

# Plant Ecology as an Indicator of Climate and Global Change

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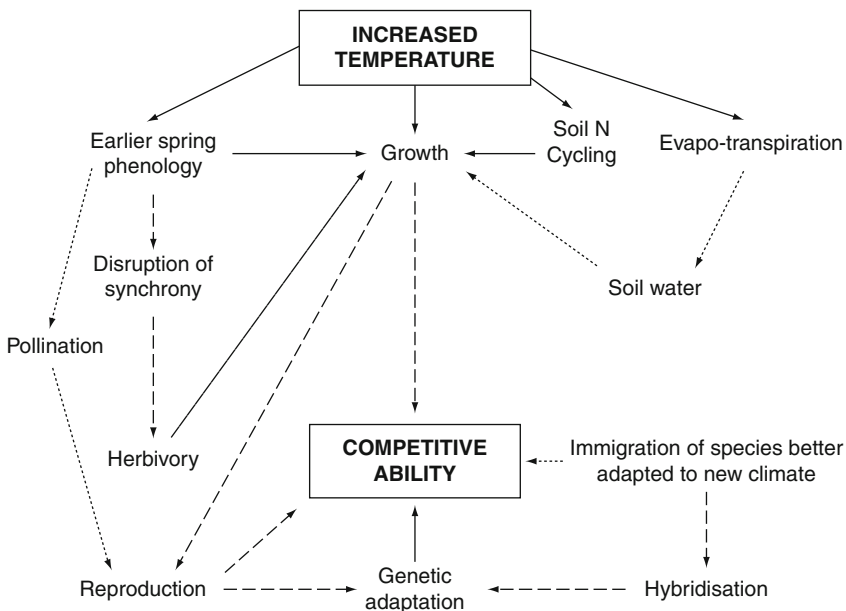
1. **Introduction**
  2. **Changes in Phenology**
  3. **Changes in Distribution**
  4. **Community Composition**
  5. **Plant Growth**
  6. **Conclusions**
- References**

## 1. INTRODUCTION

The distribution of types of vegetation around the world is clearly related to climate. Different combinations of temperature, rainfall and seasonality produce the global variety of biomes, from rainforest to tundra, which we take for granted. At a finer scale we can see changes in vegetation with more localised changes in climate such as on a mountain as conditions become cooler with altitude [1,2]. Individual species also have distribution patterns, the boundaries of which are largely defined by climate at a global scale. These distribution patterns reflect the influence of climate on plant survival, physiology and growth, together with climatic effects on ecological interactions, such as competition, pollination and herbivory. Different types of plant are adapted to different climatic conditions, from cold-tolerant, but slow-growing alpine plants, to fast-growing trees in the wet tropics.

It is therefore reasonable to expect that changes in climate would lead to a change in species distributions and community composition. Evidence of such changes has been accumulating in recent decades [3–7]. However, before we come to evaluate this evidence, we should consider some general principles.

To identify the ecological impacts of climate change with confidence, it is necessary both to be able to detect a change in an ecosystem and to reliably attribute it to a change in climate [6,8]. *Detection* of any change in an environmental variable requires a reliable dataset with repeated measurements over a period of time. Good instrumental records of climate itself go back over 100 a in many countries, but very few biological datasets extend this far. In many cases climate change impacts must be inferred from re-surveys of early work carried out for quite different purposes. Attribution of impacts to climate change requires a relationship between climate and impact variables to be established and other potential causes of change ruled out. The effects of climate change on plants are complex (Fig. 1) and the presence or absence of a species from a particular location does not solely depend on its ability to tolerate physical conditions. In many cases climatic limits are determined by the influence of climate on a plant's ability to compete with other species [9]. Climate change may also disturb interactions between plants and



**FIGURE 1** An example of complexity in plant responses to climate change. Factors influencing the effects of temperature on the competitive ability of a temperate, insect pollinated plant. Note that this is a simplified diagram and does not take account of all factors, interactions or the role of other climate change factors such as changes in precipitation or extreme events. Solid arrows indicate positive effects, dotted arrows indicate negative effects and dashed arrows indicate effects that could be positive or negative.

their pollinators, mycorrhizae, herbivores or pathogens. Rising temperatures are the best understood aspects of climate change but in the longer term changes in precipitation or one-off extreme events, which are harder to predict, may be more important. Changing atmospheric composition, including carbon dioxide concentration, can also have effects on plant performance and interactions [10].

