Gardening in the Global Greenhouse: The Impacts of Climate Change on Gardens in the UK

Technical Report
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Richard Bisgrove and Paul Hadley
Centre for Horticulture and Landscape, School of Plant Sciences, The University of Reading

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The UK Climate Impacts Programme
Union House
12-16 St. Michael's Street
Oxford, OX1 2DU

Tel: 01865 432076
Fax: 01865 432077

Email: enquiries@ukcip.org.uk
Web: www.ukcip.org.uk

Preface

There are three interrelated phenomena which need to be identified in reviewing the potential impacts of climate change on gardens.

The first is climate change itself. The climatic changes expected in the UK are described in the report *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report* (Hulme *et al*., 2002). This report examines the potential impacts of the expected climate changes on gardens in the UK.

The second phenomenon is the occurrence of extreme weather events such as floods and droughts. Climate change is expected to increase the frequency of some extreme weather events, but predictions of such events are less certain than those for average changes in climate. Predictions of gale frequency in future are particularly uncertain.

The third phenomenon is development. The Earth's surface has changed dramatically as a result of human activity. Forests have been cleared (in the UK as elsewhere), grasslands have been ploughed and fields covered with houses, factories, motorways and airports. People travel much more widely and much more frequently than was the case even twenty years ago. Some of these changes are root causes of climate change. Others serve to intensify the impacts of climate change or to bring them to wider notice. Covering previously absorbent land surfaces with concrete alters the hydrological balance and exacerbates the severity of floods and droughts caused by extreme weather events. Building houses in floodplains increases the risk and cost of flood damage by orders of magnitude. Moving around the globe results in the spread of pests and diseases, of plants and of humans, to new areas so it is often impossible to say if changes in disease incidence are the results of climate change or of human activity.

Much of the information relating to climate change and gardens is anecdotal. In order to draw on well founded scientific research it has been necessary to move outside the garden and use data from research on agricultural and horticultural crops, and in forestry and nature conservation. This is logical because the plants grown on farms and in forests, or which are managed in nature reserves, also play an important part in gardens. There are important differences though between monocultural stands of a crop in a field or forest and the mixture of many plants in a garden. There are also important differences between the behaviour of plants in a natural community and in a highly managed garden. These differences have been discussed where appropriate.

Our review is unusual in covering an exceptionally wide range of subject matter, from photosynthetic pathways and evapo-transpiration, to garden history and concepts of garden conservation. It has been necessary at times to deviate from the central topic to present short summaries of specific issues, such as the historical evolution of gardens and plant growth and development, to set the impacts of climate change in context. It has been difficult, always, to steer a path between scientific jargon and naïve generalisation. Those with expertise in particular aspects of the review will find some passages highly simplified but we hope readers will appreciate that this report is intended for an audience with wide ranging interests.

Contents

Executive summary

1. In the past forty years, the importance of UK gardens in our culture and as a significant contributor to the tourist industry has been increasingly recognised. Over that same period the effects of extreme weather events on gardens have been increasingly apparent.

2. This report is the outcome of a desktop study to review the potential impacts of climate change on gardens and to identify future research needs. It was undertaken under the UK Climate Impacts Programme (UKCIP) and funded by Anglian Water, the Department for Environment, Food and Rural Affairs (Defra), English Heritage, the Forestry Commission, the National Trust, Notcutts Nurseries, the Royal Botanic Garden, Kew and The Royal Horticultural Society. The study was undertaken by Richard Bisgrove and Professor Paul Hadley from the School of Plant Sciences at the University of Reading.

The aims of the study were:

(i) to provide an overview of the best current information on the potential impacts that climate change may have on UK gardens, garden plants and the garden industry;
(ii) to identify information gaps in assessing these impacts on gardening, heritage gardens and the garden industry and, from these gaps, to define a future research agenda.

3. Analysis of long term weather records indicates that annual mean temperatures have increased by 1.7°C since the beginning of the Industrial Revolution in 1750. 1°C of this increase has occurred in the 20th century, with the last decade being the warmest on record. The number of cold days has decreased and frost incidence has decreased very substantially. These changes have been reflected in changes in dates of leaf emergence, flowering, appearance of many species of butterfly and other phenological events.

4. Four climate change scenarios have been developed for UKCIP (the low, medium low, medium high and high emissions scenarios) reflecting uncertainties about future emissions of greenhouse gases. The UKCIP02 scenarios suggest that mean annual temperatures in the UK will increase by 2-3.5°C by the 2080s, depending on scenario and region, with increases in the south east greater than those in the north west. These increases will be associated with more hot and very hot days and less frost and snow.

The scenarios also suggest that annual precipitation will decrease slightly as a net result of higher winter rainfall (10-30% higher under the high emissions scenario by the 2080s) and decreases in summer rainfall (a 20-50% reduction by the 2080s under the high emissions scenario). The year to year variation in precipitation will also increase leading to an increased frequency of very dry summers and very wet winters.

Mean sea levels may rise by 60cm (south east Scotland) to 85cm (London) around the coast by the 2080s, increasing the risk of damaging storm surges along some coasts. Storms may become more frequent, especially in winter, when more depressions could cross the UK.

5. Climate change will affect plant growth in several ways. For example:

(i) increased carbon dioxide levels will increase rates of plant growth and perhaps development (bud burst, flowering and leaf fall);
(ii) temperature will have more complicated effects but an earlier onset of growth in spring and a longer growing season are anticipated. Spring has advanced by 2-6 days per decade and autumn has been delayed by two days per decade. With the higher emission scenarios, the chilling requirement for budbreak in fruit trees may not be met in mild winters, leading to reduced yields;

(iii) the various components of climate change will interact, often in quite complex ways. For example, while carbon dioxide increases growth in most plants, increased temperatures may hasten maturity of some plants and therefore reduce or negate the impact of increased carbon dioxide.

6. Increasing temperatures are expected to accelerate loss of organic matter in soils, releasing nitrogen which may increase plant growth or, if leached from the soil, increase pollution of watercourses.

The annual moisture content of soils is likely to decrease by 10-20% across the UK by the 2080s, with substantial reductions (of 20-50%) in soil moisture possible in the summer by the 2080s.

7. Climate change will affect garden plants indirectly by affecting the range and virulence of pests, diseases and weeds. The severity of pest and disease attacks in general is likely to increase, as will the geographical spread of many organisms currently on the edge of their climate range.

8. The impacts of climate change on plants in gardens will be less than on those in the natural environment because of the attention they receive in cultivation.

Increased temperatures in themselves will rarely be directly damaging to plant growth but will enable a much wider range of plants from warmer parts of the world to be grown. Higher temperatures combined with decreased summer rainfall, though, will cause stress, especially in plants with extensive, shallow, fibrous root systems.

Extreme weather events such as gales, floods and droughts will be much more damaging than will long term and subtle changes in average climatic conditions.

9. The impacts of climate change on gardens will depend in large measure on the regional and local setting of the garden. In Scotland and north west England, change will be less marked than in the south east where summer heat and drought are likely to pose serious problems. Throughout the UK, hilltop gardens will be particularly prone to drying and to gales while low-lying gardens will be susceptible to flooding, as at present.

The significance of climate change impacts will depend on whether the garden is a domestic garden, in which case a warmer climate and the opportunity to grow new plants may be welcomed, or a garden of significant historic interest, where conservation is important. In the latter case the cost of adapting to climate change while conserving as far as possible the form and content of the garden will often be considerable.

10. Climate change will have impacts on the many components of the garden. In particular, this report addresses the potential impacts of climate change on:

- soils, water supplies and water bodies;
- trees, shrubs, sub-shrubs, herbaceous perennials, bulbs and annuals;
- lawns;
- paths, buildings and other structures;
- garden staff.

11. Climate change will have impacts on the numbers of people visiting gardens and on the effects of those visitors in compacting wet lawns, for example. However these impacts will be relatively minor in relation to other social and cultural changes affecting visitor numbers. Each major garden will therefore have its own set of parameters determining its catchment area and anticipated threats and opportunities arising from climate change. The most important influence on a garden's attractiveness to visitors and on visitor numbers will be marketing in its broadest sense.

12. Climate change will also have impacts on garden-related industries. In terms of risks of growing and potential damage to property the impacts may be negative. In selling, the overall effects should be neutral or positive as the ability to cultivate many new plants and an increasingly outdoor lifestyle should stimulate demand. Caution in guarding against major losses from extreme weather events, and flexibility in adapting to the hazards and benefits and problems of climate change will be the keys to commercial survival.

13. By regarding the garden as a microcosm of the wider environment and using it to develop and demonstrate practices which will alleviate and mitigate the adverse effects of climate change, the gardening community has the potential to set an example of good practice which will further increase public appreciation of and support for gardens and which could ultimately alter the course of climate change.

14. In order to achieve this goal, a programme of research is proposed in the report. In particular, the establishment of a 'garden network' to exchange and coordinate observations, ideas and actions, and to combine research activity on the natural and the cultural environment to the benefit of both, is recommended.

Introduction

Francis Bacon (1625) commented that "when Ages grow to Civility and Elegancie, Men come to Build Stately, sooner than to Garden Finely: As if Gardening were the Greater Perfection". In this he recognised the position of the garden as an art form and as an essential component of a civilised society. He also pointed out that the climate in England was more conducive to being outside than in any other country but that it was seldom warm enough to sit still out of doors. To this meteorological situation he attributed the love of gardens and especially of gardening in the UK. It is this involvement of the populace with plants and the ability to grow a very wide range of plants in a mild and equable climate that gives the UK a unique character and sense of place.

The relationship between gardens and climate has taken on a new significance in recent years with the gradual awareness of the existence of climate change and its potential impacts on gardens. This report is a desktop study to review the potential impacts of climate change on gardens, and identify areas for further research.

It is necessary to start by looking briefly at the historical development of gardens in order to appreciate something of the diversity and significance of gardens in the UK before considering the significance of climate change on gardens of different types.

1.1 The UK's garden heritage

The evolution of garden design has been driven by many influences but particularly by the inspiration of new ideas, a desire to react against existing established styles, by response to the cultural and physical environment of the time, by diffusion of ideas from pioneers to the wider population and by rediscovery and reappraisal of earlier styles (Bisgrove, 2000).

As a result of these various influences the UK has witnessed the development of small, enclosed medieval gardens full of herbs and other useful plants, the larger 17th century formal gardens inspired by France and Italy, often extending into the countryside with great avenues and the 18th century landscape garden with pleasure grounds merging into broad expanses of parkland, woods and lakes. The combination of beauty and utility which the landscape garden represented helped to reshape much of the UK's lowland landscape and did much to create the 'green and pleasant land' which UK citizens take for granted as the 'natural' landscape and which tourists find so attractive.

In the 19th century gardens were greatly enriched by exotic plants from all parts of the globe and by equally exotic buildings in Chinese, Japanese, Gothic, Indian, Egyptian and other styles. The richness and diversity of plant introductions in the 19th century stimulated the creation of gardens in areas particularly suited to cultivation of these new plants: the wooded hills on acid soils near to London and other major cities, the south west of England with its exceptionally mild, moist climate and outliers such as Tresco (Scilly Isles), Bodnant (North Wales) and Inverewe (Ross and Cromarty on the west coast of Scotland).

The 19th century, especially, saw the development of the smaller suburban garden, sometimes mimicking its aristocratic counterpart but also intensifying the interest in the cultivation of plants as objects in their own right in addition to their use to create garden scenery. The introduction of exotic plants came to a climax in the second half of the 19th century as a result of growing international trade, increased wealth, improved technology for the cultivation of plants and a burgeoning nursery industry. The excitement of growing unusual or difficult plants remained a feature of 20th century gardening, to the extent that many gardeners were (and still are) more interested in their plants than in the garden as an artistic entity. The 19th century also saw the development of public parks in most major cities and towns, extensive landscapes which rivalled the large private gardens of the day and in which their superintendents vied with each other to produce the most elaborate floral displays.

The 20th century was marked by a move away from the most flamboyant excesses of the 19th century in favour of Gertrude Jekyll and William Robinson inspired wild gardens and flower gardens with carefully graded colour schemes. In the second half of the 20th century, large increases in home (and garden) ownership, increases in the media attention paid to gardens, increased travel abroad and interest in the garden as an extension of the house combined to stimulate, and be stimulated by, a flourishing garden centre industry.

At the beginning of the 21st century one can discern in the UK both the rediscovery of minimalism in gardens by the avant garde (Tunnard, 1938) and its rejection by the mainstream gardener (Taylor, 1936), combined with continued diffusion of the ideas attributed to Gertrude Jekyll (1908) and William Robinson (1870, 1879). These various strands were disseminated through Scandinavia and Germany in ecologically inspired but sophisticated plant communities of Karl Foerster, Friedrich Stahl and others (Hansen and Stahl, 1993) and returned to the UK in the late 20th century to inspire a new generation of gardeners at the end of the century. Interest in ecological or wildlife gardens in the UK paralleled enthusiasm for prairie restoration in the USA, both developments being partly in response to perceived damage to the environment by chemically based farming and gardening.

The fusion of European and American ideas in the 'bold romantic gardens' of Oehme and van Sweden (1990), the grass gardens of Piet Oudolf, Beth Chatto's 'dry garden' (Chatto, 1994) and the more recent revival of interest in earlier Victorian styles of flamboyant bedding all contribute to a lively current interest in more or less spectacular planting design. Christopher Lloyd's replacement of the Edwardian rose garden at Great Dixter (Sussex), a striking endorsement of Robinson's 'subtropical garden' is one of the most recent and most influential examples of the fusion of these many trends (Lloyd, 2000).

In the smaller domestic garden increased levels of disposable income, increased home ownership, the colour magazine and garden makeover programme have all widened demand for exciting and usable outdoor spaces. As new gardens shrink in size there has also been a revived interest in allotment gardens for the cultivation of vegetables, fruit and cut flowers, allowing the small patch of land around the house to be used entirely for recreational purposes.

Nurseries have responded to the demand for novelty by offering a wider range of architectural and increasingly 'exotic' plants: phormiums, bamboos, cannas and now palms, tree ferns, bananas and olives. Climate change is beginning to make possible the cultivation of many succulent and otherwise spectacular plants which were once the exclusive province of the gardens of the extreme south west. Tresco (Scilly Isles) has spread to Tunbridge Wells and is on its way to Teeside

On a technical level the availability of sophisticated, often computer controlled, irrigation systems, pumps and other equipment is beginning to make it easier to cultivate water demanding plants or plants in containers and to create fountains, waterfalls and other such features (see section 6.2.1). At the same time the more environmentally aware gardener is turning away from such gadgetry to adopt a more ecological approach using composting, mulches, water butts and drought tolerant plants.

One important feature of the late 20th century was a dramatic increase in interest in historic or heritage gardens. The Garden History Society was formed in 1965. In the 1970s the National Trust embarked on a series of ambitious restoration and conservation projects in such gardens as Claremont (Surrey), Erddig (Wrexham) and Westbury Court (Gloucestershire) (Bisgrove, 1990). Membership of the National Trust, which now manages the largest assembly of historic gardens in the world, grew from 278,000 in 1971 to 2.6 million in 2000 and a recent survey indicates that 57% of people joining the National Trust do so because of its gardens. In 1981 English Heritage began its Register of Parks and Gardens of Special Historic Interest in England, which now includes more than 1500 parks and gardens, while the National Council for Conservation of Plants and Gardens (NCCPG) was established in 1978 to conserve the gene pool which the immensely rich garden flora of the UK represents. Most recently the Heritage Lottery Fund has grant-aided the restoration of many formerly neglected public parks. There are now estimated to be 2,500 public parks, gardens and other designed landscapes of national, regional or local historic importance in the UK, and some 25,000 recreational open spaces (DTLR *et al*., 2001).

The result of these centuries of development is that the number and diversity of gardens and garden owners in the 21st century is such that one would need to use the sophisticated cluster analysis techniques of the plant taxonomist to begin to classify UK gardens. A garden may be a small oasis of calm in the city, a source of productive pride growing quantities of fruit and vegetables, a national collection of saxifrages or apples, a blue-decked product of last week's television garden makeover programme, a perfect example of the work of Capability Brown or an important repository of plants collected by one of the renowned plant hunters such as David Douglas.

An important characteristic of UK gardens is that very few have been designed then made and left to mature. The majority evolved year by year and perhaps generation by generation. Most gardens are essentially private places. An increasing number of the larger private gardens rely on income from visitors to support the maintenance costs of the garden, while many of the finest gardens in the UK are now owned and managed by public bodies and by organisations such as English Heritage and the National Trust. Large gardens frequently extend into even larger parks with tree-scattered pastures, lakes and woodlands which combine visual beauty with economic value and substantial nature conservation importance.

At the beginning of the 21st century gardening is established as the leading hobby in Britain with an estimated 27 million people owning or having access to a garden. Gardens form the basis of a multi-billion pound industry (Calnan, 2002).

Over the past forty years, especially, the importance of UK gardens as part of our cultural heritage has been increasingly recognised. With increased interest matched by rapidly growing personal mobility, leisure opportunities and living standards, garden tourism by UK citizens and by overseas visitors has also become a significant contributor to the national economy. Visitors to the Royal Horticultural Society's garden at Wisley, for example, increased from 181,000 in 1970 to 614,000 in 2000 (Prior, *pers. comm.*). The National Gardens Scheme, which includes 3,500 gardens in 2002, raised £1.2 million in 2001 and has raised over £20 million in its 75-year existence. There are 24 million visitors each year to gardens in the UK and garden tourism is estimated to be worth £300 million per year. Perhaps more important than this direct financial contribution to the economy, the quality and quantity of our gardens and parks also contribute to the image of the UK as a green and pleasant land and to the health and happiness of its inhabitants.

The UK has a remarkable history of gardens and gardening spanning a thousand years. This results in a rich heritage of gardens – formal and natural, planned and planted – and a lively tradition of making and cultivating gardens. There are estimated to be 27 million active gardeners and approximately 27,500 parks, gardens and other designed landscapes of national, regional or local importance. Gardens make a direct contribution to the tourist industry of about £300 million per year, but they are much more important in underpinning the essential character of the UK as a green and pleasant land, for the benefit of its citizens and visitors alike.

1.2 Climate change and gardens

In the second half of the 20th century there was an increasing awareness that the climate was changing, initially because of observed changes in the weather and subsequently through the development of climate modelling techniques. Recognising the potential problems inherent in global climate change the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) set up an Intergovernmental Panel on Climate Change (IPCC) in 1988 to assess the nature and scale of these problems.

Since the 1960s the effects of extreme weather events on gardens has also been increasingly apparent. The severe winter of 1962/3 killed many supposedly hardy plants (Anon, 1964; Booth, 1964; Salisbury, 1963). The drought of 1976 weakened large trees and caused lakes to dry out (Bisgrove, 1978). The storms of 1987 and 1990 felled an estimated 15 million trees in southern Britain alone (Rich, 1988) and the effects of devastating flooding in many parts of the country in 2000/01 are still being felt at the end of 2002 as plants whose root systems were inundated slowly die.

The increasing appreciation of gardens and the expanding catalogue of damage imposed on them by extreme weather events, combined with mounting scientific evidence of the existence and scale of climate change, has led to growing concern that the changing climate must inevitably have significant implications for the future of gardens and their management.

1.3 Background to the study

Awareness of the implications of climate change for gardens and the gardening industry led to the organisation of a workshop on Climate Change and Gardens, coordinated by the National Trust, The Royal Horticultural Society and the UK Climate Impacts Programme in April 2000.

The purpose of the workshop was to develop an understanding of the potential implications of climate change on gardens and garden-related industries, to begin to identify research needs and to test support for a study into the issue. The workshop was attended by sixty participants including representatives from botanic gardens and gardens organisations, commercial horticulturists, landscape consultants, the horticultural press, local and national government representatives, universities and other research organisations.

The primary outcome of the workshop was the expression of need for a desktop study to review the potential impacts of climate change on gardens and to identify future research needs.

This report is the outcome of that expression of need. It has been undertaken within the framework of the UK Climate Impacts Programme with funding from Anglian Water, the Department for Environment, Food and Rural Affairs (Defra), English Heritage, the Forestry Commission, the National Trust, Notcutts Nurseries, the Royal Botanic Garden, Kew and The Royal Horticultural Society.

1.3.1 AIMS AND OBJECTIVES

The primary aims of the study were:

(i) To provide an overview of the best current information on the potential impacts that climate change may have on UK gardens, garden plants and the garden industry.
(ii) To identify key information gaps in our knowledge and understanding of these impacts on gardening, heritage gardens and the garden industry.
(iii) To define a future research agenda.

The objectives were:

(i) To identify the aspects of gardens and gardening most at risk from climate change, and the general patterns of distribution and type of garden most vulnerable to these changes.
(ii) To identify those aspects of gardens and gardening which might benefit from climate change.
(iii) To suggest techniques and practices which might be used to reduce the negative impacts and derive maximum benefit from the positive aspects of climate change in gardens.
(iv) To present findings in a report to increase the gardening public's awareness of climate change and to communicate the wider benefits of environmentally sound practices in adapting to and perhaps mitigating the effects of climate change.

1.3.2 METHODOLOGY

The main focus of the study was a review of the literature, including searches of bibliographic databases. This review was facilitated and supplemented by the authors' expertise in horticultural plant physiology and landscape management. The authors also derived much support and information from the study's Steering Committee. Colleagues in or associated with the School of Plant Sciences at the University of Reading also provided valuable information.

The literature review was supplemented by consultation with key experts in the garden and landscape sector. A questionnaire (see Appendix 1) was sent to the director, curator or head gardener of fourteen major gardens strategically distributed throughout England, Scotland and Wales to obtain information on how past weather had affected their gardens and to explore expectations in relation to climate change. Three leading nurserymen were interviewed about the commercial impacts of climate change. Their contribution to this study is gratefully acknowledged.

This report first summarises observed changes in the UK climate and the changes expected over the coming century from the UKCIP02 climate change scenarios. It then considers potential implications of anticipated future changes for gardens, working from the small scale of the plant cell to the large scale of the landscape as follows:

- the effects on plant growth and development
- the effects on plants as individual organisms
- the effects on plant communities
- the effects on gardens, garden types and garden components such as borders, shrubberies, woodlands, water features and architectural structures
- the effects on human use of gardens and the consequent impacts
- the resultant economic/financial implications of climate change in gardens
- adaptive responses to climate change

It concludes with recommendations for research and action.

A long series of extreme weather events – frosts, extreme heat, floods and droughts – have caused severe damage to many gardens in the past forty years. A growing awareness of the reality of long term climate change has led to concern for the future of UK gardens.

Following a workshop to discuss the implications of climate change on gardens, a decision was made to commission this desktop study within the UK Climate Impacts Programme to consider the issues in more detail.

