasising that historic data can provide useful information on current responses. As with the Combes record some changes are greater than would be expected by changes to air temperature. There needs to be further examination to see if plants respond more to sun (i.e. non-shade) temperatures, surface or soil temperatures, sunshine hours, on maximum (presumably daytime) temperature. Mean air temperature is the average of minimum and maximum (i.e. not a mean of hourly measurements. It also measures temperature in the shade at 1.25m above ground level. Thus this may not be an appropriate surrogate for the temperatures which plants, with roots in the ground and exposed to direct sunlight, experience.

It is not just plants where these changes have been observed. A critical examination of data from the Butterfly Monitoring Scheme in the post 1976 period [12] has shown that most butterfly species seem to have had their phenology affected by a trend to warmer springs. For univoltine (single generation) species this also seems to have advanced the whole flight period. For multivoltine species warmer temperatures appear to have extended the flight period, presumably through an increased number of generations. As in the earlier paper [2] the strong correlations between first and peak dates indicate that first appearance data are not overly influenced by rogue individuals and are indicative of changes to the flight period as a whole.

All of these publications have relied heavily on data which were not recorded for the express purpose of the investigation. It is depressing to realise how valuable the Royal Meteorological Society's network of phenological recorders would have been if it had continued after 1947 to the present day providing a huge resource of material with which to monitor climate change in the post war period. My recognition of the importance of phenological monitoring led to the revival of a UK Phenology Network in 1998. Now run in partnership with The Woodland Trust (www.phenology.org.uk) the scheme has grown from a baseline of 80 recorders in 1998 to 3000 in 2001, reflecting the popularity of phenology with the general public. It has rapidly grown to be the biggest such scheme in the world.

Theme 4. Increasing awareness of public and government.

I have placed a special emphasis on bringing together and publicising results through talks, publications and the media. I believe that phenology is the perfect vehicle with which to raise public awareness of climate change. One such cross taxa review [13] was aimed at an international audience of bird conservationists, not just to emphasise changes to bird phenology but also to other aspects of the natural world. Aimed at a local audience of naturalists [14] demonstrated change at a regional level, emphasising how early have been events in recent years. Included in this is a further example of the trend towards early arrival of the sand martin mentioned above. The paper also made use of the data recorded by the new UK Phenology network. [15] was written for an ecologist audience bringing together information from a range of sources on a range of phenological events. This paper displayed the synchrony between orange tip butterfly and garlic mustard, mentioned in [2] as a figure to show how they jointly responded to temperature. Like the compatibility of historic and current snowdrop response mentioned earlier, it also demonstrated that the response of historical oak data to temperature was very similar to that of current data thus emphasising the importance of safeguarding and investigating historic records. The different responses of some species suggest that a shift in competitive balance may make maintenance of a stable community, even if such a concept is valid, unachievable under future climate scenarios.

I was really delighted by the decision of the UK government to adopt phenological events as indicators of climate change [16]. My own view is that these events have much more of an impact on the public than do bland statements of, for example, "a 0.56°C increase over the last century". The latter is not visible, whereas change in phenology is easily understood and of concern to the general public. This report has created a high level of interest and received a lot of media attention. As a result there are plans to produce regional climate indicators for Wales, New England and Ireland. I am involved in the first two of these and phenology is expected to feature strongly in all three. I would also like an extension of geographic scale and see European Indicators being considered. Within the UK report we included Jean Combes' oak leafing data, swallow migration times, some nest timing data and emergence times of insects. There have been proposals to expand the Indicators and they may then include such events as daffodil flowering dates and frog spawning dates.

The final document in this submission [17] is one aimed at a specialist audience. It attempts to emphasise that there are opportunities to be had by looking across datasets at different trophic levels. In general the numbers of these that have been investigated are few and there needs to be more collaboration between different data owners. If climate warming results in a mismatch in synchrony (as suggested between birds and their caterpillar prey) the consequences to species may be much more serious than would be concluded by examining single species in isolation.

Conclusions

In a few short years my research has made considerable advances in our understanding of phenology, how it has been affected by temperature and therefore how it may respond under future climate warming. Stephen Schneider, member of the

IPCC and editor of Climatic Change, recently declared that phenology had "acquired legitimacy". It has shaken off its dusty image as a pastime of rural clerics to be acknowledged as an important part of the climate change debate. A small group of scientists are encouraging phenological research in their own countries and collaboration between countries is developing.