A further issue is that many plant communities are composed of long-lived species and only change slowly in response to incremental changes in climate [11]. This contrasts with many invertebrate species for which clear signals of changing distributions have been found [12,13]; most of these species have short generation times and in many cases high mobility.

## 2. CHANGES IN PHENOLOGY

The recording of phenology – the seasonal timing of biological events such as leafing and flowering – provides several examples of unusually long-term data sets. A particularly good example is the Marsham family records for ‘indications of spring’ concerning over twenty plant and animal species for 200 a in Norfolk, UK [14]. Analyses of these data, particularly correlations with equally lengthy climate data, have provided important information on past effects of climate on phenological events, which in turn have been used to predict future responses of these species to projected climate change.

The Marsham data formed a component of a much larger, European wide meta-analysis of the relationship between phenology and temperature [15]. The meta-analysis included, *inter alia*, phenological trend data for 542 plant species from 21 countries. There was a clear correlation between warmer temperatures and the earlier onset of spring phenology (leaf-opening and flowering) in 78% of plants (31% significantly). In contrast, autumn onset indicators were more ambiguous, showing no overall pattern of correlation with temperature, although some individual events did correlate with temperature. The paper demonstrated a mean advance in spring and summer phenology of 2.5 days per decade in recent decades [15].

On a global scale, the most recent assessment report by the Intergovernmental Panel on Climate Change (IPCC) presented a synthesis of the current knowledge of climate change impacts on phenology. It concluded that the onset of spring has become earlier by 2.3–5.2 days per decade in the last 30 a, and that this is correlated with increasing temperatures [6]. However, of 16 studies cited, none are based in the southern hemisphere. This bias towards the northern hemisphere is a common theme throughout research into impacts of climate change on biodiversity. Satellite remote sensing has however allowed a different, more global approach to phenology. Indices based on the spectral composition of light reflected from the surface of the earth, such as the Normalised Difference Vegetation Index (NDVI), can quantify the

'greening up' of temperate zones in the spring. These techniques have broadly corroborated surface-based findings of an advancement of spring [16–18].

Phenology therefore provides a clear indicator of climate change impacts on plants. In itself, a change in phenology is arguably not a major issue if the species continues to persist in a current location. However, there is evidence that the changing phenology of a species can have important ecological consequences for pollinators [19], herbivores [20] and competitors [21].

### 3. CHANGES IN DISTRIBUTION

After phenology, the most frequently reported changes in plant ecology in response to climate change are changes in species' geographical distributions. The mapping of distributions of species and vegetation types, whether local, national or international in scale, pre-dates contemporary interest in climate change by several decades or more. Re-surveys of distributions provide an opportunity to test whether changes consistent with the impacts of climate change are taking place [22,23]. Studies of this sort have been an important component of the impacts reported in the IPCC's third and fourth assessment reports [6].

Good examples of changes in distribution can be seen in altitudinal studies. Temperatures typically fall with altitude by  $\sim 6.5\text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$  [24], although this varies with other factors, such as humidity. Plant communities consequently change markedly with altitude. The clearest example of this is the presence of tree lines, beyond which trees do not grow. Many explanations for the occurrence of tree lines have been offered, but plants are thought to respond to combinations of temperature change, atmospheric  $\text{CO}_2$  concentration, nutrient availability and solar radiation [25]. Regardless of the exact mechanism, which may vary between situations, natural tree lines (those not changed by forest management) are determined primarily by climate, particularly temperature. A warming of climate would therefore be expected to lead to tree lines shifting to higher altitudes. Evidence of this has been found with tree lines shifting at rates of  $0.01\text{--}7.5\text{ m}\cdot\text{a}^{-1}$ , depending on the species of tree involved and the type of climatic forcing [3]. The length of data collection is also likely to affect the mean shift each year (in this and other variables) because longer datasets will be subject to a smoothing of the trend through natural variation and sign switching. Latitudinal tree line shifts have also been observed, correlated with warmer summer temperatures [25].

Tree line shifts are subject to time lags in their response to environmental change because of trees' long generation time, therefore, changes in non-woody plants and dwarf shrubs might be expected to be more sensitive [3]. Evidence of changes in altitudinal distribution have been found for alpine plants [22]. In a re-survey of vascular plants in the Alps of northern Italy, 52 of the 93 monitored vascular plants were found at a higher altitude than

in the 1950s, moving upwards at a rate of 23.9 m per decade [26]. The largest change in species richness was at an altitude that had experienced melting of permafrost, associated with increasing air temperature [26].