Changes in the UK climate

2.1 Observed trends

This section describes changes that have already occurred to the climate of the UK by examining long-term measurements of temperature and precipitation.

2.1.1 TEMPERATURE

One of the longest series of temperature measurements in the world is the Central England Temperature (CET) record developed initially by Professor Gordon Manley between 1941 and 1974 (Wheeler and Mayes, 1997). This data set collates records from several sites in central England, some dating back to 1659. When the data are smoothed to remove year to year variability, or noise, from the record (Figure 1), they show that the average temperature in central England increased by 0.7°C between 1750 (the start of the Industrial Revolution) and 1900 and almost 1°C during the 20th century, with two-thirds of the 20th century warming occurring since the 1970s. The record also shows that the 1990s was the warmest decade in central England since records began. Five of the six warmest years since 1659 were 1989, 1990, 1995, 1997 and 1999. The year 2000 had the longest thermal growing season (see Glossary in Appendix 2) in a 230-year history. On a global scale, nine of the ten warmest years in the 142-year history of the Global Instrument Record have occurred since 1990, including the four consecutive years from 1998-2001 (WMO, 2001). Analysis of the data indicates conclusively that, although some warming can be attributed to natural fluctuations, the temperature rise since 1970 can only be explained if human activity is taken into account.

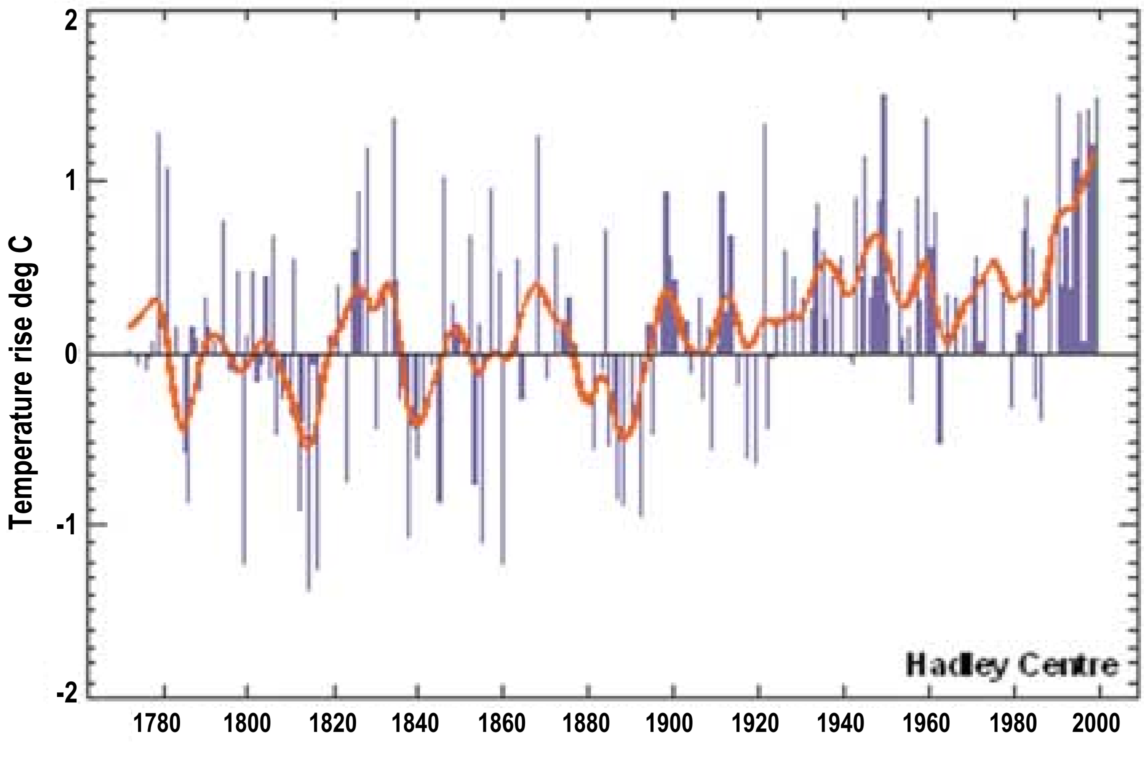

Figure 1: Observed temperature trend for Central England from 1659 to 2000. *Source: Hadley Centre for Climate Prediction and Research*

Figure 2 shows the frequency of 'hot' days (average temperature above 20°C) and 'cold' days (average temperature below 0°C) since 1772. Since the 18th century, the frequency of hot days has increased, with eight hot days per year over the last decade, about twice the long term average. In contrast, the number of cold days has fallen from 15-20 days per year, to approximately 10 days per year.

The number of days with frost in central England has also declined steadily, from about 55 per year in 1880 to 35 per year in 1980 (Figure 3).

Temperature changes have extended the growing season. The record-breaking thermal growing season of 2000 lasted for 328 days, from 29 January to 21 December. Such temperature changes have obvious impacts on plant growth.

Long-term studies in plant phenology (the study of the timing of developmental changes in plants, such as expansion of first leaves, opening of flowers, leaf fall) have played a useful part in demonstrating plant responses to climate change.

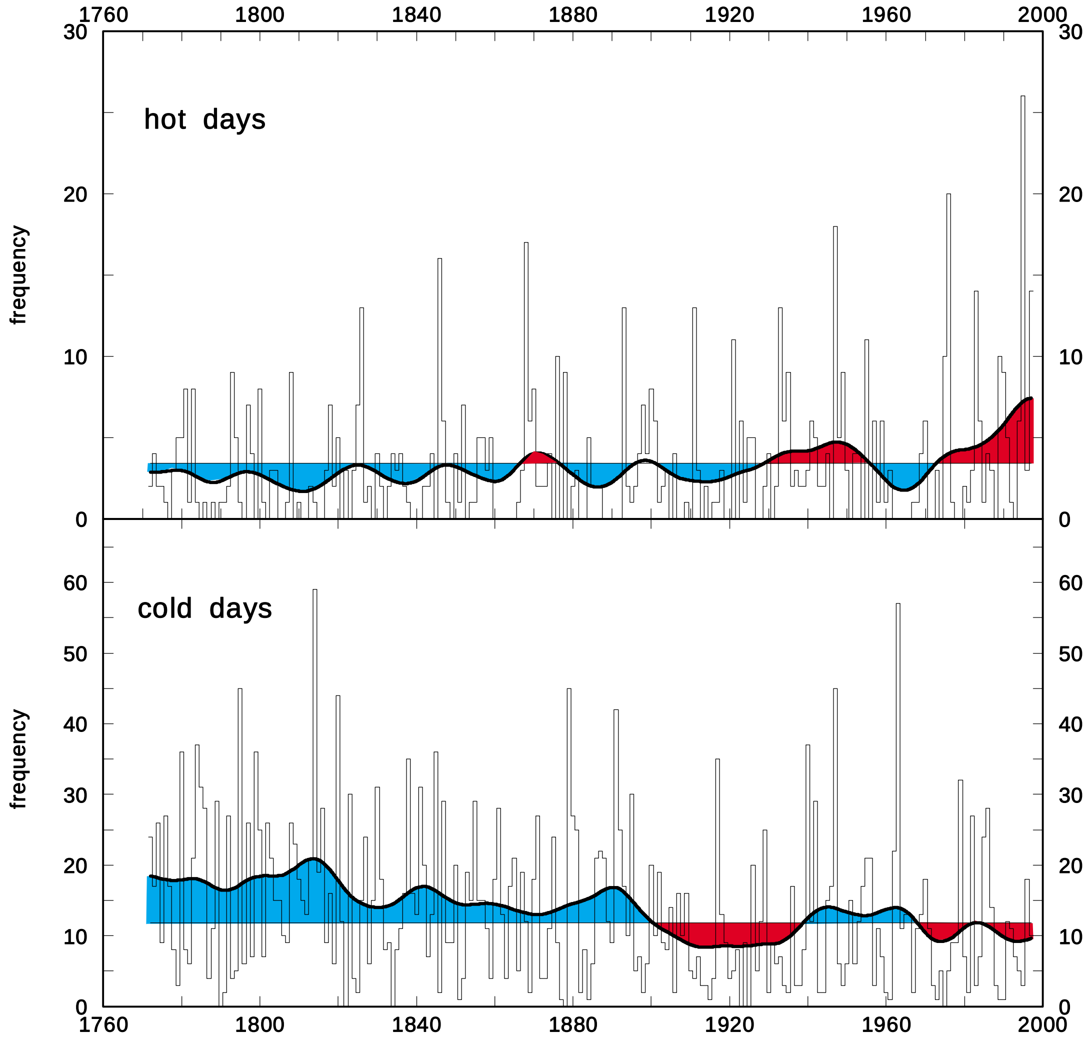

Figure 2: The annual number of 'hot' and 'cold' days extracted from the Central England Temperature series for the period 1772 to 1997. 'Hot' days are those with mean daily temperature above 20°C, 'cold' days are those with mean daily temperature below freezing. The smoothed line emphasises variations on a 30-year time scale. *Source: Hulme and Jenkins, 1998*

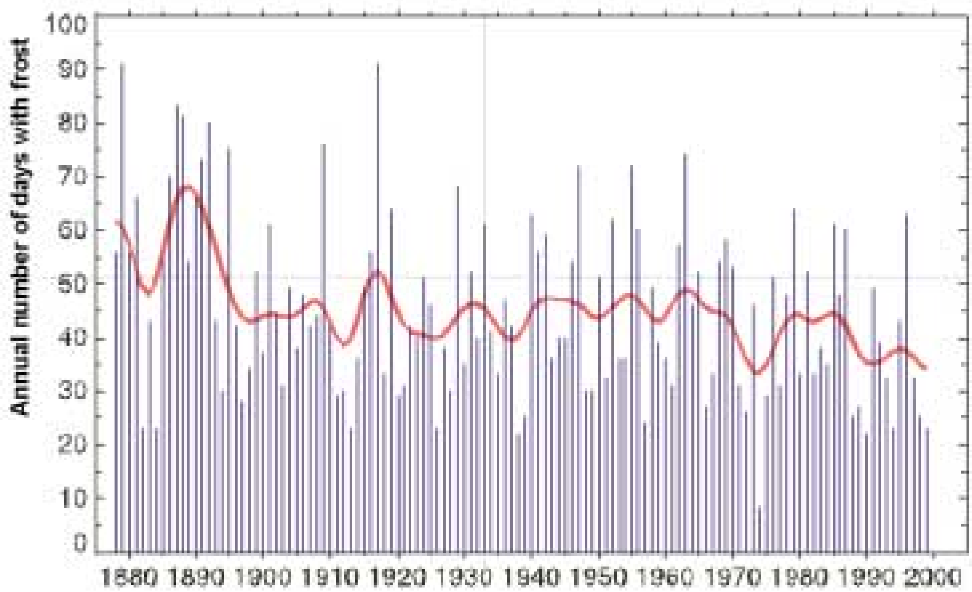

Figure 3: The number of frost days recorded in central England from 1880-2000. The smoothed line emphasises variations on a 30-year time scale. *Source: Hadley Centre for Climate Prediction and Research*

Phenological records for the past 30 years in Europe indicate that spring events such as leaf unfolding have advanced by about six days, whilst autumn leaf colouring is delayed by nearly five days (Menzel *et al*., 1999). Conditions in Britain are changing even more rapidly, with spring arriving six days earlier each decade, and autumn being delayed by two days each decade, an extension of the growing season of 24 days since records began 30 years ago. The thermal growing season extended on average by 0.7 days per year between 1920 and 1960 and by 1.7 days per year between 1980 and 2000 (Figure 4). Implications of these changes for plants are discussed in more detail in section 3.3.3.

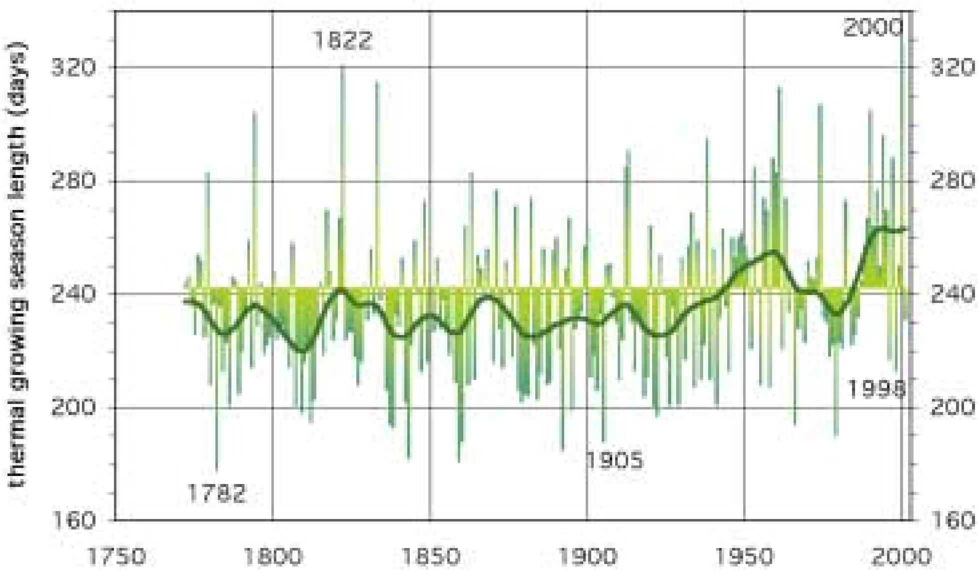

Figure 4: The length of the thermal growing season in central England. The bars emphasise deviations in duration from the 1961-1990 average (242 days). The smoothed curve emphasises variations on time scales of at least 30 years. *Source: Hulme et al., 2002*

2.1.2 PRECIPITATION

Precipitation records show that winter rainfall has increased in Scotland in recent years, whilst summer rainfall has been falling over the same period in England and Wales. Moreover, a larger proportion of winter rainfall now falls as heavy rainfall than it did 50 years ago (Figure 5).

Analysis of the Central England Temperature record shows a rise in average annual temperature of 0.7°C from 1750-1900 and nearly 1°C from 1900-2000. Nine of the ten warmest years globally since 1860 have occurred since 1990. In the past 30 years the incidence of frost has declined steadily

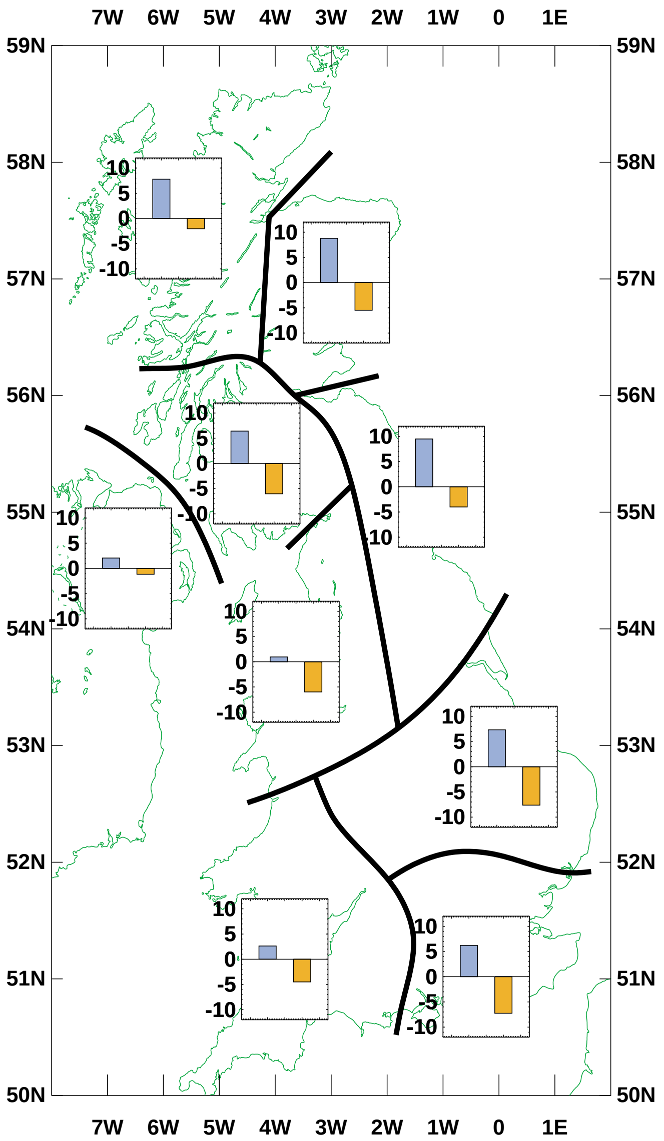

Figure 5: The trend (1961-2000) in the fraction of the total seasonal precipitation contributed by the 'most intense' precipitation events in the winter (left hand bars) and in summer (right hand bars) for a number of UK regions.
Positive numbers indicate an increasing trend in the proportion of the total precipitation that comes from the 'most intense' events, i.e. 'most intense' events are increasing either in frequency or intensity. The lower bound to the class of 'most intense' events is defined (separately to each season and region) by an amount (mm) calculated from the 1961-1990 period, namely the daily precipitation exceeded on a minimally sufficient number of days necessary to account for precisely 10 per cent of the seasonal precipitation.
Source: Osborn, TJ (2000) in Hulme et al. 2002

and the growing season has extended by 24 days. Winter rainfall has increased in Scotland, with more of this rain falling in heavy downpours. Summer rainfall has decreased in England and Wales.

2.2 Causes of climate change

There is now indisputable evidence that some of the changes in the global climate are occurring as a direct result of human activity on the planet (IPCC, 2001). One of the main causes for this is the worldwide increase in the atmospheric concentration of carbon dioxide and other greenhouse gases. Carbon dioxide concentration has been monitored at a number of locations around the world since measurements first began at Mauna Loa in Hawaii in 1955 (Keeling *et al*., 1955). They show that carbon dioxide concentrations are increasing by approximately 1% per year (Figure 6). Thus, since pre-industrial times (i.e., since 1750), the atmospheric concentration of carbon dioxide has increased by about 30%.

In the same period, atmospheric methane concentrations have increased by 145%, nitrous oxide has increased by 15% and tropospheric ozone has increased by 100% (Scarascia-Mugnozza *et al*., 2001). These changes can be ascribed directly to the use of fossil fuel for industrial use and transport, and to rapid changes in land use.

These gases have the characteristics of absorbing infra-red radiation and are commonly called 'greenhouse gases', because of their ability to trap energy within the lower atmosphere in a manner analogous to the trapping of energy within a greenhouse. Increases in these gases result in more energy being trapped, and therefore an increase in global temperatures and consequent changes in our climate. Approximately 60% of global warming can be attributed to increases in atmospheric carbon dioxide concentration, 16% to the increase in methane and 14% to increases in ozone (Shine and Forster, 1999).

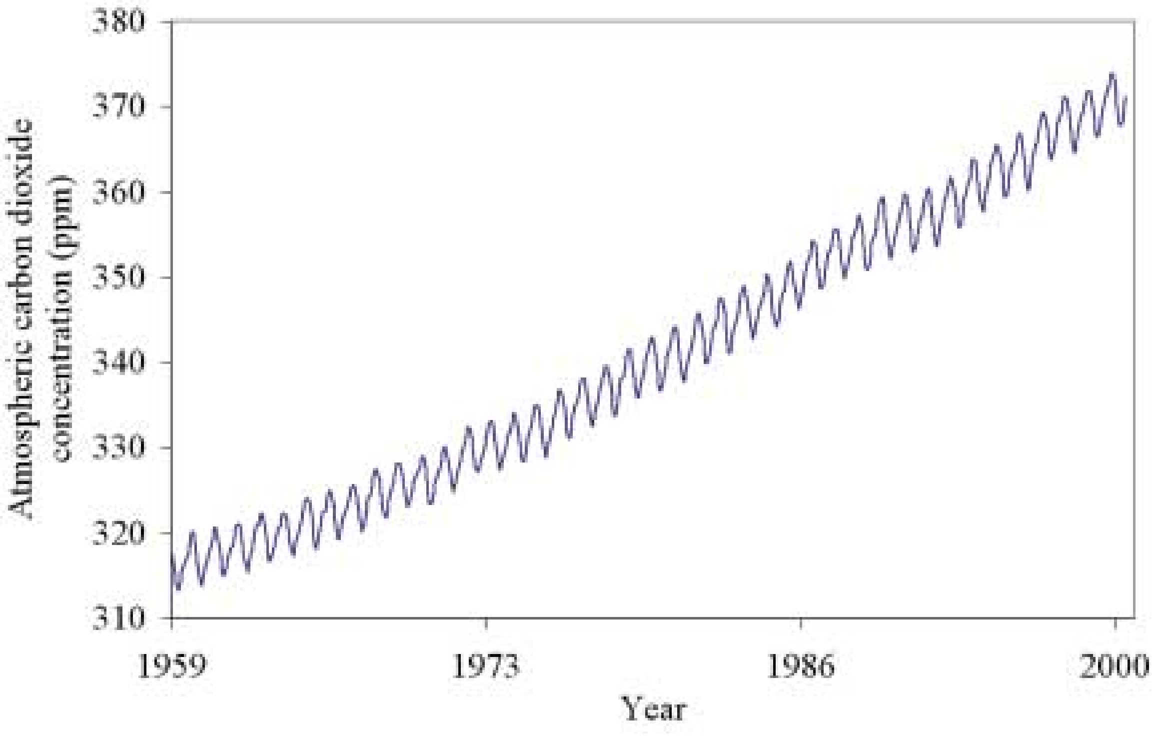

Figure 6: The steady upward trend of carbon dioxide in the Earth's atmosphere; the saw-toothed pattern reflects seasonal biospheric changes. *Source: Dave Keeling and Tim Whorf (Scripps Institution of Oceanograpny)*

The extent to which our climate changes in future, will depend largely on future rates of emissions of greenhouse gases.

Analyses of meteorological data indicate conclusively that temperature rise since 1970 can only be explained if human activity, especially increasing emissions of carbon dioxide and other greenhouse gases, is included in the climate change models.

2.3 Climate change in the 21st Century: the UKCIP02 scenarios

Scenarios of greenhouse gas emissions have been produced by the IPCC to investigate probable future climate changes. The emissions scenarios are based on different views of how the world may develop in the decades to come, in terms of economic growth, population increase, the balance between unrestrained market mechanisms and development of global approaches to sustainability and other sociological and economic factors.

Four of the most recent emissions scenarios developed by the IPCC (the SRES scenarios) have been used by the Meteorological Office's Hadley Centre for Climate Prediction and Research and the Tyndall Centre for Climate Change Research, to generate four climate change scenarios for the United Kingdom. The low emissions, medium low emissions, medium high emissions and high emissions scenarios describe future UK climate changes for three 30-year periods centred on the decades of the 2020s, 2050s and 2080s. The standard baseline climate period is used, namely 1961-1990. The scenarios are described in detail in the UKCIP02 scenarios report by Hulme *et al*. (2002) and summarised in section 2.4. They show that a certain degree of climate change is inevitable and that many components of our climate will be affected.