My published work has emphasised how responsive the natural world is to temperature fluctuations and how important climate change will be. My research has not focussed on a single species group but across trophic levels to include tree leafing, flowering of forbs, emergence of butterflies, and migration and nest timing of birds. What has emerged is that change, often dramatic change, has already taken place. Without the aid of documented evidence these changes may not be apparent because of the relatively long time scales involved and the great inter-annual variability in timing. These changes have often been impressive; for instance Norwich aconite and Surrey oak advancing by 3-4 weeks. The magnitude of these changes is repeated as records emerge from across the country. Phenology has proved its value in publicising the response so far to relatively small changes in temperature and in warning that real change may result from increased warming in the future.

My research had made use of both historic and contemporary data and on scales from local to national. Temperature response has been demonstrated in a wide range of taxa and change has been more apparent in early species since early temperatures have shown most of the increase so far. Many of the later species have not yet exhibited a change, but their response to temperature suggests that they will once warming affects the temperatures of later months. This hypothesis can be tested in the future. The data are a valuable resource; much has been done with them, but much more could be achieved. As mentioned earlier the relative merits of mean, minimum and maximum temperature, soil and surface temperatures, sunshine hours and even accumulated temperatures could be examined to see which are most influential on the phenology of species. Different species within communities (e.g. canopy species, understorey, ground flora) may well respond to different stimuli. Such an examination could explain why recent change has been greater than that expected by changes in air temperature alone. Because of the longevity of the data, another feature of data examination could be the influence of extreme events (drought, gale etc.) since these are predicted to become more frequent in the future.

A response has been revealed in the arrival dates of migrant birds, but this is less than that in plants and invertebrates. Does this suggest a potential reduction in synchrony across trophic levels? Asynchrony could be very damaging to these species if their timing mismatches with food supplies. Is the effect consequential on temperatures experienced along migration routes and the increased desertification of North Africa? Global temperature data are becoming much more widely available and an examination of temperature changes along migration routes would repay the effort.

The UK government has recognised the value of phenology as Climate Change Indicators and have adopted seven (oak leafing, emergence dates of common footman moth, orange tip butterfly and peach potato aphid, arrival date of swallow and nesting dates of chaffinch and robin) in their current report and are considering additional phenological indicators in any revision. The general public readily understands these as witnessed by the high media attention received. The regional climate change indicators under production will inevitably include phenological variables for the same reasons. Phenological measures are one of the more immediate responses to climate warming but we need to more fully understand the implications of changed phenology to populations, productivity and synchrony.

As a result of my research and that of colleagues we have learnt a great deal about changes in phenology and how phenology responds to temperature. The influence of rainfall appears to be small, although this could change if species become drought-stressed in the future. Through phenology there has been a greater public awareness of climate change issues and several thousand now participate in monitoring phenology. The research reported here has encouraged others to examine new aspects of data sets they curate and has led to new insights. Sources of data, long forgotten, have been re-examined and these will be safeguarded and made available to a much wider audience. There are many and varied possibilities of linking the data to dendrochronology, pollen timing (a growing human health consideration) and models involving frost and pest damage to agricultural, horticultural and forestry crops.

In summary this research has

- Identified a huge data resource for investigation
- Established a rule of thumb response for plants and invertebrates
- Indicated temperature induced changes to the breeding times of birds
- Shown that migration arrivals are influenced by temperature, but suggested that synchrony with plants and invertebrates may be a problem in the future
- Identified synchrony between butterflies and larval hostplants
- Publicised results to raise awareness of changes already experienced and the changes yet to take place
- Identified opportunities for further research

The main thrust of each of the cited papers is shown below

Ref No	
1	The response of historic phenological time series to temperature
2	The response of butterflies to temperature, a comparison of historic and contemporary data, and synchrony between butterfly and larval hostplant
3	The response of plant flowering to temperature at the national scale
4	The response and pattern of historic data on swallow migration
5	Ditto for three additional species.
6	A summary of bird migration data in Britain
7	An initial examination of migration across Europe.
8	The response of nest timing to temperature
9	Further work on UK bird migration and identification of the correlation between earliness and variability.
10	Contemporary response of tree leafing
11	Contemporary response of plant flowering
12	Contemporary response of butterflies and changes to flight periods.
13	A cross taxa summary of changes
14	A regional study incorporating historical and contemporary data
15	A summary of changes in the woodland ecosystem and comparison of historic and current response.
16	Identification of a set of Climate Change Indicators on behalf of HM Government
17	A discussion of the need to consider phenology across trophic levels.

Having established the foundation of the phenological response to climate change (the edge pieces of the phenology "jigsaw"), the challenge will now be to fill the remainder of the picture. There is a need to look beyond phenology and identify where climate warming may disrupt life cycles, cause changes in competitive ability, or result in a loss of synchrony between species.