

The Impact of Climatic Change on Wild Animals and Plants: A Meta-Analysis¹

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Abstract

Over the last 100 years, the global average temperature has increased approximately 0.6° C. Using information from the literature, we examine the extent to which animals and plants are already exhibiting a discernible change consistent with changing temperatures and predicted by our understanding of the species' physiological constraints. The types of changes include poleward and altitudinal range expansions, movement of abundance patterns, and shifts in morphometrics, genetics, behavior, and in the timing of events such as animal breeding or plant blooming dates. We examined over 2500 articles to find those that met the following conditions -they span at least 10 years and meet at least two of the following criteria (all association had to be statistically significant): 1) A trait of at least one species (e.g., shifting range boundary) shows a change over time. 2) That trait is correlated with changes in local temperature. 3) Local temperatures change over the time period of the study. The 45 studies meeting these criteria examine over 1250 species. Meta-analyses provide a way to combine results from different studies and, when taken together, these studies reveal an underlying consistent shift, or "fingerprint," among species from various taxa examined at locations virtually around the globe. Hence, the balance of evidence obtained from these studies suggests that a significant impact from climatic warming is discernible in the form of long-term, large-scale alteration of animal and plant populations.

Key words: climate change, fingerprint, global warming, observed impacts, phenology.

Linking Observed Changes in Animals and Plants to Climate

In this study, we demonstrate that climate is apparently already causing significant discernible changes in animal and plant populations around the globe. For example, hypotheses based on our knowledge of the physiological responses of species predict poleward and elevational range shifts in response to increasing temperatures as species move to occupy areas within their temperature tolerances (providing suitable habitat is available). These types of changes have already been noted in insects in Europe and North America (Parmesan 1996, Ellis et al. 1997, Whittaker and Tribe 1998), birds in Europe and Costa Rica (Greenwood and Baillie 1993, Pounds et al. 1999), invertebrates in the Antarctic Ocean (Loeb et al. 1997), and trees and forbs in Europe (Grabherr et al. 1994). Additionally, many species depend on temperature-related cues, from which we predict that increasing temperatures could also lead to changes in the phenology (timing) of events. Phenological changes have been observed in behaviors such as migration arrival and departure in Europe and North America (Bezzel and Jetz 1995, Bradley et al. 1999), peak insect abundance (which reflect the timing of emergence) in Europe (Sparks and Yates 1997), breeding of birds in North America (Dunn and Winkler 1999), and bud burst and blooming by trees and forbs in Europe and North America (Walkovszky 1998, Bradley et al. 1999). Other hypothesized changes include altered morphologies as natural selection acts to favor forms that perform well under the altered climatic conditions. Recorded changes of these types include decreases in melanin concentration of an insect (de Jong and Brakefield 1998), increases in the size of bird eggs (Jarvinen 1996), loss of genetic diversity in a fast-breeding insect in Spain (Rodriguez-Trelles et al. 1998), and growth rate in trees (Barber et al. 2000).

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Documented Responses of Animals and Plants

The similarity in the patterns of many recent changes in numerous species, when coupled with changes in climatic factors, provide strong correlative evidence that climatic changes can have direct, observable effects on animal and plant populations. Here we quantify some of these changes via a meta-analytic approach—a statistical aggregation of many different types of results from literature—to search for consistent patterns.

Forty-five studies are included in our analyses. The number would be higher if we examined climatic variables in addition to temperature, which is the variable predicted with most confidence to change with increasing greenhouse gases (Santer et al. 1996). Additionally, the effects of temperature on the physiology of species are fairly well understood and reliably demonstrated in the literature to cause changes in traits of species (Root 1988). These 45 studies indicate significant changes are occurring in Europe and northern Africa (32 studies), North America (six studies), Central America (one study), Antarctica (two studies), Southern Oceanic islands (one study), the North American Pacific Ocean shoreline (one study), the North Pacific Ocean (one study), and the Antarctic Ocean (one study). To measure the impact of global warming on species, the metric to use is not the number of species that changed out of the total number of species studied, but the number of species that changed in the direction expected out of the number that changed. The 45 studies report findings of change in 567+ (some studies do not provide the exact number of species examined) animal species (451+ in Europe, 24 in North America, 68+ in Central America, one in Southern Ocean islands, two in Antarctica, 18+ along the North American shoreline of the Pacific Ocean, one in North Pacific Ocean and two in Antarctic Ocean), and in 59+ plant species (14+ in Europe, 43 in North America and two in Antarctica). These 626+ species include 84+ invertebrates, one fish, 57+ amphibians, three reptiles, 412+ birds, ten mammals, six grasses, 49+ forbs, and 4+ trees. Of the 626+ 81 percent (453) show change in the direction expected based on the understanding of physiological constraints by the species to temperature.