The emissions scenarios on which they are based suggest that, by the 2080s, the atmospheric carbon dioxide concentration may be between 525 parts per million (ppm) (low emissions scenario) and 810 ppm (high emissions scenario). This represents a 45-25% increase over current carbon dioxide concentrations, or 2-3 times the pre-industrial concentration. The UKCIP02 scenarios represent the UK climate for about 124 grid squares, each 50 x 50 km.

The climate change scenarios are developed on the assumption of more or less smooth evolution of climate change within the parameters used in the model. Possible discontinuities could arise if there are chaotic changes to tropical rainforest, for example, or to the Gulf Stream.

An uncertain element in global climate modelling is the point at which the temperature in tropical rain forests exceeds the optimum for growth. Temperatures above this optimum would lead to decline in productivity, and ultimately to the death of the forest, its decomposition and a massive release of additional carbon dioxide and other greenhouse gases into the atmosphere (Betts, 2000).

The Gulf Stream (and its north eastern extension, the North Atlantic Drift) has a major influence on UK temperatures especially along the west coast, currently conferring on the west coast of Scotland, at the latitude of Labrador and Moscow, a climate in which palms and tree ferns flourish. Complete collapse of the Gulf Stream is not thought to be likely, but some weakening of the Gulf Stream is anticipated in the high emissions scenario for the 2080s.

There are many lesser unknowns and uncertainties impinging on climate change modelling which might result in more severe or more benign scenarios. However, the Hadley Centre's climate models are powerful and robust tools that validate against current climate very well. The scenarios generated by them represent convincing synopses of climate change for assessing the potential impacts on gardens. It is clear from the scenarios that a certain amount of climate change is inevitable. Steps will be needed to prepare for, and where possible to capitalise on, any benefits of these changes and to reduce the rate and the extent of any negative impacts. Key aspects of UKCIP02 scenarios are now presented.

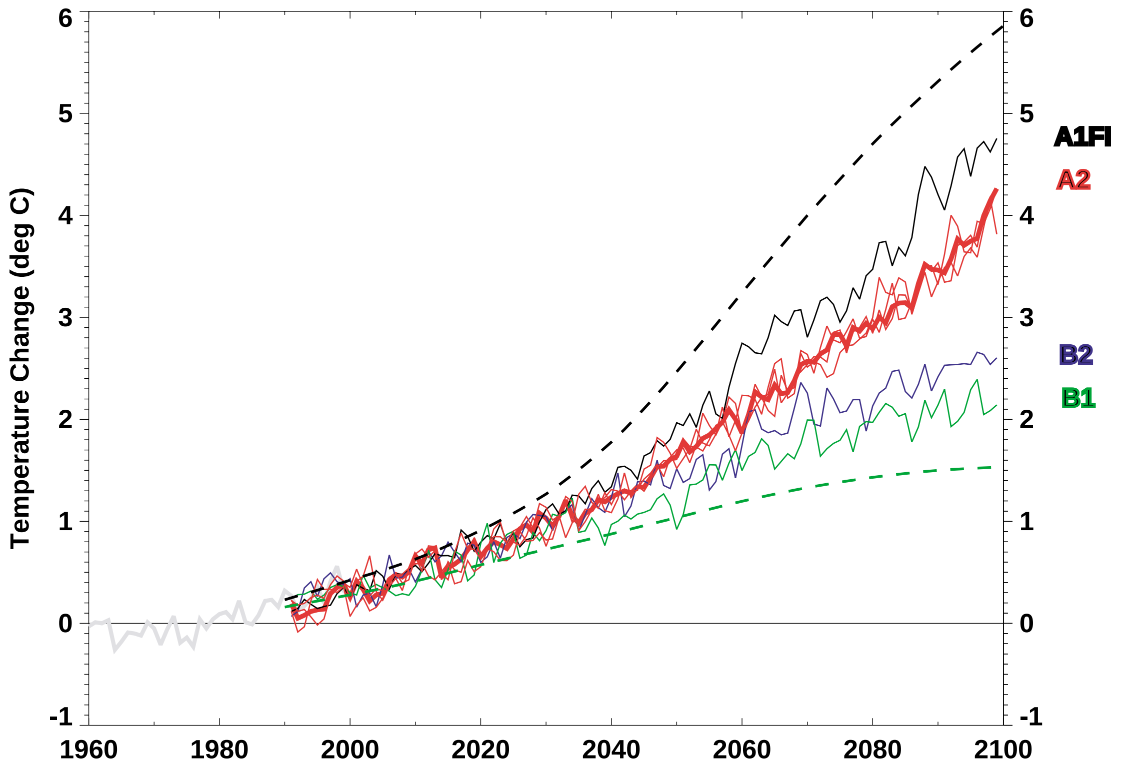

Figure 7: Annual global average surface temperature anomalies from 1961 to 2100 relative to the 1961-1990 average (14°C) as observed and as simulated by the HadCM3 model. The bold central curve represents the average of the three separate experiments (thinner lines) conducted using the same A2 (medium high) emissions scenario. The upper and lower dotted curves represent the full IPCC range of global temperature change when both emissions uncertainties and model uncertainties are considered.
Source: Hulme et al., 2002

International recognition of the existence of climate change led to the establishment of the International Panel on Climate Change (IPCC) in 1988. The Panel has produced a series of scenarios of future greenhouse gas emissions based on different views of how the world might develop.

Four of the most recent IPCC scenarios have been used in the UKCIP02 report to generate four climate change scenarios, taking the 1961-1990 climate as a baseline and forecasting changes for the three 30-year periods centred on the 2020s, 2050s and 2080s.

2.4 Climate change in the UK

2.4.1 TEMPERATURE

According to the UKCIP02 scenarios, average annual temperature in the UK is expected to rise by 0.1-0.3°C per decade (low) to 0.3-0.5°C (high). This is similar to the general pattern of global warming (Figure 7) and compares to a current observed rate of global warming of approximately 0.14°C per decade.

All four UKCIP02 scenarios suggest that warming will be greater in the summer (June-August) and autumn (September-November) than in the winter (December-February) and spring (March-May), and greater in the south east than in the north west. By the 2080s a large part of southern England and South Wales will be 4°C warmer in summer and 3-3.5°C warmer in winter, while in north west Scotland summers will be 3°C warmer and winters 2-2.5°C warmer.

Increases in temperature will lengthen the growing season for plants such that, for each 1°C increase, the growing season can be expected to increase by

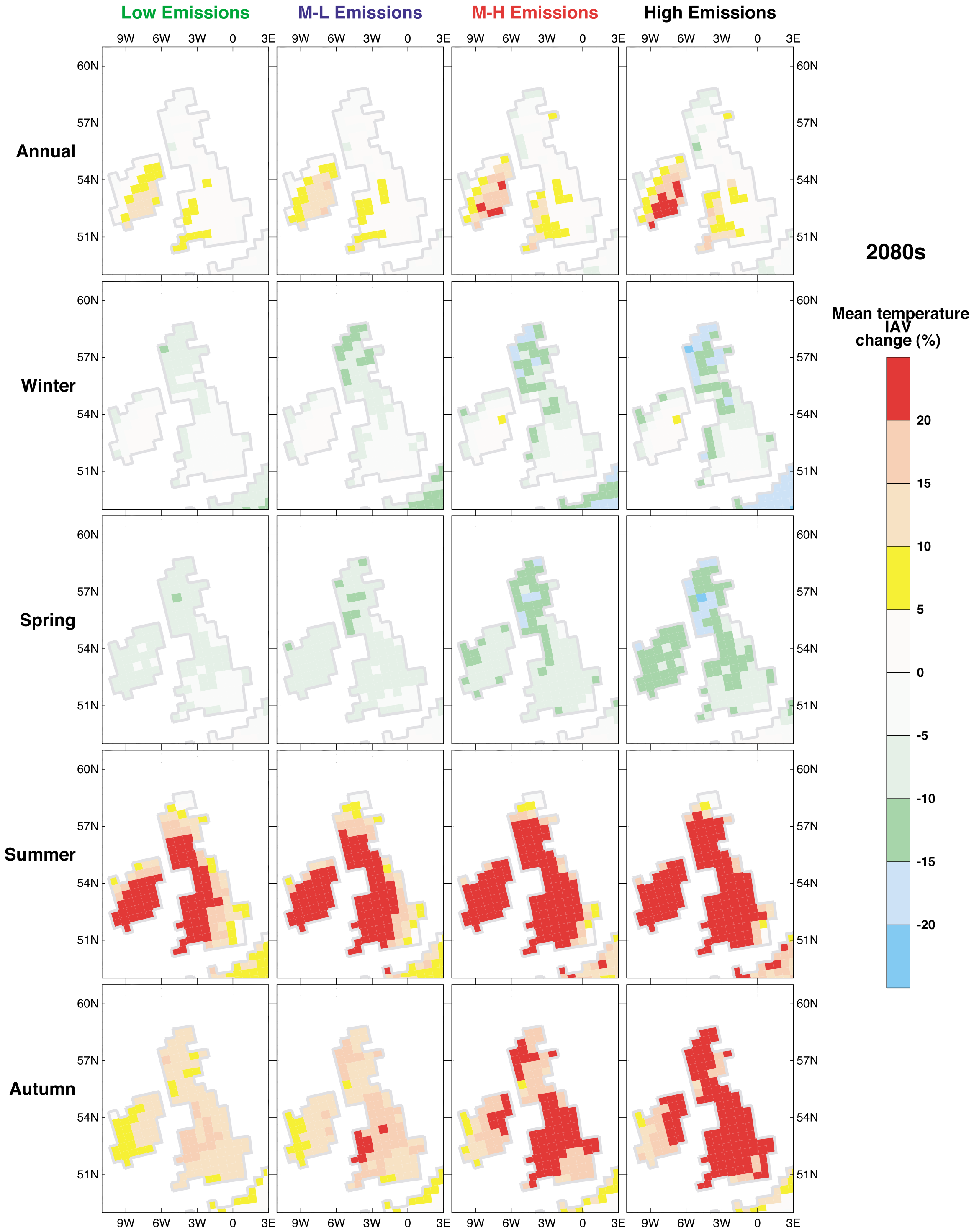

Figure 8: Relative changes in the inter-annual variability of temperature for the 2080s for the four scenarios.
Source: Hulme et al., 2002

approximately three weeks in the south east and by about ten days in northern areas. The average thermal growing season in the Scottish Highlands, currently approximately 150 days, might therefore extend by 20-60 days in the various scenarios. In south west England, where the current average thermal growing season is approximately 250 days, the extension might be 40-100 days, giving the prospect of year round thermal growing conditions in some years well before the 2080s.

In winter, minimum temperatures will rise more rapidly than the maximum temperatures, leading to warmer winters with a reduced diurnal temperature range. In summer, the opposite will occur with maximum temperatures rising faster than minimum temperatures, leading to more frequent hot summers.

Analysis of inter-annual variability suggests that winter and spring temperatures will be less variable from one year to another while summer and autumn temperatures will be more variable, especially in the west (Figure 8).

Temperature extremes are also expected to increase. The 1961-1990 average temperatures of ‘extremely warm’ days (the temperature exceeded on only 10% of days in a given period) were 11°C in winter and 23°C in summer in England, 7°C and 17°C respectively in Scotland. By the 2080s the temperature of an extremely warm day in winter could increase by 3°C (to 14°C) in south east England and by 2°C (to 9°C) in Scotland under the high emissions scenario. In summer, the gradient is from south west to north east with increases of between 7°C (to 30°C) and 4°C (to 21°C) respectively.

The effects of these increases can be expressed in a range of outcomes. For example, under the medium high emissions scenario, a hot August such as in 1995 (which was 3.4°C higher than average), might be expected to occur one year in five by the 2050s and more than one year in every two by the 2080s (Table 1). Currently, the UK might expect to experience a once in a decade daytime temperature exceeding 35°C. Under the medium high emissions scenario, such a once in a decade event may exceed 42°C in lowland England by the 2080s.

At the other end of the scale, very low temperatures are expected to become less common. A minimum temperature of less than -5°C currently occurs on 15% (1 in 7) of winter days around Inverness (eastern Scotland). In the medium high emissions scenario, this frequency decreases by the 2080s to 4% (1 in 25). Frost in many parts of the UK, particularly in the south west, will largely become a thing of the past, with frosts on the western fringe of Cornwall occurring possibly once every 10 years by the 2080s (see Figure 3 in section 2.1.1).

Although there are complex regional variations, the general picture for the high emissions scenario by the 2080s, is for a temperature increase of 2-3°C in winter and 2.5-5°C in summer, increases in the number of ‘hot’ (mean temperature above 20°C) and ‘very hot’ (mean temperature above 27°C) days, and a once in a decade chance of temperatures as high as 42°C, with a marked decline in the number of frosts.

Table 1: The percentage of years experiencing various seasonal anomalies across the southern UK (England and Wales) for the medium high emissions scenario. Simulated by HadCM3. *Source: Hulme et al., 2002*

	2020s	2050s	2080s
Mean temperature			
A hot ‘1995-type’ August (+3.4° C)	1	20	63
A warm ‘1989-type’ year (+1.2° C)	28	73	100
Precipitation			
A dry ‘1995-type summer (37% drier than average)	10	29	50
A wet ‘1994/95-type winter (66% wetter than average)	1	3	7

2.4.2 PRECIPITATION

Average annual precipitation is predicted to decrease in all scenarios by up to 10%, as a result of shifts in the pattern of precipitation with substantial decreases in summer rainfall outweighing smaller increases in winter. As with temperature, precipitation patterns will vary across the country, with the greatest changes and greatest extremes occurring in the south east.

Summer precipitation is expected to decrease by about 20-40% across the UK by the 2080s under the high emissions scenario, with a reduction of 50% or more occurring in the south east, already the driest part of the country. Winter precipitation will increase by 5-30% depending on the scenario. Spring precipitation will decrease in inland areas. Autumns may become some 5-20% drier in the south east, but slightly wetter in the north west. Autumn and winter rains will become more intense than at present.

The inter-annual variability in seasonal precipitation is also expected to change, with winter rainfall becoming more variable from one year to the next across the UK and summer precipitation becoming less variable, especially in the south and west. An increase in the frequency of very dry summers and very wet winters is likely by the 2080s.

Snowfall: As winter temperatures increase, a greater proportion of the winter precipitation will fall as rain rather than snow. Indeed, snow has already become a rare phenomenon in southern Britain. All scenarios indicate that there will be less snow over the whole UK, with the largest percentage reductions – perhaps 90% or more by the 2080s for the high emissions scenario – around the eastern, southern and south western coasts and in the English lowlands (Figure 9).

In relative terms, the Scottish Highlands and Northern Ireland experience the smallest reductions, but even in Scotland the total snowfall by the 2080s might decrease by 60-80% relative to present day totals. Some areas of the UK are increasingly likely to experience a long succession of snowless winters.

Under the UKCIP02 high emissions scenario, average annual precipitation is likely to decrease by 10-20% by the 2080s, the net result of a 20-50% decrease in summer precipitation and a 10-30% increase in winter precipitation. Autumn and winter rainfall will be more intense. Snowfall could decline by 90% in the south and by 60-80% in the north. Changes to temperature and precipitation will be most marked in the south and east.

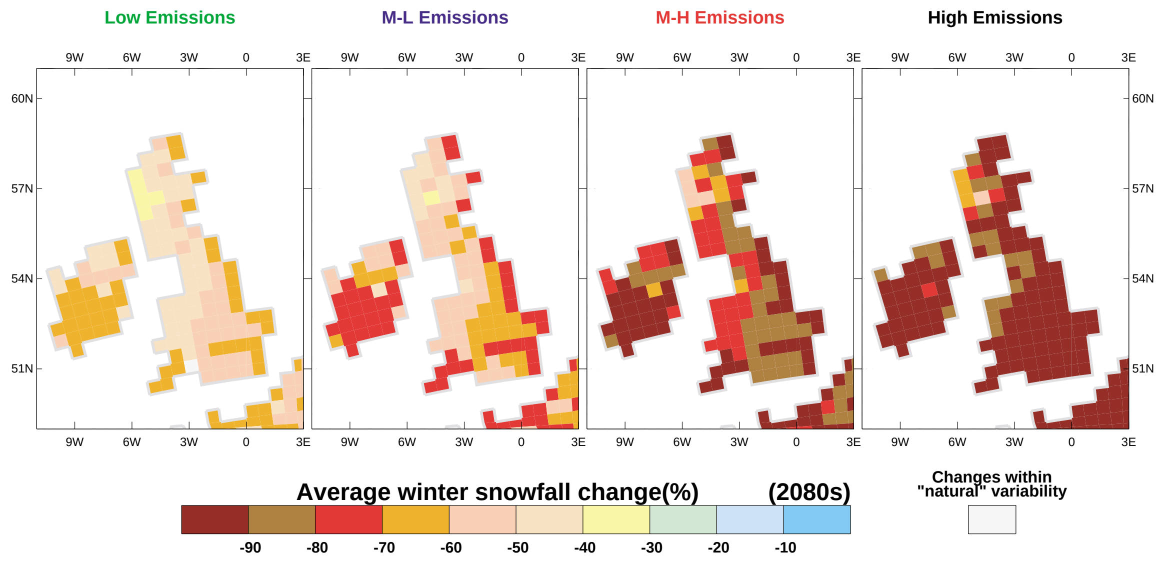

Figure 9: Changes in average winter snowfall by the 2080s (per cent) for the four scenarios. *Source: Hulme et al., 2002*

2.4.3 CLOUD COVER, RELATIVE HUMIDITY AND SOIL MOISTURE DEFICITS

The effects of changing precipitation patterns on gardens will be exacerbated by the inverse relationship between precipitation and solar radiation. Annual cloud cover and relative humidity are expected to decrease by 3-9% by the 2080s (Figure 10a, b) so evaporation will increase.

The combination of reduced precipitation and increased evaporation will have marked effects on soil moisture deficits (Figure 11). On a national scale, long term average precipitation currently varies approximately four-fold, from 600mm each year in south east England to 2500mm in west Wales and the west of Scotland. Potential evaporation varies from 350-800mm, with the higher rate of evaporation in the sunnier

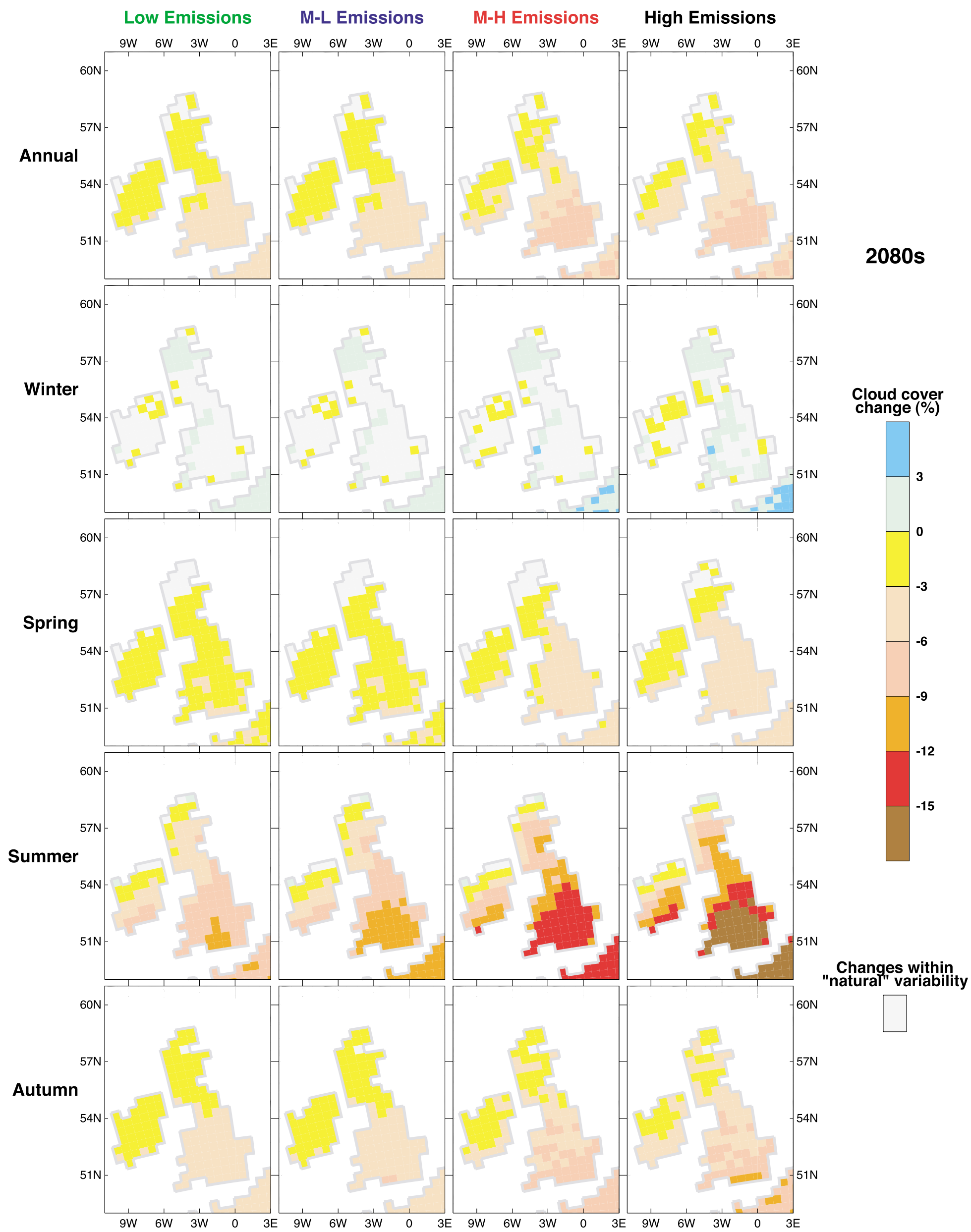

Figure 10a: Changes in annual and seasonal cloud cover (relative to 1961-1990) for the four scenarios for the 2080s.
Source: Hulme et al., 2002

and drier south and the lower rate in the north west. The potential loss of water is therefore greatest where water is least available. In future summers, average soil moisture will decrease across the UK with the largest reductions (20-50% by the 2080s) occurring in south east England compared with a 0-20% reduction in the north west by the 2080s.