#### 4. COMMUNITY COMPOSITION

Changes in distribution patterns are dependent on local extinctions and colonisations at species range margins. As this is where the effects of climate change are most likely to be seen first, they provide a sensitive early indicator of climate change impacts. They also provide some basic information on changes in plant communities. Studies such as those of Walther [3] and Parolo and Rossi [26] indicate how the nature of a community is changing with the colonisation of new, more thermophilous species. However, this sort of research will not capture changes in the abundance of species in other parts of their range. A change from abundance to rarity, or vice versa, for any given species is of major ecological significance, but undetectable if only species presence or absence has been recorded in the original survey.

The potential for changes in vegetation composition is substantial and experimental manipulations of climate have caused major changes in communities. One of the longest-running examples is an experiment in the sub-alpine zone of the Rocky Mountains (USA), where vegetation has been warmed using infrared lamps since 1990. The shrub, *Artemisia tridentata* (sagebrush) has increased in response to this treatment and herbaceous species have declined [27–30]. In this case the effect of warming is mediated through a reduction in summer water availability as a result of earlier snow melt.

Reliable detection of a change in the balance between different species in un-manipulated communities can usually only be achieved through long-term monitoring in permanent sample plots. Most monitoring programmes do not go back earlier than the 1970s and to date it is hard to find changes that can be confidently attributed to climate in the literature. One example of a possible impact of climate change on species composition was reported by Kirby et al. [31], who found changes in British woodland ground flora correlated with increases in growing season length between 1971 and 2001.

As major changes in the relative composition of different types of species are anticipated in the coming decades, various monitoring programmes have been developed to detect them. In the UK, the Environmental Change Network is a good example in which plant community composition is monitored in permanently marked quadrats [32] ([www.ecn.ac.uk](http://www.ecn.ac.uk)). In this network the vegetation quadrats form part of a larger ecosystem monitoring programme in which animal populations are also monitored, together with climate, soil nutrients and water content and other potential causes of change such as air pollution. This demonstrated a change in species composition of grasslands, specifically an increase in ruderal species in response to drought [33]. Ruderal

plants are those which grow and reproduce quickly and they colonised gaps which opened up in the grassland in response to drought, before being excluded by competitors as wetter conditions returned.

Another network is the Amazon Forest-Inventory Network (RAINFOR) comprised of long-term forest monitoring plots throughout the Amazon rainforest [34]. The network plots have provided evidence for a change in community composition of old-growth Amazonian forest, whereby slow growing tree genera are decreasing and fast growing tree genera are increasing in dominance or density [34,35]. There has also been an increase in density and dominance of lianas within these forests. These changes have been attributed with relative confidence to an increase in atmospheric CO<sub>2</sub> concentration [34].

Individualistic species responses and changes in the nature of interactions will lead to changes in the nature of plant communities. It is possible that assemblages of species may sometimes change from one currently recognised community to another. It is, however, likely that in many cases, novel combinations of species will develop as species respond to changing climate at different rates. Palaeoecology provides evidence of this happening during previous climate change events, indicating the formation of non-analogous communities, that were of a different composition from anything currently recognised [36]. This will have important implications for the functioning of communities and ecosystems and present challenges where current conservation policy is based on defined, historical communities.

## 5. PLANT GROWTH

Any change in species distribution or community composition is likely to be preceded by a change in plant growth. Plant growth may therefore be a sensitive indicator of climate change impacts. It is also of interest in its own right as it drives the production of food, materials and fuel and is responsible for the sequestration of carbon. The two main categories of plants whose growth is measured are crops and trees. Crops are dealt with in Chapter 17, but we will consider tree growth here.

The growth response of trees, as well as other plants, to climate differs between species, depending on their ecophysiology and life history characteristics. For example, Morecroft et al. [37] showed that the growth of sycamore (*Acer pseudoplatanus*) was adversely affected by drought to a greater extent than pedunculate oak (*Quercus robur*) and ash (*Fraxinus excelsior*) in a British woodland. This was associated with reduced photosynthetic rates in dry soil conditions and may reflect relatively shallow rooting. Broadmeadow et al. [38] modelled broadleaved tree species' growth responses to future climate using a model based on empirical data for species specific growth rates and their correlations with aspects of climate. They found that water limitation in southern England was likely to lead to reductions in growth and increased mortality, with beech (*Fagus sylvatica*) the worst affected.