Quantifying such a wide array of changes is problematic. Meta-analyses, however, provide a statistical method of summarizing results from many studies, even though such studies may not use common methods or databases. We used meta-analyses to investigate changes in phenology. If global warming was causing changes in phenology, then it would be reasonable to expect that phenological changes might be associated with regional temperature changes. To test this hypothesis, we performed a meta-analysis on 18 animal

studies (195 species), and on four plant studies (50 species) reporting spring phenological changes.

Eight animal studies lacked information needed to determine correlation coefficients (r). Consequently, we performed two types of meta-analyses on these data: one taking advantage of the r values that were reported (12 studies, 34 species), and a second including all 21 studies and 193 species, but only taking into account the sign of the phenological change (i.e., negative for earlier in the year and positive for later). We also performed a meta-analysis using 49 plant species.

Our meta-analysis of the correlation coefficients between animal traits and time of year allows us to estimate a common fingerprint—a common correlation coefficient underlying the several studies. The estimated common correlation is -0.38 , which is statistically significantly different from zero ($P < 0.05$) with a 95 percent confidence interval of $-0.45 \leq r \leq -0.31$. Consequently, species shifting the timing of events earlier in the spring are shifting them by approximately 4 days per decade.

The “vote counting” meta-analysis of all animals included in spring phenology studies incorporates data for species for which either a correlation coefficient or slope of the relationship between the changing species trait and time was reported. In total, we analyzed data for 195 species from 17 studies. This vote-counting statistic is based on the number of these associations indicating an earlier phenological shift compared to the number of species showing a change. The estimated common correlation using this method is -0.75 or in other words a change in the timing of events 7.5 days earlier per decade, which is statistically different from zero ($P < 0.05$). The 95 percent confidence limits indicate that r could range between -0.88 and -0.67 , which indicates the strong negative association between phenological changes and time. The association is consistent among invertebrates, amphibians, reptiles, birds and mammals from several different locations in North America and Europe.

For the meta-analysis of plants showing a change in their blooming or budding dates, the common correlational “fingerprint” for the 48 species from North America and Europe is -0.26 , which is statistically different from zero ($P < 0.05$, 95 percent confidence interval $-0.31 \leq r \leq -0.20$). Again, a strong pattern of consistent shifting toward earlier spring activities by about 2.5 days per decade is occurring in plants.

Numerous studies examined shifts in density, which can be created by a change in abundance within the range of a species, a shift in the range boundary, or both. To test for an underlying pattern using the data available we used the “vote counting” method. For

animals and plants, 201 species show a change in density, with 157 of these changes in the expected direction. The minimum number of years used in these studies was 11. The meta-analysis indicates that there is statistically significant ($P < 0.05$) movement in the direction expected for these species (0.35 ranging between 0.26 and 0.41). While “vote-counting” is often insensitive to detecting underlying effects, the strength of this result indicates that there is most likely a fingerprint in the shifts of densities in both plants and animals.

Results from most studies using long-term data sets provide circumstantial (e.g., correlational) evidence about the association between changes in climate-related environmental factors and animal traits. Circumstantial evidence, insufficient for “proving” causation by itself, is highly suggestive when numerous studies, examining many different taxa from several different locations, are found to be consistent with one phenological fingerprint. Indeed, given that 81 percent of the species showing change are changing in the manner expected, we conclude that animals and plants are already responding in concert with the increase in global average temperature of 0.6°C .

Conclusions

Many well-documented pressures (e.g., habitat loss, exotic invasive species) influence the lives of animals, plants and their communities. This study shows that temperature change is apparently also a major influence on many species. Meta-analyses provide a way to combine results from various studies and find an underlying consistent shift, or “fingerprint,” among species from different taxa examined at disparate locations. Hence, the balance of evidence suggests that a significant impact from climatic warming is discernible in the form of long-term, large-scale alteration of animal and plant populations. Clearly, if such ecological changes are now being detected when the globe has warmed by only 0.6°C , it is likely that many more far reaching impacts on ecosystems would occur in response to changes in temperature up to 6°C by 2100. Projected future rapid climate could soon become a major concern, especially when occurring in concert with the other already well-established stresses. Research and conservation attention thus needs to be focused not only on each of these stressors by themselves, but the synergism of several pressures that together are likely to prove to be the greatest challenge to animal conservation in the 21st Century (Root and Schneider 1993, Myers 1997). Because anticipation of changes improves the capacity to manage, it behooves us to understand as much as possible about the responses of animals to a changing climate. This and

further documentation of change may well indicate a need for action.