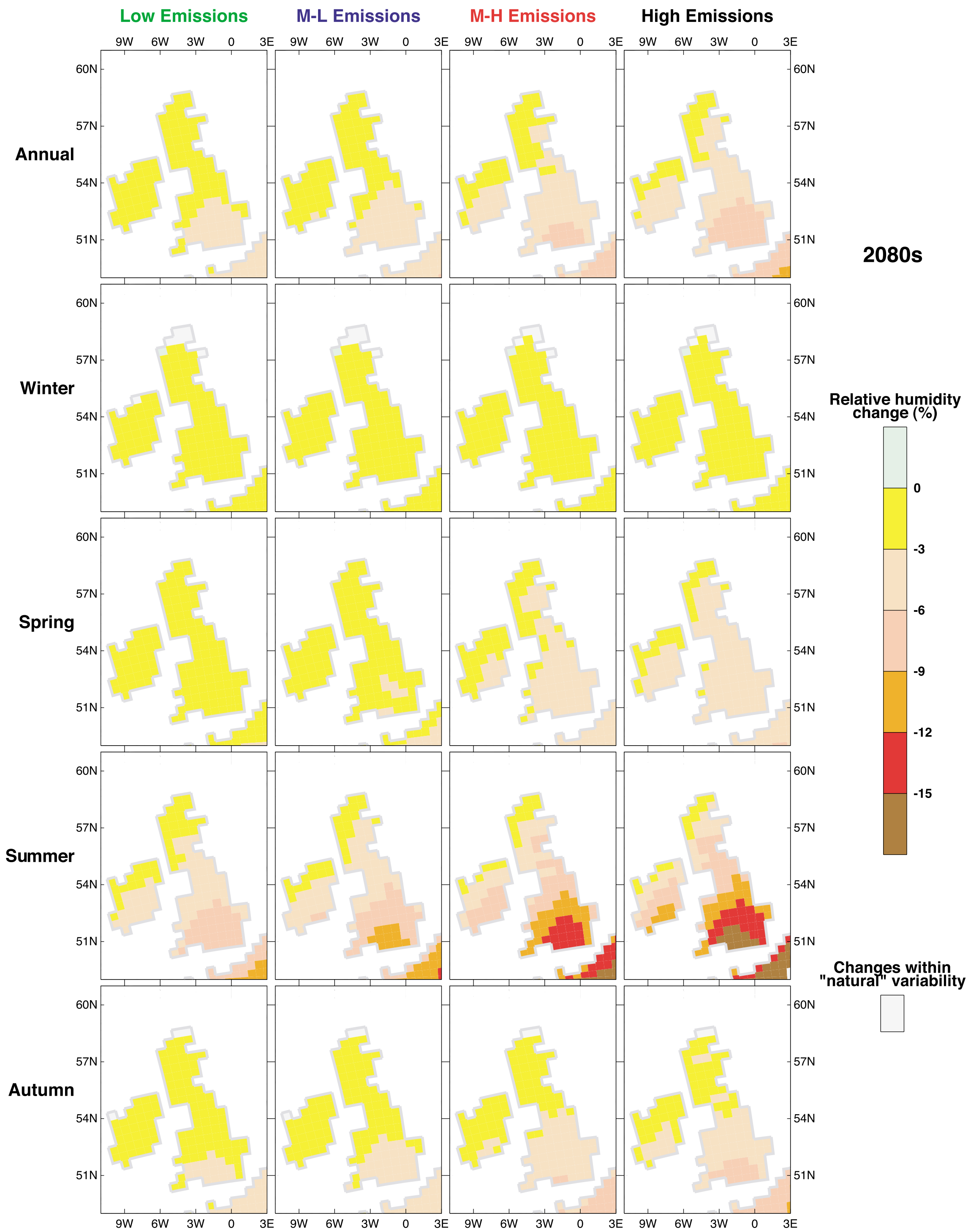

Figure 10b: Changes in relative humidity (relative to 1961-1990) for the four scenarios for the 2080s. *Source: Hulme et al., 2002*

In winter, there will probably be modest increases in soil moisture availability in Scotland and little, if any, change in Wales or Northern Ireland, but England will see a 10% decrease by the 2080s.

Foggy days are expected to decrease by 20% under the medium high emissions scenario by the 2080s because of the generally drier and warmer conditions.

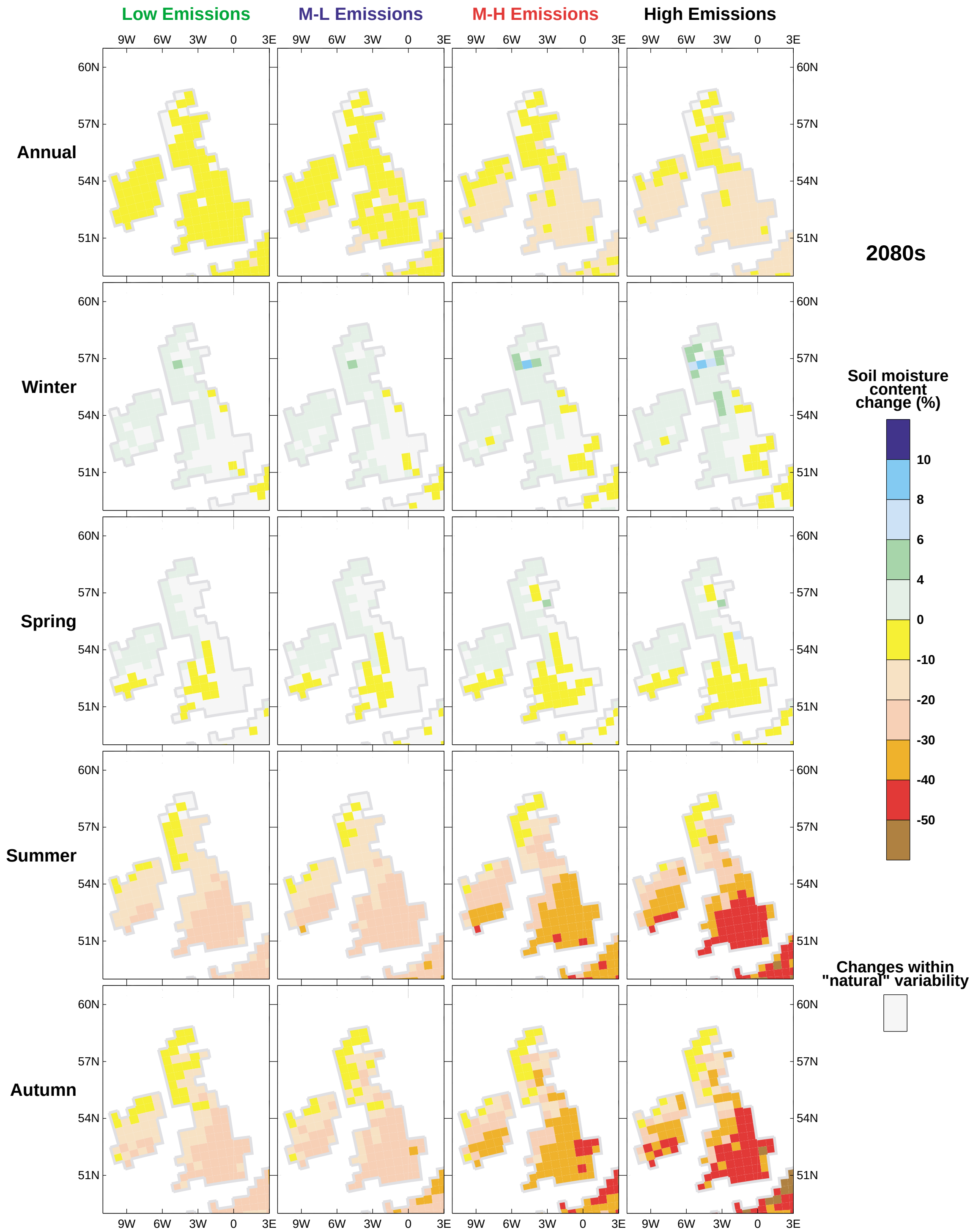

Figure 11: Changes in soil moisture (relative to 1961-1990) for the four scenarios for the 2080s. *Source: Hulme et al., 2002*

Cloud cover and relative humidity are anticipated to decrease by 5-25% by the 2080s. Soil moisture content may decrease in summer by 20-50% in the south and east under the high emissions scenario by the 2080s. In winter, soil moisture content will increase slightly in the north and west. The combined effects of lower rainfall and higher evaporation rates may lead to increasingly severe water shortages in future in some parts of the country by the 2080s.

2.4.4 WIND

Average wind speeds over the UK are expected to change little as a result of climate change, although this is uncertain. In winter, there may be somewhat higher average wind speeds in south and central England with the largest increase (4-10% by the 2080s) expected along the south coast. No change is expected in the north or west.

In summer, changes along the south coast are expected to be even smaller, with probable small reductions in average wind speed in other coastal areas. In spring, changes will be small, if any, and in autumn a 5% decrease in average wind speed in England is likely in the high emissions scenario by the 2080s.

Little change is expected in mean wind speed, although there is a possibility of more strong winds in the winter in the south, especially along the south coast.

2.4.5 WEATHER EXTREMES

One very important consideration in many climate impact studies, not least in relation to gardens, is the possible increase in extreme weather events. These are potentially much more damaging than steady long term climatic changes, as plants do not have the opportunity to adapt to the stresses imposed by them.

There is much anecdotal evidence on a global scale that increasing energy in the climate system as a whole is leading to more erratic weather patterns: torrential rains, very strong winds or short periods of exceptionally high or low temperatures. Extreme weather conditions associated with El Niño have increased in frequency in recent decades from one year in ten, to one in four (Pain, 2002).

Climate change is expected to increase the frequency of some extreme events, such as droughts and high temperature events (see Table 1); but trends in future extremes of wind speed cannot be predicted with a great deal of confidence, because of the small number of gales in the historical record. The period of increased gale frequency between 1960-1990, for example, is matched by similar periods at the end of the 19th and beginning of the 20th centuries. However, although the UKCIP02 report states that "the evidence for the recent increase in gale frequencies over the British Isles being related to human-induced warming remains unconvincing", the graph plotting deviation of gale frequency from the 1961-1990 average (with data smoothed over 30-year averages), does show that frequencies were below the 1961-1990 average of 12.5 gales per year for much of the period 1881-1980, then climbed steadily to 17 gales per year in 2000. Only one year since 1987 has had fewer gales than the 1961-1990 average (Figure 12).

Winter depressions across the UK are expected to increase in number, from an average of five each year currently to eight by the 2080s in the medium high emissions scenario. The track of depressions is also expected to move further south, resulting in more strong winds in the winter over the south. Depressions in the summer months may fall from five to four in an average season.

Although extreme event predictions, particularly for storms, are less certain than those for average changes in climate, the investment that a garden represents, and the long time scales over which most historic gardens are managed, make it wise to consider the potential implications of increased gale damage in any long term management strategy.

Scenarios of the frequency or severity of storms and gales remain uncertain, but the severity of damage that these events can cause is such that their potential impacts should be considered when planning for climate change.

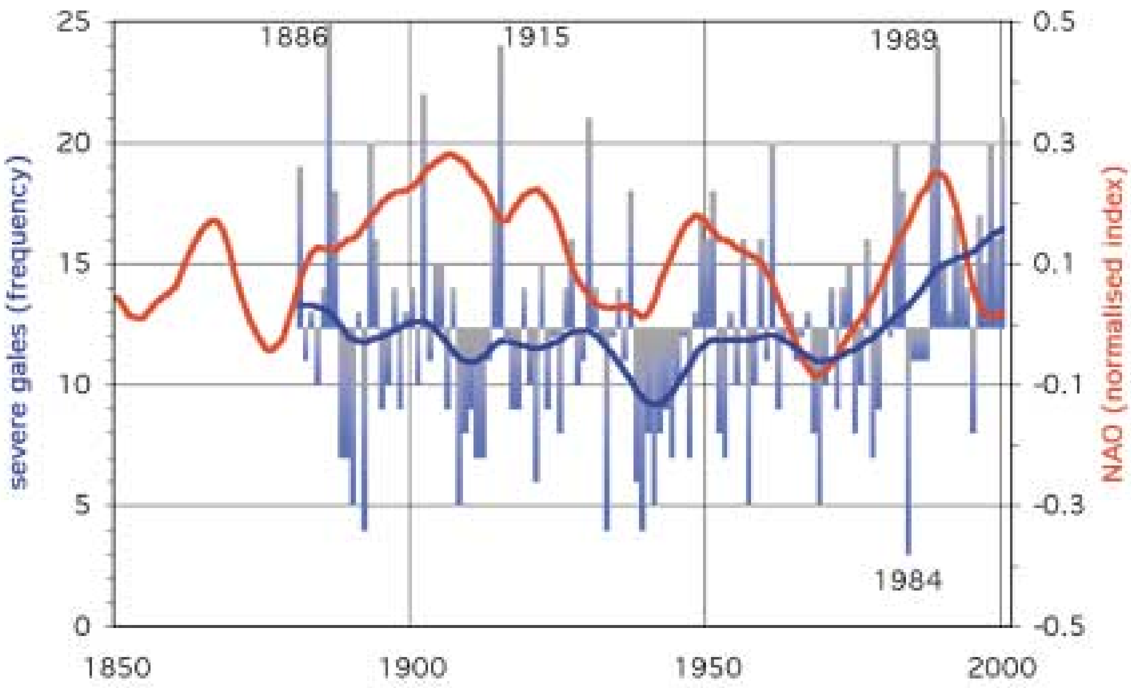

Figure 12: The annual frequency of severe gales over the UK for a July-June year (1881/82 to 2000). The bars emphasise deviations from the 1961-1990 average (12.5 gales), and the lower curve emphasises variations over time scales of at least 30 years. The upper curve is the normalised July-June index of the North Atlantic Oscillation (1850/51 to 2000/01), smoothed to emphasise variations over time scales of at least 30 years. *Source: Osborn, TJ (2000) in Hulme et al., 2002.*

2.4.6 SEA LEVEL RISE

The average global increases in sea level from the UKCIP02 scenarios range from 14-18cm by the 2050s, and from 23-36cm by the 2080s, depending on the scenario.

The change in sea level will vary across the UK, mainly because of the readjustment of the landmass since the last ice age, with much of southern Britain sinking at between 1-1.5mm per year, and much of northern Britain rising at between 0.5-1.0mm per year relative to the sea. Net sea level changes by the 2080s range from 0-60cm for Scotland and 15-85cm for much of England.

Even modest sea level rises will have impacts on low-lying coastal gardens by raising the water table beneath, thereby increasing the risk of flooding, and possibly resulting in salt intrusion into aquifers.

Storm surges will potentially be much more damaging than steady rises in sea level but are much more difficult to model. Surges occur when high tides are combined with low atmospheric pressure and strong on-shore winds. They can be exacerbated by tidal conditions and the shape of the coastline. Surges are expected to increase most significantly on the south east coast, by 80-140cm in the 2080s for the high emissions scenario. A decrease is implied by the model for the Bristol Channel ,but this does not take into account the shape of the channel (Figure 13).

Even modest rises in sea level can have disproportionate impacts by allowing increased transmission of wave energy to the shore. The combined effects of increased wave energy, wave height and small increases in wind speed could result in an order of magnitude increase in frequency of surges. The north west coast, for example, experienced a 10cm rise in mean sea level in the last century. An extra 15cm rise in levels, and 2mm increase in wave height likely to be achieved by the 2050s could double or treble dangerous storm surges in the Irish Sea (Shackley and Wood, 1998).

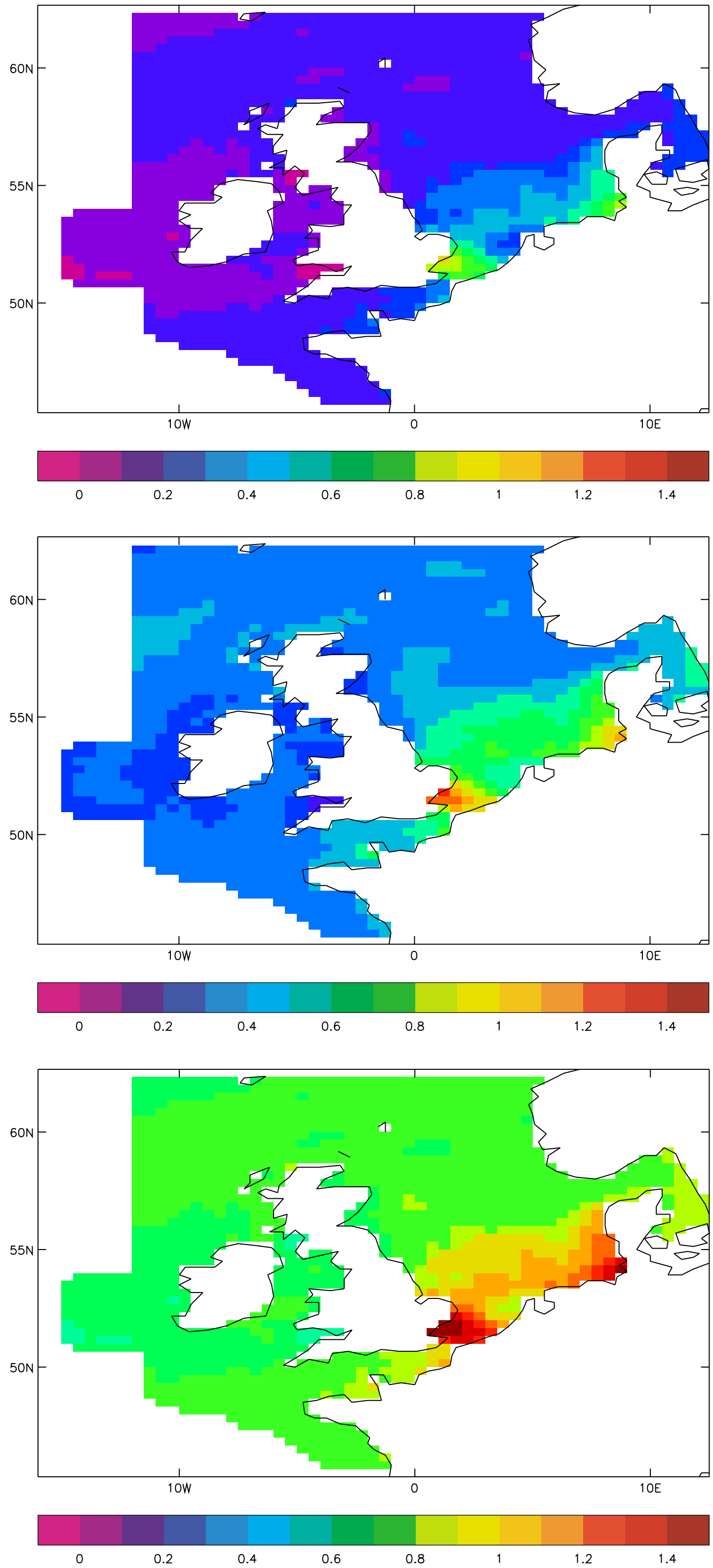

Figure 13: Change in 50-year return period surge height (metres) for the 2080s for three different scenarios. The combined effect of global average sea level rise, storminess changes and vertical land movements (from Shennan, 1989) are considered. (Top) Low emissions scenario (low sea level rise estimate; 9cm); (Middle) medium high emissions scenario (central estimate; 30cm); (Bottom) high emissions scenarios (high estimate; 69cm). *Source: Hulme et al., 2002.*

Higher sea levels combined with increases in wind speed may also result in salt spray being carried in larger volumes and over longer distances, causing damage to plants and soil structure further inland than hitherto.

Sea levels will increase as sea water warms and expands. Changes are likely to be small in the low and medium low emissions scenarios but might reach 60-85cm in the high emissions scenario by the 2080s. Even small increases in mean sea level, combined with a modest increase in wind speed and wave height, could result in a significant increase in damaging storm surges. Higher seas and stronger winds could also result in salt spray being carried farther inland.

These various components of climate change will have significant influences on plant life and therefore on gardens. In the next section we look at how plants, the main components of gardens, will be affected by climate change.

The physiological basis of plant responses to climate change

Plants are fundamental to life, utilising the sun's radiant energy to combine carbon dioxide and water to produce sugars and oxygen by the process of photosynthesis. The sugars are combined with nutrients from the soil to produce proteins and other complex compounds which enable the plant to grow and to function. The pattern of growth and development from seed to flowering plant producing more seeds is governed by many factors such as carbon dioxide concentration, the quantity, quality and duration of light and availability of water and nutrients. Each species of plant has evolved to suit a particular ecological niche, using signals from the environment - especially temperature and day length - to synchronise their growth with seasonal changes. This chapter provides a basic outline of how plants function and explores how changes in climate might affect their growth.

3.1 Plant growth and development

Plants *grow*, by accumulating material to become larger, and they *develop*, in response to internal and external stimuli, from juvenile to mature state, from vegetative to flowering, and from active to dormant for example.

The fundamental process driving plant growth is photosynthesis, by which the green tissues of the plant, especially its leaves, combine carbon dioxide from the air with water taken up from the soil by roots to produce carbohydrates (sugars, starch and cellulose), the basic building materials of the plant. Oxygen is also produced in the process. The photosynthesis process may be summarised as;

6 CO_2 (carbon dioxide) + 6 H_2O (water)

➜ with energy from sunlight ➜

$C_6H_{12}O_6$ (glucose) + 6 O_2 (oxygen)
(a carbohydrate)

The carbon dioxide needed for photosynthesis diffuses into the leaves through small pores (stomata) mainly in the undersides of the leaf. In order to survive the plant has to balance its need to take in carbon dioxide with the need to reduce loss of water vapour through the stomata. It does this by opening and closing the stomata through very sensitive feedback mechanisms which respond to carbon dioxide and water availability. The energy required for photosynthesis comes from sunlight.

The plant then combines the products of photosynthesis with nitrogen (usually as nitrate), phosphorous, potassium and other nutrients taken up from the soil in solution, to produce proteins and other complex materials. The factors which most affect the growth of a plant are those required for photosynthesis (light, water and carbon dioxide) and the levels of available nutrients (nitrogen, phosphorus, potassium and minor nutrients).

Water plays a key role in plant growth by making nutrients in the soil available to the plant, but it is also vital in keeping the plant turgid. If water supplies in the soil are inadequate, or if evaporation from the plant's leaves exceeds the ability of the plant roots to replenish this loss, the plant will suffer water stress.

The immediate response to water stress is closure of the stomata, thereby preventing further water loss but at the cost of cutting off the carbon dioxide supply needed for growth. If water stress continues the plant will usually react by wilting, then shedding leaves to reduce its evaporative surface. Continued water stress will lead to damage to cell tissues and ultimately to the death of the plant.