One of the areas in which tree growth rates have been a particular subject of research interest has been the Amazon rain forest, with the RAINFOR network of old-growth forest plots again providing long-term observational evidence of changes [34]. The plots have shown evidence of an increase in growth rates and biomass in recent decades. More importantly when considering the carbon sink function of the Amazon forest, there is also an increase in turnover of tropical forest trees that is thought to be a function of increased mortality following more rapid growth. These responses are, like the associated changes in community composition, most parsimoniously explained as a response to higher CO<sub>2</sub> concentrations, possibly combined with nutrient enrichment resulting from ash deposition from an increasing number of forest fires [34]. Under certain recruitment/mortality rate ratios, an increase in forest turnover could decrease the carbon sink potential of the Amazon [34].

The trunks of most temperate and some tropical trees have annual rings, reflecting seasonal differences in growth rates. These provide a particularly valuable historical record of growth rates and are often used as proxies for the estimation of past climates. Tree ring data are useful indicators of climate change because they provide a 'self-kept' record of climate response over the lifetime of an individual tree, thereby circumventing the challenge of obtaining long-term monitoring data. Width of tree rings can be correlated with environmental data. In addition to assessing general trends in tree growth to trends in climate, tree rings are very useful for examining the response of trees to extreme climatic events. A reduction in productivity demonstrated by reduced tree ring width of old beech forests in Italy, has been attributed to recent drought during the growing season [39].

A further strength of the use of tree ring data as an indicator of climate change is that changes can be explored in the context of a longer time frame, potentially increasing our understanding of current trends. Touchan et al. [40] analysed tree ring records from North West Africa for approximately the last 600 a to ascertain the influence of drought and found that the most recent drought (1999–2002) was probably the most severe since the fifteenth century and consistent with projections from global circulation models.

## 6. CONCLUSIONS

There is clear evidence that plants are responding to climate change through changing phenology and distribution patterns, with species tending to disperse towards cooler areas. More far reaching changes in community composition are starting to be recognised and are likely to become increasingly obvious in the coming decades. Responses to temperature have been clearest to date at a global scale, but in the long term, local changes in precipitation or extreme events may be more important than the global trend in temperatures. There are also likely to be complex interactions within ecosystems and with other pressures, which we need to understand and model if attempts to mitigate climate change and adapt to it are to be successful.

## REFERENCES

1. A. Hemp, *Plant Ecol.* 184 (2006) 27–42.
2. B. Sieg, F.J.A. Daniels, *Phytoecologia* 35 (2005) 887–908.
3. G.R. Walther, *Perspect. Plant Ecol.* 6 (2004) 169–185.
4. C. Parmesan, G. Yohe, *Nature* 421 (2003) 37–42.
5. T.L. Root, J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, J.A. Pounds, *Nature* 421 (2003) 57–60.
6. C. Rosenzweig, G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski, in: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (Eds.), *Assessment of Observed Changes and Responses in Natural and Managed Systems. Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2007, pp. 79–131.
7. G.R. Walther, E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.M. Fromentin, O. Hoegh-Guldberg, F. Bairlein, *Nature* 416 (2002) 389–395.
8. G.F. Midgley, S.L. Chown, B.S. Kgope, *S. Afr. J. Sci.* 103 (2007) 282–286.
9. M. Morecroft, J. Paterson, in: J. Morison, M. Morecroft, (Eds.), *Effects of Temperature and Precipitation Changes on Plant Communities*, Blackwell Publishing, Oxford, 2006, pp. 146–164.
10. E.A. Ainsworth, S.P. Long, *New Phytol.* 165 (2005) 351–371.
11. J.P. Grime, J.D. Fridley, A.P. Askew, K. Thompson, J.G. Hodgson, C.R. Bennett, *Proc. Natl. Acad. Sci. USA* 105 (2008) 10028–10032.
12. R. Hickling, D.B. Roy, J.K. Hill, C.D. Thomas, *Global Change Biol.* 11 (2005) 502–506.
13. C. Parmesan, N. Ryholm, C. Stefanescu, J.K. Hill, C.D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W.J. Tennent, J.A. Thomas, M. Warren, *Nature* 399 (1999) 579–583.
14. T.H. Sparks, P.D. Carey, *J. Ecol.* 83 (1995) 321–329.
15. A. Menzel, T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kubler, P. Bissolli, O. Braslavskaja, A. Briede, F.M. Chmielewski, Z. Crepinsek, Y. Curnel, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatca, F. Mage, A. Mestre, O. Nordli, J. Penuelas, P. Pirinen, V. Remisova, H. Scheffinger, M. Striz, A. Susnik, A.J.H. Van Vliet, F.E. Wielgolaski, S. Zach, A. Züst, *Global Change Biol.* 12 (2006) 1969–1976.
16. W. Lucht, I.C. Prentice, R.B. Myneni, S. Sitch, P. Friedlingstein, W. Cramer, P. Bousquet, W. Buermann, B. Smith, *Science* 296 (2002) 1687–1689.
17. R.B. Myneni, C.D. Keeling, C.J. Tucker, G. Asrar, R.R. Nemani, *Nature* 386 (1997) 698–702.
18. L.M. Zhou, C.J. Tucker, R.K. Kaufmann, D. Slayback, N.V. Shabanov, R.B. Myneni, *J. Geophys. Res.-Atmos.* 106 (2001) 20069–20083.
19. J. Memmott, P.G. Craze, N.M. Waser, M.V. Price, *Ecol. Lett.* 10 (2007) 710–717.
20. E. Post M.C. Forchhammer, *Philos. Trans. R. Soc. B* 363 (2008) 2369–2375.
21. E.E. Cleland, N.R. Chiariello, S.R. Loarie, H.A. Mooney, C.B. Field, *Proc. Natl. Acad. Sci. USA* 103 (2006) 13740–13744.
22. G.R. Walther, S. Beissner, C.A. Burga, *J. Veg. Sci.* 16 (2005) 541–548.
23. A.E. Kelly, M.L. Goulden, *Proc. Natl. Acad. Sci. USA* 105 (2008) 11823–11826.
24. C.D. Whiteman, *Mountain Meteorology Fundamentals and Applications*, Oxford University Press, Oxford, 2000.
25. J. Grace, F. Berninger, L. Nagy, *Ann. Bot-Lond.* 90 (2002) 537–544.
26. G. Parolo, G. Rossi, *Basic Appl. Ecol.* 9 (2008) 100–107.