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Literature Cited

- Barber, V. A., G. P. Juday, and B. P. Finney. 2000. **Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress.** *Nature* 405: 668-673.
- Bezzel, E. and W. Jetz. 1995. **Delay of the autumn migratory period in the Blackcap (*Sylvia atricapilla*) 1966-1993: A reaction to global warming?** *Journal für Ornithologie* 136: 83-87.
- Bradley, N. L., A. C. Leopold, J. Ross, and W. Huffaker. 1999. **Phenological changes reflect climate change in Wisconsin.** *Proceedings of the National Academy of Sciences of the United States of America* 96: 9701-9704.
- de Jong, P. W. and P. M. Brakefield. 1998. **Climate and change in clines for melanism in the two-spot ladybird, *Adalia bipunctata*.** *Proceedings of the Royal Society of London - Series B* 25: 39-43.
- Dunn, P. O. and D. W. Winkler. 1999. **Climate change has affected the breeding date of tree swallows throughout North America.** *Proceedings of the Royal Society of London - Series B* 266: 2487-2490.
- Ellis, W. N., J. H. Donner, and J. H. Kuchlein. 1997a. **Recent shifts in phenology of Microlepidoptera, related to climatic change (Lepidoptera).** *Entomologische Berichten (Amsterdam)* 57: 66-72.
- Grabherr, G., M. Gottfried, and H. Pauli. 1994. **Climate effects on mountain plants.** *Nature* 369: 448.
- Greenwood, J. J. D. and S. R. Baillie. 1993. **Effects of density dependence and weather on population changes of English passerines using a non-experimental paradigm.** *Ibis* 133: 121-133.
- Hedges, L. V. and I. Olkin. 1985. **Statistical methods for meta-analysis.** New York, NY: Academic Press, Inc.
- Intergovernmental Panel on Climate Change (IPCC). 2001. **Climate Change 2001: The Science of Climate Change.** New York, NY: Cambridge University Press.
- Jarvinen, A. 1996. **Correlation between egg size and clutch size in the Pied Flycatcher *Ficedula hypoleuca* in cold and warm summers.** *Ibis* 138: 620-623.
- Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. Fraser, W. Trivelpiece and S. Trivelpiece. 1997. **Effects of sea-ice extent and krill or salp dominance on the Antarctic food web.** *Nature* 387: 897-900.

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- Myers, N. 1997. **The rich diversity of biodiversity issues.** In: M. L. Reaka-Kudla, D. E. Wilson, and E. O. Wilson, editors. *Biodiversity II*. Washington, DC: Joseph Henry Press; 125-138.
- Parmesan, C. 1996. **Climate and species' range.** *Nature* 382: 765-766.
- Pounds, J. A., M. P. L. Fogden, and J. H. Campbell. 1999. **Biological response to climate change on a tropical mountain.** *Nature* 398: 611-615.
- Rodriguez-Trelles, F., M. A. Rodriguez, and S. M. Sheiner. 1998. **Tracking the genetic effects of global warming: *Drosophila* and other model systems.** *Conservation Ecology* [online] 2, 2. Available at: <http://www.consecol.org/vol2/iss2/art2>.
- Root, T. L. 1988. **Environmental factors associated with avian distributional boundaries.** *Journal of Biogeography* 15: 489-505.
- Root, T. L. and S. H. Schneider. 1993. **Can large-scale climatic models be linked with multi-scaled ecological studies?** *Conservation Biology* 7: 256-270.
- Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds. 2003. **Fingerprints of global warming on animals and plants.** *Nature* 421: 57-60.
- Santer, B. D., T. M. L. Wigley, T. P. Barnett, and E. Anyamba. 1996. **Detection of climate change and attribution of causes.** In: J. Houghton, L. Meiro Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell. *Climate Change 1995: The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press; 407-433.
- Sparks, T. H. and T. J. Yates. 1997. **The effect of spring temperature on the appearance dates of British butterflies 1883-1993.** *Ecography* 20: 368-374.
- Walkovszky, A. 1998. **Changes in the phenology of the locust tree (*Robinia pseudoacacia*) in Hungary.** *International Journal of Biometeorology* 41: 155-160.
- Whittaker, J. B. and N. P. Tribe. 1998. **Predicting numbers of an insect (*Neophilaenus lineatus*: Homoptera) in a changing climate.** *Journal of Animal Ecology* 67: 987-991.