Plants not only grow, by accumulating carbohydrates and proteins, but they develop by germinating from seed, producing new shoots and leaves, by flowering, and setting seed. In a temperate climate such as that experienced in the UK, perennial plants (those which live for several, often many, years) have yearly cycles in which they produce leaves, flowers and seed then prepare for winter, for example by developing underground resting organs (bulbs, tubers) or by losing their leaves and producing resting buds tolerant of low temperatures. This winter resting state often develops into true dormancy which can only be broken by a period of low temperatures or short day lengths or both. When dormancy is broken the plant is ready to begin growth again as soon as the temperature increases sufficiently.

The growth of a plant is controlled mainly by light levels, the availability of carbon dioxide, water and nutrients, and temperature. Its development, from vegetative to flowering to resting for example, is often controlled by more complex mechanisms such as changes in day length or changes in temperature. The onset of dormancy and release from it are particularly complex processes. In some plants temperature change is the main stimulus. In others the process is entirely or predominantly controlled by day length while in other plants day length and low temperature will substitute for each other in varying degrees.

From this brief and very much simplified description of plant growth and development it is clear that some aspects of growth and development will be significantly affected by climate change (when carbon dioxide concentration, temperature or water availability are important for example) while other aspects, especially those controlled by day length, will be largely unaffected.

Plants grow and develop in response to a range of stimuli but especially to the availability of carbon dioxide, water and mineral nutrients and to the quality and quantity of light. Most of these stimuli will be affected directly or indirectly by climate change, except that light quality and the natural rhythm of variation in day length will remain unaltered.

3.2 Plant responses to carbon dioxide

In most climate change impact studies carbon dioxide concentration is important only insofar as it is the principal driver of climate change. In studying the impact of climate change on gardens, as with agriculture, forestry and nature conservation, carbon dioxide itself has a significant impact by its involvement in photosynthesis.

3.2.1 CARBON DIOXIDE AND GROWTH

If other factors remain favourable, increased carbon dioxide concentrations will lead to greater rates of photosynthesis in plants. Current carbon dioxide concentrations limit plant photosynthesis. Growers of protected horticultural crops have known for some many years that artificially raising the concentration of carbon dioxide in greenhouses can substantially increase crop growth and yield. It is generally accepted (Kimball *et al*., 1983; Poorter, 1993) that a doubling of carbon dioxide concentrations will lead to approximately a 40-50% increase in the growth of plants. However, there are strong interactions between increased temperature and carbon dioxide such that increases in carbon dioxide concentration will not always lead to increases in the yield of food crops for example (see Section 3.3.6).

Response to elevated carbon dioxide concentrations varies between different species. A review by Poorter (1993) indicates that herbaceous crop plants responded more than herbaceous wild species (58% vs 35%), and potentially fast growing wild species increased more than slow growing species (54% vs 23%). Leguminous species capable of symbiosis with nitrogen fixing organisms had larger responses to carbon dioxide compared to other species. There is also a tendency for herbaceous dicotyledons (broadleaved plants) to show a larger response than monocotyledons like grasses. Poorter (1993) suggests that the more responsive plants are those with a greater sink strength, that is in those plants with active regions such as developing fruits or rapidly expanding shoots capable of utilising the products of photosynthesis.

There have also been comprehensive reviews of the effects of elevated carbon dioxide levels on woody plants, notably Curtis and Wang (1998). The rate of growth accumulation in trees will be significantly higher as a result of elevated carbon dioxide concentrations (Jach and Ceulemans, 1999). Recent findings have shown that forests are currently growing at an accelerated rate, particularly in the northern hemisphere. Annual increase of wood volume in coniferous and hardwood forests in Sweden, Germany, France and other European countries has increased by up to 50% as a result of rising carbon dioxide levels, a longer growing season and increasing nitrogen deposition (Spiecker *et al*., 1996; Scarascia-Mugnozza *et al*., 2001). Broadmeadow (2002b) suggests that timber yields in the UK may be 20-40% higher over the course of the 21st century as a result of higher carbon dioxide levels.

The benefits of elevated carbon dioxide levels may, however, be relatively short term. A process of acclimation (becoming adapted to) is often seen in plant responses to carbon dioxide. Here, the short term photosynthetic response to instantaneous changes in carbon dioxide is much larger than the long term response. Long term exposure to elevated carbon dioxide leads to the accumulation of carbohydrates in the photosynthetic tissues of the plant and this accumulation leads to a reduction in photosynthetic rates (Clough *et al*., 1981). Medlyn *et al*. (2000) noted an initial 20% increase in net primary productivity of coniferous forests in response to a doubling of carbon dioxide concentration but the increase was not persistent, whereas a 2°C increase in temperature caused a 10-15% increase in long term productivity in both cool (Swedish) and warm (Australian) climates. (Medlyn attributed this temperature effect to increased soil nitrogen availability at the higher temperatures.)

In the long term, leaves developing under elevated carbon dioxide concentrations appear, in many species, to have fewer stomata than under lower carbon dioxide levels (Woodward, 1993). In fact, studies of herbarium specimens indicate that stomatal numbers in leaves collected from tree species at early stages of the industrial revolution were higher than present day numbers (Woodward, 1987, Penuelas and Matmala, 1990). Since the late 18th century the mean atmospheric carbon dioxide concentration has increased from about 277 parts per million by volume (ppmv) to current levels of over 350 ppmv and thus there appears to be a close relationship between the historical trends in stomatal number and carbon dioxide concentration.

Nevertheless, although photosynthetic responses to carbon dioxide are less marked in the long term than those anticipated from short term measurements, these responses are significant and contribute substantially to the increase in growth and dry matter accumulation under climate change conditions. The increase in carbohydrate concentration of tissues leads to higher dry matter content (cellulose, starch etc) of plant tissues which could have implications for the quality of some horticultural products. This may have less importance in gardens than in commercial horticulture but it could, for example, affect the storage life of allotment and kitchen garden produce. It might also affect pest and disease incidence (Ciesla, 1995) (see section 3.5).

3.2.2 PARTITIONING OF ASSIMILATES

About half of all assimilates (carbohydrates and proteins) are exported from the shoot to below ground parts of the plant where they are used for root respiration, nutrient uptake and transport processes in the roots, and as an energy source for nitrogen fixing bacteria and mycorrhizal fungi associated with the plant (Lambers, 1987). Under optimal levels of water and nutrient supply, this partitioning of assimilates to the roots does not appear to be changed by elevated carbon dioxide concentrations (Stulen and Hertog, 1993). When nutrients are in limited supply, varying responses have been noted but some experiments (eg Oberhauer *et al*., 1986) have demonstrated a higher allocation to roots in elevated carbon dioxide conditions where naturally occurring species are growing under nutrient limited conditions. This suggests that, in soils with low nutrient status, the higher carbon dioxide concentrations associated with climate change may enable plants to forage more effectively for their nutrients.

Experiments in which the effects of elevated carbon dioxide on the responses of plants to water stress have been examined show a variable response. In some species, partitioning to the root is not influenced by elevated carbon dioxide concentration whereas in other species there is an increased proportion of photosynthetic products moving to the root system implying a greater investment in roots to increase their access to available soil moisture (Tolley and Strain, 1985). In these species, higher carbon dioxide concentrations in the air will enable the plant to tap limited soil water resources more effectively.

3.2.3 CARBON DIOXIDE AND DEVELOPMENT

In addition to their impact on photosynthesis and therefore plant size, carbon dioxide levels can also affect other aspects of plant development. Cannell (1990) noted an effect on timing of bud burst and the cessation of growth: altered concentrations of carbohydrates and plant hormones in turn altered the dormancy status of trees thereby changing the timing of bud burst and the length of the active growing period. Jach *et al*. (2001) compared thirteen different studies of the effects of doubling of carbon dioxide concentrations on bud burst in nine different tree species. They showed that, whilst time of bud burst of five species was unaffected by elevated carbon dioxide concentrations, one species (Scots Pine [*Pinus sylvestris*]) was advanced and three were delayed (Sitka spruce (*Picea sitchensis*), Sweet chestnut (*Castanea sativa*) and the hybrid poplar (*Populus trichocarpa x Populus deltoides*). There did not appear to be any differences in the responses between coniferous and broad leaved species. In addition, elevated carbon dioxide resulted in a shortening of the growing season in three species (*Castanea sativa*, *Picea sitchensis* and *Populus sp*.). In one of the reported studies on *Pinus sylvestris* (Jach and Ceulemans, 1999), elevated carbon dioxide also stimulated the buds to develop more rapidly than under ambient conditions. However, there appears to be strong interaction between these responses and nutrient availability. Increased nutrient availability increases the growing season in many tree species (Bigras *et al*., 1996) and may mask the effects of elevated carbon dioxide concentration.

Flowering and fruiting of trees are likely to be hastened under conditions of elevated carbon dioxide. For example, flowering of roses is hastened and the number of flower buds is increased (Andersson, 1991). The yields of Valencia orange (*Citrus sinensis*) (Downton *et al*., 1987) and orange trees (*Citrus aurantium*) (Idso and Kimball, 1997) were increased when they were grown in elevated carbon dioxide levels. These increases in yield resulted from increases in both fruit numbers and fruit size.

The evidence for an effect of carbon dioxide concentration on leaf senescence and leaf fall is rather contradictory and may be species dependant. Some studies (eg, McConnaughay *et al*., 1996) suggest that leaf fall could be accelerated by elevated carbon dioxide. However, others (eg, Gunderson *et al*., 1993) suggest that leaf fall in some species is unaffected whilst yet other studies suggest that leaf fall can be delayed (Norby *et al*., 1986, McConnaughay *et al*., 1996). Clearly, the effect of carbon dioxide concentration on leaf senescence is still poorly understood and requires further study.

Most predictions of the direct effects of carbon dioxide suggest that average yields will increase by about 40-50% with a doubling of carbon dioxide concentrations. However, this does not address how plant growth responses to carbon dioxide are affected by changes in other climatic variables such as water and soil nutrient availability or temperature conditions. Interactions of carbon dioxide and temperature are particularly important and are described in section 3.3.6 below.

3.2.4 INTERACTION OF RESPONSES TO CARBON DIOXIDE AND WATER

The plant manages its intake of carbon dioxide and its control of water loss by the same mechanism, the opening and closing of its stomata. As mentioned briefly in section 3.1 and discussed more fully in section 3.4 the plant responds to water stress by closing its stomata. Conversely, if the supply of carbon dioxide is greater than the plant can utilise, it will react by closing its stomata and it will, in so doing, reduce its water use.

Leaves are able to detect and respond rapidly to carbon dioxide concentration. Stomatal opening decreases in response to increased carbon dioxide concentrations (Woodward *et al*., 1991). Decreased stomatal aperture under conditions of elevated carbon dioxide also leads to an increased resistance to water loss from leaves. Thus, as carbon dioxide concentration increases, the water use efficiency (carbon dioxide gained in relation to water lost) also increases. This suggests that the rate of evapo-transpiration decreases under conditions of elevated carbon dioxide. Crop simulations used to predict the irrigation requirements of potatoes under climate change conditions suggest that there will be very little change in irrigation requirements under most climate change scenarios, as reduced precipitation is balanced by increased water use efficiency (Wolf, 2000). Indeed, use of an earlier crop variety and an earlier planting date, made possible by increased temperatures, could considerably reduce irrigation requirements.

Taking into account long term reductions in stomatal numbers and short term closure of stomata in response to increased carbon dioxide concentration, Woodward (1993) estimates that leaf water use efficiency has increased by about 28% over the last century. Kimball *et al*. (1983,1984) measured seasonal water use (essentially evapo-transpiration) for well watered, field grown cotton in open top carbon dioxide chambers. Although not very consistent the data overall showed a slight decrease in water use at elevated carbon dioxide concentrations. This, coupled with the large increase of yields, suggest that these beneficial effects of elevated carbon dioxide may, in some instances at least, compensate for increased evaporation from plants in the drier conditions anticipated by climate change scenarios.

Response to elevated carbon dioxide may be influenced by water stress. Kimball *et al*. (1993) again showed that seed cotton yields were increased more by a doubling of carbon dioxide concentrations under drier than under wetter conditions (74% compared to 54%).

It is important to remember, though, that while the impact of the environment (in terms of higher carbon dioxide levels) on the plant may be to increase the efficiency of water use, the impact of the plant on the environment will be to reduce humidity (Ciesla, 1995) and, by not using energy for evaporation, to increase the temperature of both the plant and its surroundings. The valuable air-conditioning effect of plants will be reduced during periods of water stress.

3.2.5 INTERACTION OF RESPONSES TO CARBON DIOXIDE AND NITROGEN

The increase in carbohydrate content of tissues under elevated carbon dioxide is not necessarily accompanied by increases in nitrogen uptake and so a likely response to climate change is a decrease in the nitrogen concentration in plant tissue and an increase in the nitrogen efficiency of plants. Overall, therefore, nitrogen use by plants may stay essentially the same and fertiliser requirements will be unaltered by increasing carbon dioxide levels.

One of the many uncertainties surrounding climate change impacts on gardens is whether nitrogen availability in the soil will increase (as a result of higher nitrous oxide levels in the atmosphere and higher rates of mineralisation in soils) (Medlyn *et al*., 2000) or will decrease as a result of increased leaching (Jeffery, 2001). This would be a fruitful area for research.

The response to carbon dioxide may also change under conditions of low soil fertility. Data from Kimball *et al*. (1993) show that, even under nitrogen limited conditions, the response to a near doubling of carbon dioxide concentration led to a 53% increase in seed cotton yields under both irrigated and dry conditions.

Carbon dioxide is important because carbon atoms form the structural skeleton of the plant. A doubling of carbon dioxide levels may increase plant growth by 40-50% though continuous high levels saturate the plant's ability to use carbon dioxide and the benefits decrease with time. Higher carbon dioxide levels also allow the plant to use water more efficiently and may make the plant sturdier, more fruitful and more resistant (or less appetising) to pests.

3.3 Plant responses to temperature

There are two main categories of temperature effects on plant growth and development. The first is the effect of temperature and temperature fluctuations on general growth and development; the second is the effect of temperature extremes on survival.

3.3.1 TEMPERATURE AND GROWTH

Each plant species has its own characteristic response to temperature. Most biological activity slows almost to zero below 5°C. At still lower temperatures cell functions may be impaired and the plant damaged. At some point below 0°C ice may form between and within plant cells, causing damage or death of the plant, although many plants have strategies for surviving temperatures far below 0°C.

Above 5°C growth increases exponentially towards an optimum which varies widely from plant to plant, usually reflecting the natural climate within which a particular species has evolved.

Higher summer temperatures, like higher carbon dioxide concentrations, will favour plant growth if other factors are not limiting. As temperatures exceed the optimum for any particular plant its growth rate then falls, often sharply, to the point at which damage to tissues leads to complete cessation of growth and ultimately to the death of the plant. Temperatures in the UK are unlikely to reach levels in the next 50-100 years at which they cause direct damage to plants (essentially 'cooking' the plant) rather than causing indirect damage by increasing water stress, although the possibility can not be ruled out on very hot days, especially in greenhouses.

3.3.2 TEMPERATURE AND DEVELOPMENT

Plant developmental responses are somewhat different to the growth response to temperature, in that developmental rates increase approximately linearly with temperature above a threshold temperature which is often referred to as the 'base temperature' for plant development (Ellis *et al*., 1990). As for growth (see section 3.3.1 above) this base temperature is about 4.5-5°C for many species but can be lower for some species such as some Brassicas (Hadley and Pearson, 1999) and higher for species from a tropical or subtropical origin (Hadley *et al*., 1984). This linear increase in the rate of plant development reaches an optimum typically at between 20°C and 25°C but again this varies between species, varieties and even different developmental processes in the same plant. Above this optimum temperature, developmental rates often decline at approximately the same rates at which they increase at sub-optimal temperatures.

Because rates of plant development increase linearly with temperatures above a threshold, events such as germination, leaf appearance and flowering of day length insensitive species and varieties often occur after a fixed accumulation of heat above this base temperature, often called 'thermal time' and measured in day degrees (number of days multiplied by degrees above the base temperature). This can be very useful in predicting the effects of climate change. For example, if time from germination to flowering for a particular species occurs after the accumulation of 900 day degrees above 5°C, then flowering time will be 90 days at 15°C (90 days x 10 degrees above 5°C). The effects of an average increase in season temperature of 2°C above 15°C over the period of flower development would then lead to a date of flowering 15 days earlier (75 days at 12 degrees above 5°C). Thus, providing that the thermal time requirements for particular events are known, the effects of increased temperature on these events can be estimated relatively easily. However, the resources needed to determine thermal time requirements are such that the information is likely to be available only for important crop plants. This may yield useful information for the management of kitchen gardens and allotments but for most ornamental plants, phenological studies of flowering dates and other developmental responses to temperature change are likely to be more informative.

As already stated, higher temperature generally increases the rate of growth and of development of plants, particularly at the lower end of the range of temperatures suitable for growth. One effect of an extended growth period which has thus far been little studied is that plants will be growing at substantially lower light levels and in shorter days at any given temperature than at present (van de Geijn *et al*., 1998). The effect of this on quality of growth and, for example, on susceptibility to pest attack, needs further investigation.

One of the most important effects of climate warming is likely to be changes to the onset and cessation of growth (i.e. the beginning and the end of the growing season). Current estimates suggest that spring is advancing by 2-6 days per decade and autumn is delayed by about two days per decade (see section 2.1.1), and it is anticipated that a year round thermal growing season may be experienced in the south of England before the 2080s in the high emissions scenario (Hulme *et al*., 2002). This will affect the rate of development (the 'phenology') of the plant.

Temperature has very complicated effects on plant growth. Higher temperatures increase growth and speed up the rate of plant development so plants will flower earlier, though the scale of the response is different in different plants. In recent decades spring has been advancing by 2-6 days per decade and autumn has been delayed by two days per decade. With temperature increases anticipated in the high emissions scenario, a year round growing season in the south of England will be likely in some years before the 2080s.

3.3.3 PLANT PHENOLOGY

As mentioned in section 2.1.1, examples of long delayed autumn leaf fall, flowering extending into the winter months, 'unseasonal' flowering of spring bulbs, and other indicators of climatic change are widespread in the horticultural and national press (see, eg, Anderton, 2000; Fletcher, 1999; Greenwood, 2000) to the extent that it is becoming necessary to redefine what is meant by 'unseasonal'. Observations show already that in years with mild winter temperatures and warmer springs, bud burst is advanced and the onset of growth occurs earlier (Last, 2001).

The most conspicuous manifestation of climate warming in a garden situation will be earlier flowering times of many plants. Historical data on flowering times of many of our garden species provide a useful guide to how our gardens many change under conditions of climate change. Many long term records exist and already show substantial changes in flowering time as a result of recent changes in our climate. Analysis of long term records of flowering of a number of garden plants (eg Last, 2001) suggests that some species, including Mexican orange (*Choisya ternata*) and *Rhododendron* 'Praecox' will be very responsive to climate change, whilst others, such as Honesty *(Lunaria annua*) and bleeding heart (*Dicentra formosa*) will flower at approximately the same time as they do now.

Table 2 shows trends in flowering times of some common garden plants recorded by Mary Manning in her garden since the mid 1960s (Sparks and Manning, 2000) with flowering times for many species advancing by one to two weeks per decade over the last twenty years.

Table 2: Flowering time of some common garden plants recorded in East Anglia over the last forty years expressed as a mean date of flowering averaged over the periods 1965-1980, 1981-1990 and 1991-2000
Source: Sparks and Manning (2000)

	1965-1980	1981-1990	1991-2000	Days earlier per decade
Primrose (*Primula vulgaris*)	Feb 8	Jan 6	Nov 23	23.1
Aconite (*Eranthis hyemalis*)	Jan11	Jan12	Dec 14	10.7
Hazel (*Corylus avellana*)	Feb 3	Jan 14	Dec 14	10.7
Daffodil (*Narcissus cv.*)	Mar 10	Mar 7	Feb 25	7.9
Crocus (*Crocus sp.*)	Feb 8	Jan 22	Jan 24	7.1
Snowdrop (*Galanthus nivalis*)	Jan 19	Jan 10	Jan 6	5.5
Willow (*Salix sp.*)	Feb 16	Feb 19	Feb 8	–

A more detailed analysis of 23 British native and garden species is given by Sparks *et al*. (2000). This shows that 22 out of 23 species showed a significant advancement in flowering time with a 1°C increase in temperature (Table 3).

The results suggest a 2-10 day earlier flowering for each degree Centigrade of temperature rise. Interestingly, autumn crocus produced the only positive response, an indication that in plants responding to declining temperatures as a stimulus for autumn flowering, flowering may be delayed as mean temperatures increase.

Butterfield *et al*. (2000) simulated the effect of climate change on grape vine production in the UK and showed that under climate change conditions predicted by the HadCM2 climate model, date of bud burst occurs 10 to 25 days earlier, while date of maturity occurs 20-50 days earlier. Currently the area suitable for grape production (where grapes are able to reach maturity by 15 November) covers the southern and central counties of England, with Lancashire in the west and Humberside in the east marking the northern limits. Maturity in the UK varies from late September to mid November with maximum achievable yields varying from 175-200 grams per square metre (gm^{-2}). Although temperature has a negative effect on grape yields this is more than offset by the substantial positive effect of increased carbon dioxide. The net effect will be increases in yield ranging from 10-25% by 2050. It is estimated that mean yield, quality and quantity of grapes used for wine making in the UK will increase under conditions of climate change (Bindi and Fibbi, 2000). Grape production, at present on the northern limit for economic production in the UK, could extend into Scotland as the Iberian peninsula becomes less and less suitable (Schulz, 2000). In gardens, the grape might eventually replace such fruits as raspberry and blackcurrant which will not respond well to increasing temperatures.

One result of warming at the lower end of the temperature range is already, and will increasingly be, the near continuous growth of lawns through the winter months. In recent research at the Cambridge

Table 3: Results from stepwise regression of flowering time on Central England monthly temperatures (from the preceding October through to the month of mean flowering of that species). *Source: Sparks et al., 2000*

The value in the second column gives the pooled effect of a 1°C rise across all months on the date of flowering (expressed in days). A negative sign indicates an advancement in flowering time, a positive sign indicates a delay in flowering time.
Six species for which 58 years of data exist are given first followed by species with 20 years of data.