27. J. Harte, *Bioscience* 51 (2001) 332–333.
28. J. Harte, R. Shaw, *Science* 267 (1995) 876–880.
29. T. Perfors, J. Harte, S.E. Alter, *Global Change Biol.* 9 (2003) 736–742.
30. F. Saavedra, D.W. Inouye, M.V. Price, J. Harte, *Global Change Biol.* 9 (2003) 885–894.
31. K.J. Kirby, S.M. Smart, H.I.J. Black, R.G.H. Bunce, P.M. Corney, R.J. Smithers, Long-term ecological change in British woodland (1971–2001). A re-survey and analysis of change based on the 103 sites in the nature conservancy ‘Bunce 1971’ woodland survey, (English Nature Research Report 653) English Nature, Peterborough, 2005, p. 137.
32. J.M. Sykes, A.M.J. Lane, *The United Kingdom Environmental Change Network: Protocols for Standard Measurements at Terrestrial Sites*. Stationary Office, London, 1996.
33. M.D. Morecroft, C.E. Bealey, E. Howells, S. Rennie, I.P. Woiwod, *Global Ecol. Biogeogr.* 11 (2002) 7–22.
34. O.L. Phillips, S.L. Lewis, T.R. Baker, K.J. Chao, N. Higuchi, *Philos. Trans. R. Soc. B* 363 (2008) 1819–1827.
35. W.F. Laurance, A.A. Oliveira, S.G. Laurance, R. Condit, C.W. Dick, A. Andrade, H.E.M. Nascimento, T.E. Lovejoy, J. Ribeiro, *Biotropica* 37 (2005) 160–162.
36. J.W. Williams, S.T. Jackson, *Front. Ecol. Environ.* 5 (2007) 475–482.
37. M.D. Morecroft, V.J. Stokes, M.E. Taylor, J.I.L. Morison, *Forestry* 81 (2008) 59–74.
38. M.S.J. Broadmeadow, D. Ray, C.J.A. Samuel, *Forestry* 78 (2005) 145–161.
39. G. Piovesan, F. Biondi, A. Di Filippo, A. Alessandrini, M. Maugeri, *Global Change Biol.* 14 (2008) 1265–1281.
40. R. Touchan, K.J. Anchukaitis, D.M. Meko, S. Attalah, C. Baisan, A. Aloui, *Geophys. Res. Lett.* 35 (2008) L13705.