Species	Net effect (days)	Species	Net effect (days)
Greater bindweed (*Calystegia silvatica*)	-9.9	Ox-eye daisy (*Leucanthemum vulgaris*)	-4.9
Bird cherry (*Prunus padus*)	-9.1	Redcurrant (*Ribes rubrum*)	-4.9
Almond (*Prunus dulcis*)	-8.9	Horse-chestnut (*Aesculus hippocastanum*) – leafing	-4.9
Purple lilac (*Syringa vulgaris*)	-8.8	Winter aconite (*Eranthis hyemalis*)	-4.7
Hawthorn (*Crataegus monogyna*)	-8.6	Coltsfoot (*Tusilago farfara*)	-4.2
Dog rose (*Rosa canina*)	-8.2	Hazel (*Corylus avellana*)	-4.1
Laburnum (*Laburnum anagyroides*)	-7.9	Garlic mustard (*Alliaria petiolata*)	-4.1
Horse Chestnut (*Aesculus hippocastanum*) – flowering	-7.7	Wood anemone (*Anemone nemorosa*)	-3.6
Ivy (*Hedera helix*)	-7.3	Snowdrop (*Galanthus nivalis*)	-3.4
Lesser celandine (*Ranunculus ficaria*)	-6.7	Harebell (*Campanula rotundifolia*)	-2.6
Elder (*Sambucus nigra*)	-6.5	Christmas rose (*Helleborus niger*)	-1.9
Madonna lily (*Lilium candidum*)	-6.4	Autumn crocus (*Colchicum speciosum*)	+3.8
Yellow crocus (*Crocus aureus*)	-5.8		

Botanic Garden, Jeffery (2001) found that lawn growth in plots heated to 3°C above ambient was higher in March (a small but significant increase) and 18% higher in April.

Another effect of a general increase in temperature, especially if combined with wetter winters, might be the increased incidence of mosses and algae, many of which have lower threshold temperatures for growth than those of most flowering plants. Hotter and drier summers may limit or counter this increase, or at least result in the mosses and algae adopting their dry resting state for a larger proportion of the summer. However, difficulties could well arise as more gardens open earlier in the year in response to progressively earlier flowering seasons: algae and mosses will exacerbate the slipperiness of wet paths.

3.3.4 DORMANCY

Much of the UK garden flora consists of species that have a perennial habit, for example, trees, shrubs and herbaceous perennials. These have distinct annual growth cycles which can be divided into three phases; a rest period, a period of quiescence and an active growth period (Leinonen, 1996; Battey, 2000). The rest period and the quiescent period together constitute the dormant period. The rest and quiescent period are often described as periods of innate and induced dormancy respectively and have evolved to ensure that plants have no soft, young growing tissues that could be damaged by the unfavourable conditions that prevail during the winter period.

During the autumn and winter, active growth ceases and plants then have very limited ability to grow even if placed in conditions that allow active growth. Although the plant appears to be inactive during dormancy, this is often a period of high internal activity, with the plant producing leaf and flower initials in readiness for rapid spring growth. Exposure to a period of low 'chilling' temperatures is required before a plant can resume active growth. This chilling requirement is often measured as the accumulation of temperature below a particular threshold temperature. For example, sweet cherry requires the accumulation of 1000 chill units at 3.8°C in order to complete or 'break' dormancy (Mahmood *et al*., 2000). If chilling is inadequate, the development and/or the later expansion of leaf and flower buds may be impaired. Problems have already been experienced with poor cropping of blackcurrant after mild winters (Carew, *pers. comm*.) and the same might happen with raspberry, apple and other fruits as winter temperatures continue to increase.

After the completion of the rest period, plants enter a quiescent period in which they have the potential to grow but are limited by the prevailing conditions in late winter and early spring. Once temperatures attain a certain threshold, plants then begin their active growth period. During this growth phase, providing the temperature is warm enough, the amount of growth is a function of the amount of light intercepted by the plant canopy and the efficiency of photosynthesis. Finally, growth is brought to a halt again by a combination of shortening day lengths, lower light levels and cooler temperatures during the autumn.

Cannell (1989) assumes a continuously changing response to temperature for woody perennials from autumn through to spring flowering, so that the need for chilling temperatures is related to the thermal time requirement for flowering. Thus, as autumn progresses and the tree accumulates exposure to chilling temperatures, the thermal time required for flowering decreases progressively. Using Cannell's approach, Battey (2000) points out that beech (*Fagus sylvatica*), which has a large chilling requirement and thermal time for bud burst (beech is one of the last trees to leaf out in the spring), will accumulate less chilling under conditions of climate change. This will increase the thermal time for bud burst and make bud burst even later. However, species such as hawthorn (*Crataegus monogyna*) have a small chilling requirement which is easily met by the British climate. Here climate warming would cause earlier bud burst.

Although dormancy has been studied widely in woody plants, it has received less attention in herbaceous perennials. However, commonly the underground resting organs of species from temperate regions require a period of chilling before growth can recommence (Heide, 2001). Many herbaceous perennials possess prominent winter buds, whilst the shoot dies down in the autumn. Studies by Heide (2001) on *Sedum telephium*, and preliminary studies on three other herbaceous perennials with prominent winter buds, *Rhodiola rosea*, *Epilobium adencaulum* and *Oxyria digyna*, suggest that dormancy was controlled by day length rather than by temperature, with the plants becoming dormant under short days and being released from dormancy under long days. Clearly, this suggests that, for those herbaceous perennials which are under strict photoperiodic control for dormancy release, this mechanism will prevent early growth initiation in mild winters and suggests a much greater stability of emergence under conditions of climate change.

Many perennials found in cool temperate climates adapt to low winter temperatures by becoming dormant, in which state they are resistant to low temperature damage. Many trees and shrubs in particular have periods of dormancy which can only be broken by more or less prolonged periods of chilling, which is most effective at 0-5°C. Although externally dormant, many plants undergo active internal development, producing leaves and flowers which will emerge in the following spring.

Higher mean winter temperatures will have a variety of effects. Some plants, such as hawthorn, have a small chilling requirement so higher temperatures will accelerate growth. Others, notably beech, have a longer chilling requirement. If this is not met, growth in spring will be delayed, so increasing winter temperatures will result in later leafing.
In blackcurrant, raspberry, apple and other fruits the plant needs a cold period to form flower buds. Insufficient chilling will result in delay, abnormality or failure of flowers.

3.3.5 FROST SUSCEPTIBILITY

A widely expressed concern among horticulturists and gardeners is that climate change will lead to earlier growth and therefore to greater susceptibility to, and damage from, late spring frosts. Increases in winter temperatures, anticipated in all scenarios, will result in a very substantial increase in the number of days with temperatures above freezing, and above 5°C, thus extending and advancing the growing season. The concern expressed is that such early onset of growth as a result of climate change may increase the risk of frost damage to plants (Hanninen, 1991).

However, the earlier onset of spring growth in perennial species has to be seen in the context of a decline in the number of damaging spring frosts. For tree species, modelling exercises suggest a probable decline of spring frost damage in trees with climate warming, at least in the Netherlands and Germany (Kramer, 1994). Other predictions (eg, Hanninen, 1997) range from no change to a moderate increase in the incidence of frost damage.

Although this aspect of climate change merits further study, it is logical that damage to precocious young growth from late frosts is unlikely to increase in response to an increase in average temperature. At worst, damage may occur earlier in the year but at the same erratic frequency and with the same unpredictability as at present. What is more likely is that the reduced frequency and severity of frosts as average temperatures increase will result in less frost damage, including less damage to precocious growth. This is not to say that growers and gardeners can ignore the possibility of a severe frost. In terms of mathematical probability it is unlikely that another winter of 1962/3 severity will occur but, taking an indefinitely long term view, another winter of 1962/3 severity is almost inevitable at some time in the future.

Although the incidence of spring frost damage to precocious growth is not expected to increase with climate change, there is some indication that autumn frosts may become more damaging. Reduced or delayed hardening of plants in the autumn combined with reduced cloud cover and an increased diurnal temperature range could lead to increased damage (Broadmeadow, 2002a).

Frost damage can also occur during the dormant period, so the ability of plants to withstand winter frosts may also be affected by climatic warming.

Higher rates of tree activity under elevated carbon dioxide concentrations may result in increased metabolic activity during the dormant period, particularly at elevated temperatures. Plants may become less deeply dormant, leading to an increased probability of frost damage (Repo *et al*., 1996; Ogren *et al*., 1997). However, equally, increased soluble carbohydrate concentrations under future elevated carbon dioxide conditions (effectively increasing the concentration of antifreeze in dormant plants) may improve frost hardiness in some species (Ogren *et al*., 1997). In a UK context, Murray *et al*. (1994) concluded that elevated carbon dioxide concentrations and climatic warming would reduce the risk of frost damage to Sitka spruce (*Picea sitchensis*) in Scotland. Nevertheless, mild winters could also lead to higher rates of respiratory activity, resulting in a decrease in soluble sugars and thus a loss of cold tolerance (Ogren, *et al*., 1997). Certainly, the range of possible outcomes to the effects of climate change on the internal tissue conditions during the dormant phase reflects the spectrum of responses that have been recorded on frost hardiness in dormant tree species (Jach *et al*., 2001) which range from increased frost hardiness in Scots pine (*Pinus sylvestris*) to increased frost injury in Black spruce (*Picea mariana*).

In colder climates than that of the UK, snow can play an important role in gardens in protecting plants against winter injury, by providing a protective blanket against freezing in very low winter temperatures and desiccation in cold winter winds. However, the climate of the UK is not usually such that the protection from snow cover is vital. In most of the UK, lack of snow will signify more genial growing conditions and reduced winter injury rather than an increased risk of low temperature damage.

An important aspect of temperature on plant growth is the effect of very low temperatures which may freeze plant tissues and kill the plant. Plants vary enormously in their tolerance of low temperatures. Some people fear that climate change will encourage earlier growth of soft new shoots and that this will increase risk of frost damage. It is more likely in most cases that precocious growth will be paralleled by reduced incidence of frost. The timing of frost damage to precocious growth may change but its frequency will not increase. As frost becomes increasingly rare, especially in the south, then frost damage will also be reduced.

There is some risk that clearer skies in autumn and delayed dormancy in plants may lead to increased frost damage in autumn, and possibly in winter.

Reduced snow cover will not usually result in increased winter damage to plants.

3.3.6 INTERACTIONS OF RESPONSES TO TEMPERATURE AND CARBON DIOXIDE

There is widespread evidence of a positive interaction between carbon dioxide concentration and temperature. Response to higher carbon dioxide concentrations is greater at higher temperatures (Idso *et al*., 1987) and the optimum temperature for photosynthesis increases with increasing carbon dioxide concentration (Allen *et al*., 1990). The combination of increased temperature and increased carbon dioxide predicted in all climate change scenarios suggests that for some species the growth stimulation may be greater than the 40-50% suggested above (section 3.2.1). Kimball (1993) predicts from an extensive data set, that a doubling of carbon dioxide concentration combined with a 3°C increase in temperature could lead to a 56% stimulation in growth. This is similar to values obtained for carrots under increased temperature and carbon dioxide concentrations presented below (Wheeler *et al*., 1994). Conversely Kimball *et al*. (1993) suggest that the response to carbon dioxide may be very variable or even negative at cool temperatures, suggesting that photosynthesis may be stimulated less, or even be reduced, at cool temperatures by increasing carbon dioxide concentration. This implies that an increase in temperature should be even more effective in stimulating the benefits of increased carbon dioxide levels at the low end of the temperature range than at the higher end.

Although very little information exists for ornamental garden plants, studies of the effects of climate change, including the interaction of carbon dioxide and temperature, on growth, development and yield of several important crop plants have been conducted over the last decade. Most of these are also widely grown in gardens.

In general, all crops show a positive effect of carbon dioxide on yield. However, it appears that only crops that are harvested at an early stage of their physiological development (eg, carrot) show a positive effect of increased temperature. Crops that are harvested later in their physiological development (eg, onion and cauliflower) show a negative effect of increasing temperature. The net effect of increased carbon dioxide levels and increased temperatures therefore varies from plant to plant.

Carrot yields are likely to increase substantially with predicted changes in climate in the UK. Studies by Wheeler *et al*. (1994) showed that carrot growth is stimulated by increases in temperature, although temperatures greater than 18°C lead to progressively more foliage growth than root growth. A 1°C increase in soil temperature increased yield by 34%. Responses to increased carbon dioxide are also large: an increase in carbon dioxide concentration from 325 to 530 ppm also increased yield by 34%. This reflects the responses to climate change of most root crops which are considered to be larger and more positive than most other crops (Kimball, 1983).

In onion, warmer temperatures shorten the duration of growth whilst elevated carbon dioxide stimulates growth with no overall effect on crop duration (Daymond *et al*., 1997). However, the negative effect of temperature on crop duration appears to predominate, so that the overall effect of climate change is likely to reduce yield, because the stimulation in growth brought about by carbon dioxide is more than offset by a shorter period of bulb growth brought about by elevated temperatures. In general, it appears that a 1°C increase in average temperature decreases bulb yield by 3.5-15% whereas an increase in carbon dioxide levels, from current ambient levels to 530 ppm, lead to an increase in bulb onion yield of 30-50%.

It has long been known that reproductive growth in cauliflower and broccoli (the initiation and growth of the cauliflower curd or broccoli spears) is very sensitive to temperature (Salter, 1969). Thus, the date of curd or spear initiation is advanced by increased temperature but unaffected by light and carbon dioxide (Wheeler *et al*., 1995). Curd or spear growth for both species is increased by temperature up to a maximum of 14-15°C, but temperatures above this lead to a decrease in growth (Hadley and Pearson, 1999). Although mean curd dry matter yield is increased by 34% when carbon dioxide concentrations are increased from ambient levels to 530 ppm, a 1°C rise in temperature reduces yield by approximately 6% (Wheeler *et al*., 1995).

The optimum temperature conditions for production of potato, the main tuber crop grown in the UK and an important plant in many gardens, are typically those that are currently experienced (Wolf, 2000). Increases in temperature alone, as a result of climate change, will accelerate the senescence and death of foliage and therefore precipitate the end of growth. There are also more days with reduced growth as a result of higher temperatures, resulting in lower tuber production. However, this is compensated for by a positive response to increased carbon dioxide concentrations so that, for most climate change scenarios, small yield increases are expected. Warmer seasons offer the possibility of earlier planting dates than are presently possible, although the risk of frost during the early spring will limit the earliest date of planting. Earlier planting dates will give higher potato yields and this yield increase will become larger if carbon dioxide levels continue to increase.

There are varietal effects on potato yield. In general, early maturing varieties have a lower optimal temperature range than late maturing varieties, suggesting that earlier varieties may be more negatively affected by increases in temperature. The variation will inevitably be exploited to produce new potato varieties suited to changing climatic conditions, so potato yields are not likely to change significantly in response to climate change.

Temperature and carbon dioxide concentrations interact. Higher temperatures and higher carbon dioxide levels combine to stimulate more rapid growth and development but the end result is not always a higher yield. Increased speed of development may mean that the plant is unable to use the full length of the growing season before it dies. Plants like carrot, which are harvested early in their development, will increase in yield.
Plants harvested at the end of their natural growing season, like broccoli, cauliflower and onion, may produce lower yields as the accelerating effect of temperature exceeds the increase in growth caused by carbon dioxide.

There has been little work on ornamental plants but it is likely that they will respond in the same way. Hardy annuals, in particular, may go to seed earlier so their flowering season will be curtailed.

3.3.7 PLANT ADAPTABILITY AND PLANT BREEDING

The facts, cited above, that the optimum temperatures for tuber production in potato are typically those currently experienced, and that early varieties have a lower optimum temperature range than later maturing varieties, indicate a very important aspect of the responses and adaptations of cultivated plants to climate change. There is variability within the population of any one species and this will lead to some adaptation to climate change by natural selection. The pace of change anticipated by climate change scenarios is such that plants in the natural environment may be unable to adapt sufficiently quickly and may face elimination, but in a horticultural context the plant breeder will have a marked influence in accelerating the selection process and in shaping plant responses to the environment. This will be the case especially in annual plants, where the life-cycle is very short, and in plants of widespread use and value, such as turf grasses. For trees and for plants which have very limited commercial importance, intervention by plant breeders is unlikely.

As an example of past success, old varieties of beetroot were subject to bolting (accelerated flowering instead of root formation) in cold springs and this restricted sowing dates. ‘Boltardy’ beet was selected for reduced susceptibility to bolting in response to low spring temperatures, allowing earlier production. Similarly the production of sweet corn varieties able to mature in shorter and cooler seasons has greatly extended the range of UK gardens in which sweet corn can be cultivated. These selection and breeding practices will undoubtedly make a significant contribution in the adaptation of annual garden plants, especially, to climate change.

3.4 Plant responses to water

Water plays a vital role in plant growth and survival in three ways: as one of the ‘raw materials’ of photosynthesis, in transport of dissolved nutrients from the soil into and through the plant, and in maintaining plant turgor. Before one can consider the impacts of climate change resulting from plant responses to water, it is necessary to have a basic understanding of the distinction between water supply and water availability.

3.4.1 WATER SUPPLY

Water supply to the plant is derived from precipitation and in some situations from the net result of inflow to and outflow from the catchment area in streams or rivers. In all the UKCIP02 scenarios, water supply to the plant is expected to decrease in spring, summer and autumn. Although precipitation is expected to increase throughout the UK in the winter, evaporation will also increase in the south, so winter water supply will be increased in the north but reduced in the south. The wider environmental implications of water supply in affecting run-off, erosion and flooding, for example, are considered in section 6.2.

3.4.2 WATER AVAILABILITY

Water availability to the plant depends in part on the presence of an adequate water supply, but it is also affected by evaporation from the plant which, in turn, depends on solar radiation. Water evaporates from the cells inside the leaf and is lost to the atmosphere through the stomata. This process of transpiration uses energy supplied by solar radiation and depends on the humidity of the air and on windspeed.

As the temperature increases, the capacity of the air to carry water vapour increases very steeply. The humidity of the air decreases or, put another way, its drying capacity (and therefore its capacity to 'pull' water from a plant) increases. If water is available it will evaporate and, by absorbing very large amounts of energy in so doing, will cool the plant and its surroundings (or prevent them heating up). If the water supply is limited, evaporation is necessarily reduced and more energy will be used in heating the plant and its surroundings. The valuable air-conditioning role of plants will decrease when they are subjected to water stress.

The plant is not a passive tube conducting water from the soil to the air. Water movement through the plant results partly from active uptake by the roots (requiring food reserves and oxygen) and partly from evaporation by the leaves. If root uptake cannot keep pace with evaporative loss, as is often the case in hot, dry and windy weather, the plant will close its stomata. This prevents further water loss, but also prevents carbon dioxide uptake for photosynthesis.

The impacts of climate change on water availability and the resulting impacts on plant growth will arise in part from changes in the water supply itself, but also from increased temperatures and decrease in atmospheric humidity. Changes in supply to the plant will result from increased precipitation in the winter (when water is least useful for growth) and decreased precipitation in the summer and autumn, when high light levels and increasingly high temperatures combine to maximise potential evapo-transpiration. The change in temperature is expected to be upwards in all seasons in all scenarios, leading to increased evaporation of water.

3.4.3 IMPACTS OF WATER DEFICITS

As discussed briefly in section 3.1, water deficits in the plant will lead in the short term (seconds, minutes, hours), to closure of stomata, loss of ability to take up carbon dioxide for photosynthesis and wilting of soft plant tissues. Even short periods of wilting can cause substantial reductions in plant growth.

In the longer term (days, weeks, months), the plant will respond to water stress by shedding its older leaves and by becoming more compact with smaller, thicker leaves. It may also divert more resources to root development in order to exploit water resources in a greater soil volume. Annual plants, especially, will often flower more rapidly in conditions of water stress in order to set seed before they die, so the flowering season will be curtailed.

In the very long term (centuries, millennia), plants subject to the continuous selective pressure of water stress evolve adaptive mechanisms such as hairiness (to reflect light and thus reduce evaporation) or waxiness (to reflect light and reduce water loss through the surface), resulting in grey or silver foliage. In continuously dry environments, evolution results in very compact habits, succulent water storage tissues (as in cacti and succulents), and specialised metabolism to allow photosynthesis to take place while stomata are closed. These long term adaptations, which often have an ornamental value in themselves, are also subject to short term variation. In low light conditions or with plentiful water supplies, leaf hairiness will be reduced and normally grey or silver leaved plants will become more green. Plants grown in gardens for their grey leaves usually look less attractive in the winter months but in the wetter and duller winters anticipated in climate change scenarios they will look worse.

The impact of decreased precipitation in other seasons will depend on the interaction of many factors, especially on regional variation and on soil type. In the north and west, reduced summer precipitation and higher light levels (from reduced cloudiness) may result in a more favourable climate for plant growth. Those plants attuned to a cool, moist climate, such as *Meconopsis*, primulas and ferns, may suffer. In the south and east, already the driest parts of the UK, temperature increases and precipitation decreases are anticipated to be greater than elsewhere. Water deficits and their impacts on plant survival and growth may be severe, especially for long established plants attuned to a softer climate. Particular concern has been expressed for the future of beech trees (Harrison *et al*., 2001; Wade *et al*., 1999), an important and characteristic component of the landscape in the south east of England and an important feature of many larger gardens (see section 6.3.1).

Paradoxically, though, adaptation to increasing water deficits may be easier in some respects in the south east than in other regions. There are many highly attractive plants which will tolerate very dry conditions, but they will only flourish if they can escape winter wet. Although winter precipitation is anticipated to become higher in all parts of the UK, higher temperatures in winter are expected to result in reductions of soil moisture content in the south east, rather than increases. In areas in which the summer becomes drier but the winters distinctly wetter the potential of adapting by using 'xeriscape' planting schemes (i.e. using xerophytic, or drought tolerant, plants) will be severely limited.

Soil type will also have a major influence. The drying of heavy and poorly drained soils in reduced precipitation scenarios will increase the range of plants which can be grown, and will reduce the risk of waterlogging, though it will, of course, reduce the opportunity to grow plants specifically adapted to wet conditions (and may have serious implications for factors other than plant growth, such as the oxidation of soils, as discussed in section 6.1).

3.4.4 IMPACTS OF WATER SURFEITS

Increase in winter precipitation is a feature of all UKCIP02 scenarios, but more rain does not necessarily mean more waterlogging. On light soils, increasing winter precipitation will be a great benefit in improving the health of trees and in recharging the water table, thus extending the period for which water will be available for growth in spring and summer.

Water surplus will only be damaging to the plant if it causes waterlogging of the soil. The impact of waterlogging is to deprive the plant roots of oxygen so that they cease to function. In the short term, the symptoms of waterlogging of leafy plants are similar to those of drought: roots are unable to pump water into the plant, so the upper part of the plant wilts. More seriously, in the anaerobic conditions of waterlogged soils, plant metabolism is altered and toxic compounds accumulate. If conditions do not improve, the roots and then the whole plant will die.

Some plants are highly adapted to waterlogged conditions in the soil, with air channels in the leaves, stems and roots - or the pneumatophores ('knees') of swamp cypress (*Taxodium distichum*) - conducting atmospheric oxygen down to the roots. Many other plants will tolerate short periods (hours, days, even weeks) of waterlogging especially if the plant is inactive in winter so that oxygen demand is minimal. Others are very intolerant of waterlogging, or even of wet soils, and will quickly be killed either as a direct result of reduced oxygen supply or indirectly as a result of succumbing to root pathogens. In general, those plants which are most highly adapted to dry conditions (xerophytes) are the least tolerant of wet and especially waterlogged soils.

One important implication of climate change is that increasing winter temperatures will increase the activity (and therefore the oxygen demand) of plants in the winter, so roots may become less tolerant of waterlogging. This will especially be so in the south west, where both temperature increases and winter precipitation increases are expected to be high.

Water is vital to plant growth and to all life.
Water availability to the plant depends on the relative rates at which water is taken up from the soil by the roots and lost from the leaves.
If water is in short supply in the soil, or water loss from the leaves is too high because of increasing temperatures and increasing light levels, the plant will suffer water stress. It will react by closing its stomata (leaf pores) to conserve water and will therefore shut off its carbon dioxide supply.
Growth will suffer. Prolonged stress will cause loss of leaves and hardening of the plant. Extreme stress will kill it.

Adaptability to water stress varies greatly. Plants adapted to growing in cool, shady positions, ferns for example, will wilt after a few minutes in full sun even if the roots are freely supplied with water. Succulents, on the other hand, have reduced or fleshy leaves and very thick, waxy or hairy light-reflecting leaf surfaces, so can tolerate very severe drought for months or years.

With too much water, plant roots will be deprived of oxygen and will die. Again, plants differ widely in their tolerance of waterlogging, but those most adapted to very dry conditions will be least tolerant of wet soils and vice versa. Where drier summers are combined with wetter winters, plant choice will present considerable challenges, but it will often be possible to circumvent the worst effects of waterlogging by improving drainage.

3.5 Plant responses to changes in pest, disease and weed incidence

The general increase in summer and winter temperatures, combined with wetter winters and drier summers, are likely to have considerable impact on the severity of pest and disease attack on horticultural plants. These effects are among the most difficult to extrapolate from climate change scenarios because of the complexity of interactions, particularly in relation to specialised feeding relationships of pests. For example Visser and Holleman (2001) found that increasing spring temperatures advanced the hatching of oak moth (*Operophtera brumata*) more than they accelerated the unfolding of the oak leaves on which it feeds. Such disruption of the synchrony could have disastrous consequences for the moth but would result in reduced pest damage to oaks unless and until the moth, is able to evolve sufficiently rapidly to adapt to the changing situation. Where the interactions extend to the synchronous development of the host plant, an insect pest and a disease transmitted by the insect, each with its own particular responses to climate change, attempts to extrapolate from climate change scenarios to disease incidence become increasingly difficult.

This is clearly an area in which further research is needed in relation to garden plants.

3.5.1 CLIMATE CHANGE AND PESTS

The focus in this section is on those insects and other arthropods which cause damage to plants but consideration is also given to other species associated with gardens, such as butterflies and bees.

For example, an increase in the mean annual temperature of 2°C (as anticipated for south east England by the 2050s under the medium high emissions scenario), will mean that butterflies will appear 2-3 weeks earlier (Sparks and Yates, 1997) and the range and distribution of butterflies will shift dramatically (Fox *et al*., 2001). Many native butterflies will extend their territories northwards while new species, or those with only a localised existence in southern England, will migrate from the European mainland. The same will be true for pest species of insects. On the other hand, warmer winter temperatures are already leading to greater winter activity in bee populations and are resulting in poorer winter survival (Fletcher, 2000).

Many insect pests cause damage by eating leaves and other plant parts, so the nutrient status of the plant has a very significant effect on its susceptibility to attack. Increasing carbon dioxide levels will result in ‘harder’, less succulent plants which should be more resistant to attack (Ciesla, 1995). A well documented effect of increased carbon dioxide is a decrease in the nitrogen concentration of plant tissues, leading to a reduced nutritive value to insects (Nicolas and Sillans, 1989). Leaf nitrogen is a limiting nutrient in many herbivorous insect diets (Lincoln *et al*., 1986). When feeding on leaves of low protein content, insects respond in a number of ways including increasing consumption, choosing more nutritious leaves or species, reduced fecundity (production of young) and/or survival, reduced population density or more efficient food use (Scriber and Slansky, 1981). Such responses have also been observed when insects feed on plants that have been grown in elevated carbon dioxide concentrations. Consumption can be increased by 20-40%, compared to feeding on plants grown under ambient carbon dioxide conditions (Lincoln *et al*., 1986). This has been attributed directly to the reduction of nitrogen concentration in the leaf (Lincoln, 1993).

On the other hand, reduced water supplies will lead to increases in cell sap concentration. Sucking insects and mites will have a more concentrated food supply and may increase more rapidly. It is well known that low humidity in greenhouses encourages the build up of red spider mite. In the very dry summer of 1995, red spider mite and aphids were major problems on outdoor crops, such as lettuce, apple and raspberry (Orson, 1999). In experiments with sap feeding insects on plants grown in elevated carbon dioxide concentrations, responses varied from no significant effect (Docherty *et al*., 1997; Salt *et al*., 1996; Butler *et al*., 1996) to increased settling times (Smith, 1996) and increased fecundities (Awmack *et al*., 1996).

There is little direct evidence that chemical deterrents in the leaf, which many plants have evolved to resist pest or grazing attack, will be altered in plants growing under elevated carbon dioxide concentration.

Arthropod species that are likely to be most responsive to the effects of climate change are those that produce many generations in a single season ('multivoltine' arthropods). These include, for example, thrips, aphids and spider mites and represent the opportunistic insects and mites which, given a suitable food supply, will multiply rapidly on plants. Many of these cannot survive cold winters as adults and so the first insects to appear in the spring hatch from over wintered eggs. However, the speed of development and thus the number of generations that will be produced, is a direct function of temperature. Two components of climate change will have a direct impact on this type of pest.

First, milder winters will enable some species to over winter as adults rather than as eggs as at present. This will allow the pest to have a significant head start given the appropriate food supply, since they will not need to go though an initial generation prior to reproducing. Zhou *et al*. (1995) showed that warmer winter and spring temperatures will increase the over wintering survival of aphid species in the UK and, in some cases, advance the appearance of winged adults by as much as a month. An increase in spring temperatures of 2°C will mean that cabbage root fly will also become active a month earlier than at present (Collier *et al*., 1991). Mild winters will also favour such insects as green spruce aphid (*Elatobium abietinum*) which can feed and multiply throughout the year (AAIS, 1999).

Second, higher average temperatures will mean shorter intervals between generations.

Both factors will increase the potential for earlier pest attacks than at present, and for more serious attack as a result of rapid population growth. This effect will be exacerbated in the case of many sucking pests, as higher temperatures will be accompanied by increased water stress, leading to increased uptake of increasingly concentrated plant sap, as referred to above (Orson, 1999) in relation to red spider mite.

Insect population growth increases by 10-14 fold between generations, so that just one more generation over a growing season can have a profound effect on population numbers. A good example of an insect pest in this group is the cabbage aphid (*Brevicoryne brassicae*) which in a mild winter will over winter in rural areas on oil seed rape. This pest can then attack a wide range of garden brassicas (cabbage, cauliflower, Brussels sprout) in the spring and, since the population is initiated by adults, generations of invasive winged aphids occur much earlier than after a cold winter, when populations are initiated from eggs. Work at the Institute of Arable Research, Rothamsted has shown that typically, aphid attacks occur approximately two weeks earlier for every 1°C increase in average temperature. This has been confirmed by observations made over the last twenty years, during which spring temperatures have increased.

Many aphid species in particular are of concern to gardeners, not only as plant pests but as vectors (transmitters) for a number of serious virus diseases. Many of the impacts of climate change on population dynamics of aphids will, therefore, have consequential effects on virus disease attack. Zhou *et al*. (1996) conclude that the severity of aphid outbreaks in the UK will be increased under climate change conditions and will lead to an increase in the period of virus infestation further into the growing season (see section 3.5.2 below)

Warmer autumns may lead also to greater numbers of aphid vectors later in the season and may give greater problems to over wintering plants. Climate change, whilst increasing the opportunities for over wintering of vegetables and bedding plants, for example, may also be responsible for direct effects of later surviving insect pests and their indirect effect through the spread of virus diseases.

Water stress in plants results in greater nutrient concentration in the sap, and thus in greater growth rates and fecundity in aphids feeding on the plants. However, predator levels would also be expected to build up in response to increased food supply. One of the most important natural controls of aphid populations is rainfall, as the impact of raindrops dislodges the aphids or damages their feeding parts (Doggett, 1863; van Emden, *pers. comm.*). Whether lower summer rainfall will reduce the operation of this control mechanism, or less frequent but heavier rainfalls will increase it, is uncertain.

Higher temperatures may allow some pests that are largely confined to the sheltered environment of the glasshouse to move out into the open. This is already happening with red spider mite (*Tetranychus urticae*). However, while extending the period of pest activity, warmer conditions may also extend the period during which biological control agents can operate. Currently the nematode used for biological control of vine weevil is not as effective outside as it is under glass, because soil temperatures are too low. Consistently higher outdoor temperatures may result in better control, and perhaps even control by naturally accumulating nematode populations.

There is considerable evidence of changes in the natural distribution of birds and butterflies with a general northward movement of species as temperatures rise (Fox *et al*., 2001). This leads to loss of species favoured by low temperatures, but inward migration of species from mainland Europe. This same phenomenon can be expected for insect and other pests, especially if the spread of exotic species is exacerbated by international transport of crops or individual plants.

Termites have already been found in Cornwall. Japanese beetle, spruce moth, and stem-borers of birch, *Sorbus* and other woody species make the cultivation of many garden plants difficult in the USA where summer temperatures are substantially higher than in Britain. *Cameraria ohridella*, the moth which has devastated horse chestnuts in Spain (Bedoya, *pers. comm.*) and has recently spread into northern Italy (Garibaldi, *pers. comm.*), is now to be found in Belgium and, as of July 2002, in Wimbledon (Prior, *pers. comm.*). A small colony of the voracious Asian gipsy moth already present in Epping Forest could spread if a series of dry springs allows it to gain a firm foothold (Gruner, 2000). A comprehensive review of the effects of climate change on insect pests is given by Canon (1998).

Among larger organisms, roe deer and grey squirrel are both favoured by warm winters, and are both likely to survive in increasing numbers as a result of climate change. The grey squirrel has a particular predilection for the bark of beech trees. The combined effects of increasing squirrel damage and direct impacts of climate change on attempts to retain or regenerate plantings of beech in gardens, parks and woodlands will pose major challenges in the future. Attempts to regenerate beech woodland on Box Hill, Surrey in the past fifty years have failed because of the total destruction of the young trees by bark stripping (Piggott, 1988). Grey squirrels have also caused widespread damage to sycamore and Japanese maples in National Trust and other gardens, including the University campus at Reading.

3.5.2 CLIMATE CHANGE AND DISEASES

As with pests, with diseases it is very difficult to determine the exact impact of climate change on the development of a particular disease because of the complexity of the relationship between pest, host plant and environment. It is also very difficult to differentiate between the effects of climate change and the effects of increased international travel as causes of increased attack. The general impact of climate change on diseases, however, can be summarised as follows:

- wetter, warmer winters will favour diseases such as *phytophthora* that need water to spread;

- drier, warmer summers will favour disease such as powdery mildew that can spread in dry conditions;

- warmer conditions will allow diseases that cannot establish under current climatic conditions in the UK to survive and establish, but will cause the decline of existing diseases unable to adapt to higher temperatures.

For most diseases, the important epidemiological implications of climate change stem from warmer winters, which will result in greater availability of surviving host material, greater survival of overwintering inoculum (spores or growing fungi), and thus a more rapid onset and spread of disease as the growing season proper begins. However, this could be offset by greater dryness in the summer. Perennial plants growing on the margins of their climatic tolerance are likely to be subjected to long term, chronic stresses, resulting in a decline in plant health and increased susceptibility to diseases.

Faster rates of reproductive development under higher temperature conditions may well also increase the rate of disease spread, as will the more rapid increase of insect vectors of disease. For example, higher aphid vector populations generally mean that virus diseases will increase (Zhou *et al*., 1995). Moreover, earlier attacks by aphid vectors will lead to virus disease infection occurring earlier in the development of plants. Generally, virus diseases are always more serious when plants are infected at an early stage of development. As a plant becomes older it has a greater inherent tolerance of attack by virus diseases. Thus, the effects of climate change on virus diseases may well be more serious plant infection.

This may have implications for the Scottish seed potato industry. Some of the important potato viruses are aphid vectored. By raising the seed in Scotland, growers are currently able to produce virus free stock because the low temperatures inhibit the development sufficiently to allow the potatoes to produce tubers before the virus gets into them. Warmer, earlier seasons in Scotland could eliminate that advantage. The same problems arise with raspberry and strawberry, threatening the supply of virus free plants for gardens as well as for commercial growers.

Milder winters will also favour winter activity of a wide range of bark and wood invading fungi which are able to overcome the defences of trees during dormancy, and are likely to result in increasing severity of fungi which are currently limited by low temperatures (such as *Phytophthora cinnamomi*), while summer drought will favour diseases such as sooty bark disease of sycamore (*Cryptostroma corticale*) which attack drought stressed trees (AAIS, 1999). In a survey of horticultural crop responses to the hot, dry summer of 1995, Orson (1999) found reduced disease levels overall, but higher incidence of powdery mildews, rusts and *Fusarium* diseases.

The establishment of exotic diseases in the UK under conditions of climate change will provide great challenges for quarantine research in the UK. A number of diseases which have a wide host range and which are currently ubiquitous in the tropics and subtropics could prove major threats. For example, *Athelia (Corticium) rolfsii* is a wide spread disease in warmer climates where it infects a number of species including cotton, tomatoes and groundnuts. It is a soil borne disease, which is equivalent to *Sclerotinia sclerotiorum* and, given the opportunity, will attack a wide range of garden plants. *A. rofsii* is known to have been accidentally introduced into the UK once (where it was a problem during the season of its introduction), but died out. Under climate change conditions, the likelihood is that, if reintroduced, it would be able to survive the winter. Quite clearly, there is a threat waiting to happen.

Climate change conditions will offer an opportunity to introduce new plants into the UK, but each will have its own suite of pathogens. This will put great pressure on plant health authorities to ensure that future quarantine measures are effective. There are already instances where lack of plant quarantine measures have lead to the introduction of diseases, because quarantine is usually imposed only when plants are of economic importance. For this reason, no quarantine measures were approved when mature olive trees were imported into the UK, with the result that olive scab (*Spilocaea oleagina*), a major disease of olive in Mediterranean areas, was introduced. The problem is already here, therefore, if olives become a more common feature in the UK in the future.

Other problems are likely to occur if plant health authorities concentrate their quarantine efforts only on plants of economic importance and not on plants of garden interest. Camellia petal blight (*Ciborinia camelliae*), a disease of the petals at flowering time, originated in Japan but has spread around the world. It poses a threat to UK gardens as it is spreading up through Europe. The plant health authorities did not think it necessary to impose strict quarantine measures on imported Camellias but posters were distributed alerting the nursery industry to the chances of this disease. Within months of the issue of the posters, the disease was found in Cornwall and Devon, where it had probably already been present for several years. Under current conditions the disease is not devastating, presumably because the fungus is at its northern limit. However, under conditions of climate change its effects could be more severe and the potential for its spread to the rest of the UK much greater. In 2002 there has in fact been a significant spread eastwards to the south and east of England.

Many diseases are spread by insect vectors and the effect of climate change on the biology of vectors may also effect the spread of disease. For example, Oak Wilt (*Ceratocystis fagacearum*) is a North American disease spread by insect vectors which are not found in Britain. Their distribution and activity and the number of generations each year are limited by climate in North America. Under conditions of climate change, the environment of the UK could become more favourable for these insects, increasing the potential threat from the disease.

Aphids and thrips are vectors for a number of diseases. The potential impact of climate change on virus transmission in Scottish seed potatoes, for example, has already been discussed. Western flower thrips, a pest that was introduced a few years ago from Holland, is a major vector for tomato spotted wilt virus and impatiens necrotic spot virus. Currently this insect is mainly a problem under greenhouse conditions, but it could move outside under climate change conditions and could then attack a range of vegetables. This could be accompanied by a large increase in other viruses spread by thrips.

Popular garden species such as yew (*Taxus baccata*) and box (*Buxus sempervirens*) have recently been affected by serious diseases. Box, a major feature of many formal gardens and shrubberies, is under increasing threat by box blight (*Cylindrocladium buxicola*) (Henricot *et al*., 2000). This is a disease which is dependent on water splash for its spread and will therefore be favoured by wetter, warmer conditions. *Phytophthora* root rot of Yew is a very destructive disease of hedges caused by *Phytophthora cinnamomi*. This is also likely to be more severe under wetter warmer winters. Brasier and Scott (1994) suggest that, under climate change conditions, the fungus will cause more severe damage in the regions where it is currently present and will tend to spread northwards and eastwards. They also predict that the host range of the fungus will increase if it spreads into areas where it is not currently present. *Phytophthora* is an important disease associated with poor drainage, as its spores are spread by water movement through the soil and host plant resistance is decreased in anaerobic conditions. Increased rainfall and higher winter temperatures, allowing the fungus to develop during periods of waterlogging, are likely to lead to increased incidence of the disease and symptoms will be exacerbated when plants suffering root loss caused by *Phytophthora* are further stressed by summer drought.

Holly is affected by holly leaf blight caused by *Phytophthora ilicis*, a disease that was first described in the USA but came to Britain in the 1980s. Recently, in the late 1990s, there have been upsurges of the disease for reasons that are unclear, but may be associated with wetter, warmer winters. It has caused serious damage to hollies at the National Trust's garden at Nymans, Sussex, in 2001/02.

Lawsons Cypress is attacked by *Phytophthora lateralis*, a disease which is native to the northern United States but has spread to other countries, and, for example, is present in France. It is not thought to exist in Britain but, as with all *Phytophthoras*, it is favoured by warmer wetter winters, so that the threat from other disease will be greater under conditions of climate change and exacerbated by the free movement of plants throughout the European nursery industry. As with yew, a combination of warmer and wetter winters, predisposing to infection, and of hotter, drier summers increasing root stress will greatly increase potential damage from these root pathogens.

Brasier (2000) has studied a new *Phytophthora* disease affecting alder. This is an interesting potential effect of climate change since it is believed that this new disease has arisen as a result of the hybridisation between two *Phytophthora* species which may have come into contact as a result of flooding. Although the individual parent species do not attack alder, the hybrid does. This clearly introduces new possibilities for the threat by *Phytophthora* diseases.

On lawns one might expect an increase in red thread (*Laetisaria* (formerly *Corticium*) *fuciformis*) which has a high optimum temperature and perhaps a reduction in the incidence of snow mould (*Monographella nivalis*), which thrives at lower temperatures (Dawson, 1977). However, if climate change results in longer periods when the temperature is at 5°C rather than zero, for example, snow mould could increase rather than decrease in severity.

Reasons for a widespread decline in tree health in Britain are not well understood, but stress caused by water shortage in the summer (as a result of decreasing precipitation, increased evaporation and higher rates of extraction), or flooding in the winter, is probably already contributing to accelerated losses of trees and shrubs to *Armillaria, Phytophthora* and other pathogens.

Plants will be affected by climate changes indirectly, by the effects of these changes on the virulence of pest and disease attack, as well as directly. Pests and diseases are likely to be more troublesome as a result of climate change, because higher temperatures will allow increased survival and activity in winter and more rapid increase in spring. Some pests (mites, aphids) and diseases (powdery mildews, rusts) will be favoured by hot, dry summers. Leaf eating pests may be slightly disadvantaged by the higher carbohydrate status (and therefore reduced protein content) of host plants growing in the higher concentrations of carbon dioxide, and higher light levels associated with climate change. Warmer but wetter winters will favour root rots of various kinds, especially phytophthora.

Hotter summers will encourage the spread of new pests from warmer parts of Europe as well as the northward migration of pests found commonly only in the south of England. With increasing human mobility from other parts of the world, more care will be needed to monitor pests and to develop quarantine procedures to prevent the import of new pests and diseases.

3.5.3 CLIMATE CHANGE AND WEEDS

As weeds are simply plants in the wrong place, the effect of climate change on weeds will be as for plants in general. Higher carbon dioxide levels, higher winter temperatures and perhaps greater water availability in early spring will favour earlier germination and growth of weeds. This will especially be the case for highly competitive annual weeds which demonstrate the high sink strength identified by Poorter (1993) (see section 3.2.1). Many annuals will be able to germinate and grow through the winter and to set seed before the onset of summer drought. The result will be a need for increased garden maintenance.

Drier summer conditions may reduce weed growth, but will also reduce the effectiveness of glyphosate and hormone weedkillers such as 2-4D and MCPA which work best when the treated plants are in active growth. It will be more necessary to ensure that herbicide spraying is carried out earlier in the year, with a narrower window between the weed achieving sufficient leaf cover for chemical uptake and the onset of dry conditions, and the prospect of having to spray at a time when maintenance demands are at a peak.

Bracken (*Pteridium aquilinum*) is expected to benefit significantly from climate change (Farrar and Vaze, 2000; Pakeman and Marrs, 1996). Intolerant of exposure or shade, it will be able to colonise at higher altitudes as the temperature increases and to penetrate further into thin woodland as light levels increase.

Garden escapes which come from warmer and/or drier climates will also be favoured by climate change. The classic example is Oxford Ragwort (*Senecio squalidus*), a native of Sicily and southern Italy which is thought to have escaped from the Oxford Botanic Garden (Clapham *et al*., 1962). It was first noticed on walls in Oxford and subsequently spread through much of lowland Britain, its spread accelerated in the 19th century by the development of the railway system. The ballast on which the rails were laid provided the very dry conditions needed by the plant and the air currents caused by the trains helped to distribute the wind borne seeds along the track. In the late 20th and early 21st centuries the road system has had the same effect: dry embankments and expanses of gravel or coarse stone along hard shoulders and on traffic islands - and the wind currents created by speeding juggernauts - have created enormously expanded areas suited to the weed. Hotter and drier summers have also undoubtedly assisted in the Ragwort's success.

Rhododendron ponticum, Himalayan balsam (or 'policeman's helmet', *Impatiens glandulifera*) and Japanese knotweed (*Fallopia japonica*) have also invaded large areas of the UK, the north and west in the first two cases (Farrar and Vaze, 2000), the south in the case of Japanese knotweed. In this last case, human activity in spreading the plant, initially deliberately as a garden ornamental and more recently accidentally in transporting knotweed-contaminated soil, has been a major factor in its invasion, but all three have been, and will increasingly be, favoured by climate change. The spread of these plants erodes the biodiversity of habitats and the quality of parks and gardens.

Vines (2002), refers to the "tender" and very ornamental perennial *Hedychium gardnerianum*, as now growing out of doors in Durham in a sheltered garden. *Hedychium* is becoming a major pest in New Zealand in a climate not dissimilar to that of southern England.

There are very well documented cases of damaging spread of introduced plants in the hotter parts of the world: water hyacinth blocking African rivers, prickly pear in the Australian desert and Kudzu vine engulfing areas of the southern United States for example. *Phormium tenax* has naturalised on St Helena to the exclusion of large areas of natural vegetation (though mainly because of its tolerance of the heavy grazing pressures imposed by feral goats), and *Gunnera manicata* is becoming naturalised in southern Ireland. As the UK climate continues to heat up, it will be necessary to monitor carefully the potential and observed threats of invading exotic plants.

It is important, though, to maintain a sense of proportion when dealing with this potential problem. To speak in terms of 'alien invasions' raises the spectre of a triffid conquest. The first 150 years of increasing temperatures in the UK have not resulted in a dramatic change in its vegetation cover, other than that attributable directly to habitat destruction due to urbanisation and changes in farming practice (Bailey, 2000; Milne and Hartley, 2001). *Rhododendron ponticum* (introduced in 1763), Oxford ragwort (1794) and Japanese knotweed (1886) have become serious weeds in some locations, but only in recent years (in part, at least, because of changes in land use and management) and have not yet colonised to the exclusion of other species.

Clearly, the rate of temperature change, in particular, is accelerating and it will be necessary to monitor carefully the distribution and activity of any potentially invasive species. Hossell *et al*. (2001) suggest that attention should be given to updating the list of invasive species in Schedule 9 of the Wildlife and Countryside Act to include species with the potential to become invasive. However, given a history of exotic plant introductions to Britain extending over at least a thousand years and an immensely rich and widely distributed garden flora, there is as yet a conspicuous absence of invasive species.

A review of the characteristics of potentially invasive plants and the potential causes and impacts in a UK context would be very helpful, not only in identifying the nature of any potential risk but equally in reducing the likelihood of any panic reaction which might pose an even greater risk to UK gardens, by limiting the movement and use of exotic plants.

The impacts of climate change on weeds will be the same as for plants in general. Increased carbon dioxide levels will favour growth of competitive annual weeds more than it will favour plants in general. Higher winter temperatures and increased water availability, where the latter does not result in waterlogging, will allow overwinter growth of many annuals, more rapid growth in spring and earlier seeding as summers become hotter and drier. Perennial weeds will grow more quickly and most will flower earlier, if not controlled. Chemical weed control, with glyphosate in particular, will be less effective in hot, dry conditions.

A small number of introduced plants have become serious nuisances in recent decades. The reasons for the recent territorial expansion of plants present in the UK for a century or more are not clear, but a combination of climate change and changes in land management are probable contributors to the spread. Other garden species have the potential to become weeds if climate change accelerates, so careful monitoring will be needed.

3.6 Climate change and symbiotic organisms

Many plants have symbiotic (mutually beneficial) relationships with other organisms. This is most commonly seen in the relationships between leguminous plants (peas and beans for example) and nitrogen fixing bacteria, and between many coniferous trees and mycorrhizal fungi. The microorganisms benefit from the photosynthates produced in the leaves of the trees and provide in return soil mineral nutrients which the tree roots are themselves unable to acquire.

Although there has been limited research in the area of climate change impacts on these symbiotic relationships, it appears that the exudation of soluble compounds from roots tends to be greater in carbon dioxide enriched plants so that more carbon is available for mycorrhizal associations (Norby *et al*., 1986, 1987). Similarly, the greater allocation of carbon to the roots of carbon enriched legumes leads to increased nitrogen fixation as a result of greater nodule mass, although there is little evidence for any effect on specific nodule activity. This ability of mycorrhizae to extend their exploitation of soil nutrients and to supply their host plant with additional nitrates could help to offset some of the disadvantages associated with reduced summer precipitation and drier soils.

More research is needed to investigate the impacts of increasing temperatures and increasing water stress on the mycorrhizae themselves and on the potential uses of mycorrhizae to aid tree establishment and growth.

Plants in natural and managed communities

The behaviour of individual plants to climate change can be anticipated with some degree of confidence, because plants function in accordance with well established principles of plant physiology (see Chapter 3). However, when plants grow in close association with other plants, the outcome of any change in the environment will be subject to the complex science of ecology. As a very simple example, use of fertiliser in 1970s public planting schemes resulted in poor tree growth. The grass around the tree was stimulated by the fertiliser and competed more strongly with the tree roots for water, so tree growth suffered.

In examining the effects of climate change on plants in gardens, it is therefore necessary to consider the character of the garden and the extent to which the plants in it exist as individuals or as parts of a community. Gardens vary greatly in this respect. Some 'wild' gardens or 'wild' parts of gardens, and many of the18th century parklands and woodlands, were planned and planted to be gardened and managed as natural landscapes. Indeed, many landscape parks are now valued and managed as much for their nature conservation value as for their aesthetic appeal.

At the other extreme, a garden may be a collection of individual specimens, whether prizewinning delphiniums, North American conifers, or old apple varieties. In such cases, management intervention is more intense with pruning, staking, spraying and other maintenance practices aimed at fostering the growth of the individual and protecting it from external threats.

There are important differences between plants in the natural environment and plants in the highly cultivated garden in relation to the impacts of climate change. It is, therefore, necessary to consider, in each garden, the extent to which the particular garden resembles a natural community or, in J C Loudon's words, "a work of art and a scene of cultivation" (Loudon, 1838).

4.1 Plants in the natural environment

The survival of a plant in nature depends on its fine adjustment to many components of the habitat, and the ability to exploit a niche more effectively than any potential competitor. It is not a matter of how it will respond to higher carbon dioxide levels, but whether it will respond to higher carbon dioxide levels more or less successfully than its neighbour. Very subtle changes in soil moisture levels, light levels (as nearby plants grow, for example), or nutrient levels can make the difference between a plant dominating its surroundings, or becoming eliminated. Increased susceptibility to, or prevalence of, pests or diseases will also have long term impacts on the success or failure of a species, and hence affect the composition of the plant community as a whole.

The static nature of a plant, being literally rooted to the spot, is a challenge to its survival in a changing environment. In natural, as in managed forests, there is some evidence that trees are capable of surviving (Myking, 2000) and even benefiting from (Saxe *et al*., 2000) the higher mean temperatures experienced to date. However, the current rate of change in annual mean temperature is unprecedented. As is already apparent in the Chiltern beechwoods, for example, some trees have adapted to 150 years of moderate climate change, but continuing increases in temperature and particularly the more taxing extremes of temperature and drought, are resulting in widespread decline (see section 6.3).

In nature, plant species have responded to climate change by physiological changes in the individual plant (fewer stomata for example), and by changes in distribution of the species as seeds are dispersed to more or less favourable sites and flourish or perish accordingly.

Experience in nature conservation suggests that dispersal of many species will be too slow to respond to the changes anticipated in the climate change scenarios. Van de Geijn *et al*. (1998) equate a 1°C rise with a geographical shift of 150-200km, and Ciesla (1995) with a 100km shift, or a 170m rise in altitude. Given the 3-5°C rise in temperature anticipated by the high emissions scenario by the 2080s for the UK, a plant species would need to migrate 4-7km each year to stay in the 'same' climate, assuming of course that the terrain permitted this.

Harrison *et al*. (2001) have simulated the response of 34 terrestrial plant species to climate change using the UKCIP98 climate scenarios (a previous generation of climate change scenarios that have since been updated and replaced by the UKCIP02 scenarios). Their results show that the distribution of some species such as Beech (*Fagus sylvatica*) and bog rosemary (*Andromeda polifolia*) declines (Figure 14), but the distributions of others, such as cross-leaved heath (*Erica tetralix*), remains unchanged.

Another factor in the potential risk to natural plant communities to climate change, is the very limited mobility of many plant species, and thus their inability to migrate from one area to a more favourable one if there are discontinuities in the landscape because of habitat fragmentation. A species may be able to spread northwards to escape or exploit higher temperatures, but it will rarely be able to move from one mountain top to a higher one across a valley, or even from one damp hollow to a nearby wetter one across dry ground, so it may be eliminated as the local or microclimate changes. In mountainous areas of Europe, plant communities are moving to higher altitudes as temperatures increase (Ciesla (1995) estimates 1-4m higher each year in Austria), but local extinctions are anticipated as plants are unable to relocate from a previously favourable area to a new area, because of habitat discontinuity (Gottfried *et al*., 1999). Management and selection – human intervention – will be needed if substantial components of natural ecosystems are to be conserved.

When plants grow together in communities it is much more difficult to anticipate the impacts of climate change than when they grow as individuals or as a crop of one plant type. Survival of a plant in a natural community will depend on how much more or less able it is to respond to climate change than its competitors, rather than on its innate response.

Because plants are static, those in natural communities, in particular, need to be closely adapted to their environment. Changes in that environment are likely to threaten their survival. In natural communities, plants will respond to higher temperatures and reduced water availability by migrating to cooler, wetter areas (north and west in the UK) and/or to higher altitudes – by about 1-200km, or 170m in altitude per degree Celsius. This migration can only occur if there is a continuum of suitable environment across which migration can take place. Plants with patchy, localised distribution, such as those in heaths, bogs or mountain tops, could be threatened with extinction.

4.2 PLANTS IN THE GARDEN ENVIRONMENT

In a garden, the 'habitat' is often extensively modified prior to planting, by soil cultivation and fertiliser addition, for example. This modification continues with mulching, feeding, irrigation, pest and disease control and, most importantly, removal of potentially competing plants, often throughout the life of a plant. Even in supposedly 'wild' gardens, grass is cut and bracken, brambles, sycamore and other potentially dominant plants are controlled periodically. Competition seldom plays a major part in determining the fate of individual garden plants.

In gardens, plants are not necessarily required to flower (especially in the case of vegetables) or to set seed. Plants do not require pollinating insects because, if an increase in numbers is required, seed can be obtained from suppliers in warmer climates or plants can be propagated vegetatively. Under natural conditions, plants are especially vulnerable during seed germination and early growth, which is why a plant may produce tens of thousands of

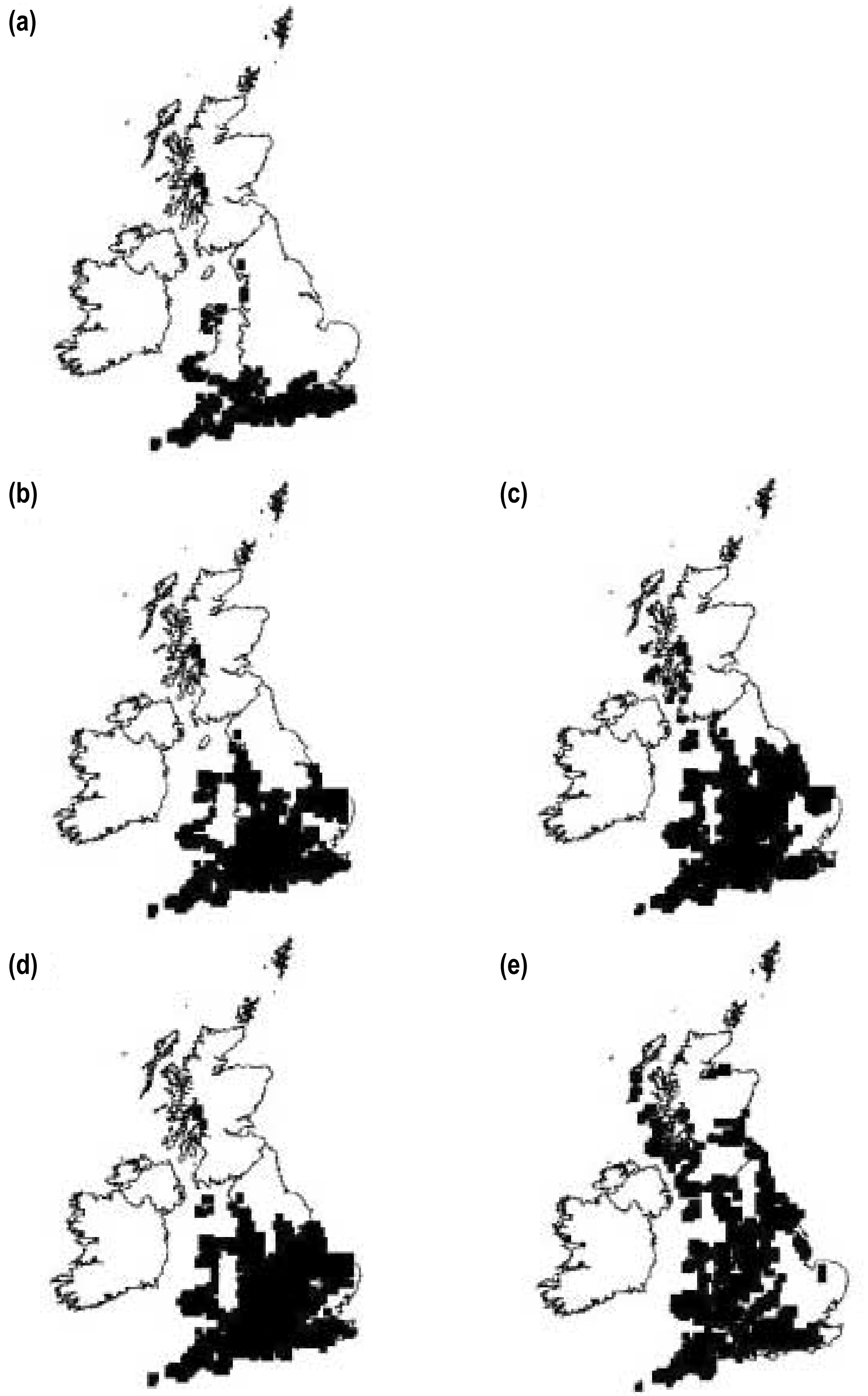

Figure 14a: Current and future distribution of beech (*Fagus sylvatica*) using the SPECIESv1 model and the UKCIP98 climate change scenarios: (a) simulated current distribution (1961-90); (b) 2020s low scenario; (c) 2020s high scenario; (d) 2050s low scenario; and (e) 2050s high scenario. *Source: Harrison et al. (2001)*

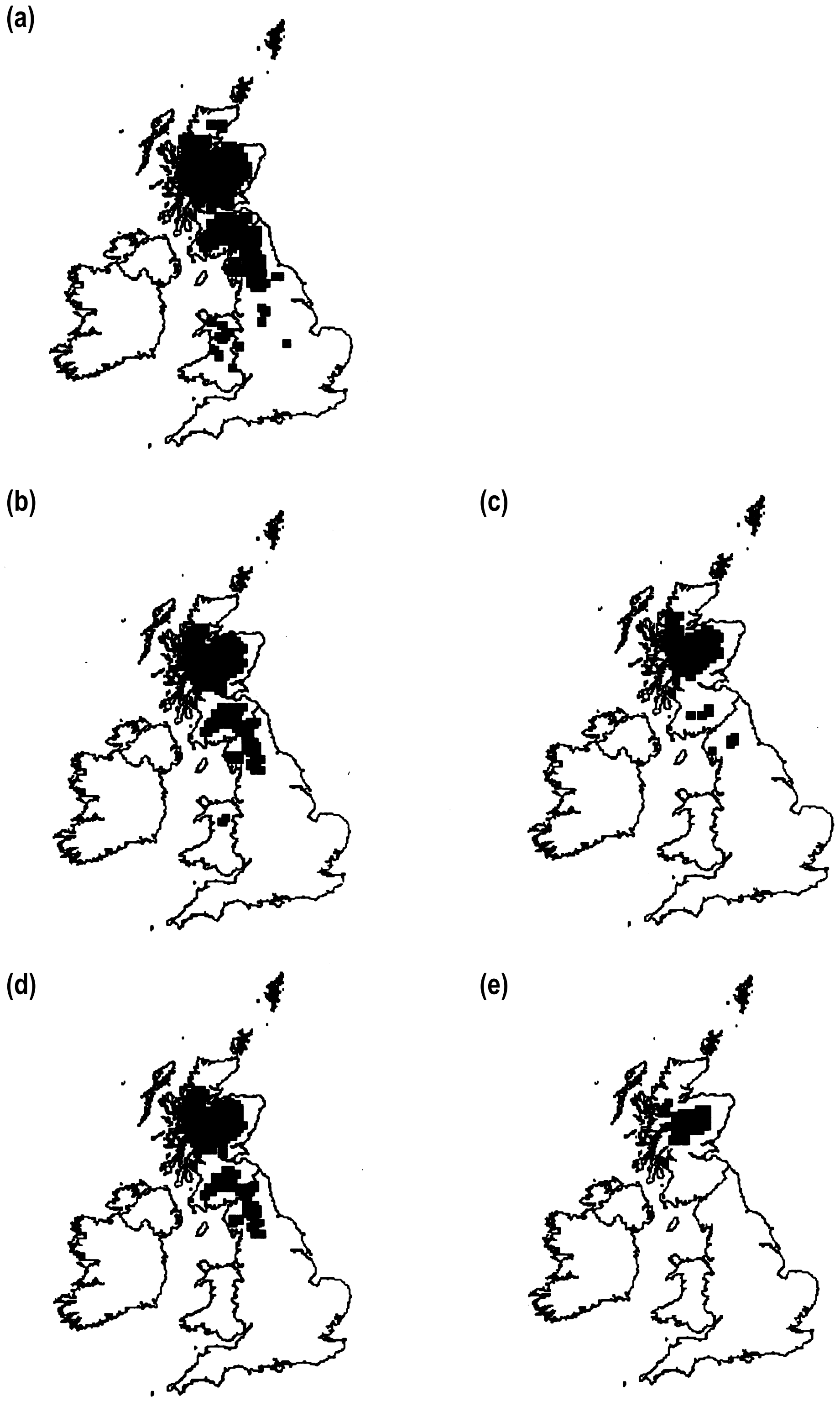

Figure 14b: Current and future distribution of bog rosemary (*Andromeda polifolia*) using the SPECIESv1 model and the UKCIP98 climate change scenarios: (a) simulated current distribution (1961-90); (b) 2020s low scenario; (c) 2020s high scenario; 2050s low scenario; and (e) 2050s high scenario. *Source: Harrison et al., 2001.*

seeds in order to continue the survival of the species by establishing one successor. In the garden or nursery, seedlings and young plants are grown in carefully controlled conditions, using sterilised compost for example, and are only planted in the open ground at a later, more robust stage of the life-cycle, into carefully prepared sites. It is unusual to see natural seeding of the great majority of our garden plants in gardens.

The effectiveness of all these cultivation practices is clearly evident when one compares the very poor native flora of the UK, estimated at 1500 species, with its immensely rich garden flora of 10000-15000 species (Royal Horticultural Society, 1992) or the 70000 taxa (species, subspecies, varieties and cultivars) listed in *The RHS Plantfinder* (Lord, 2002). The very wide geographical distribution of many garden plants throughout England, Scotland and Wales, and the ability of plants produced in Italian, German or Dutch nurseries to acclimatise more or less successfully to British gardens, all testify to the ability of plants to tolerate a much wider range of conditions in cultivation than they would normally experience in the natural environment.

Because of these advantages, garden plants are very elastic in their response to environmental conditions, and are likely to display a similarly elastic response to climate change. However, some changes in the garden flora will undoubtedly occur as a result of increasing temperatures and, especially, changing patterns of precipitation. Where conservation of the existing plant population of a garden is a high priority, for example in historically important designed landscapes or in gene banks of particular species, careful management will be required to accommodate and adapt to changing conditions.

Two key factors influencing the tolerance of garden plants to climate change will be their hardiness and their water requirements.

In gardens, plants grow in very favourable conditions. They are usually propagated in controlled conditions, planted into carefully prepared ground and protected to a greater or lesser degree from pests and diseases and especially from competing plants. In such conditions, the elasticity of response to climate change is very much greater than in nature. Two factors are particularly important in determining climate change impacts: hardiness and water availability.

4.2.1 HARDINESS OF GARDEN PLANTS

Low temperature tolerance varies greatly amongst garden plants. Some plants, for example dahlias and *pelargoniums*, will not survive even short periods below freezing, while others will tolerate temperatures of -40°C or lower.

The United States Department of Agriculture (USDA) developed a system for defining plant hardiness by dividing the United States into ten hardiness zones based on 6.25°C bands of average annual extreme minimum temperatures (the lowest temperature recorded in each year averaged over a number of years). These bands extend from zone 1 (eg, central Alaska) where the average annual extreme minimum temperature is below -46°C to zone 10 (eg, southern Florida) where the annual extreme minimum temperature is between -1°C to 4°C. In the context of the large land mass of the United States, the zones run in more or less parallel east-west bands across the country, curving southwards across the major mountain ranges and northwards as the moderating influence of the Atlantic and Pacific Oceans on winter temperatures is felt along the coasts.

The USDA system has also been adopted in Europe (Krussmann, 1984; Royal Horticultural Society, 1992; Schacht and Fessler, 1990) but in Europe as a whole, and especially in the UK, the zones are much less neatly defined (Figure 15). The patchy influence of changing altitude on temperature and the moderating influence of the sea are greater than the smooth influence of latitude is in Europe, compared with the United States.

The relationship between hardiness zones and plant survival is also less clear, because milder winter temperatures in the UK are not currently accompanied by high summer temperatures. In particular, the uncertain progression from autumn to winter to spring in the UK frequently leads to winter damage of young twigs which were not sufficiently matured or 'ripened' in the previous summer, and to frosting of premature growth in spring. Plants such as sugar maple (*Acer saccharum*), redbud (*Cercis canadensis*) and flowering dogwood (*Cornus florida*) tolerate very low temperatures in the northern United States but are much more temperamental in the UK.

As a broad generalisation, however, much of the UK equates to zone 8 (-12°C to -7°C), the Scottish highlands to zone 7 (-17°C to -12°C), and the southern and western coastal fringe to zone 9 (-7°C to -1°C) (Figure 15). Significantly, zone 9 plants include *Abutilon vitifolium*, *Callistemon*, *Carpenteria californica* and *Phlomis fruticosa*, which can now be found thriving in many gardens in the south west and in sheltered locations much farther north.

The 1-4.5°C rise in mean temperature anticipated by the 2080s by the UKCIP02 scenarios equates to about half a zone in the USDA scheme. Although mean *annual* temperature and mean *annual extreme minimum* temperature are very different, this comparison does serve to put the temperature effect of climate change in the UK into some kind of context. Most plants currently growing in UK gardens would be expected to survive a temperature lift of this magnitude, especially as it has been estimated that 85% of plants grown in UK gardens originate from areas with warmer climates (Thoday, *pers. comm.*).

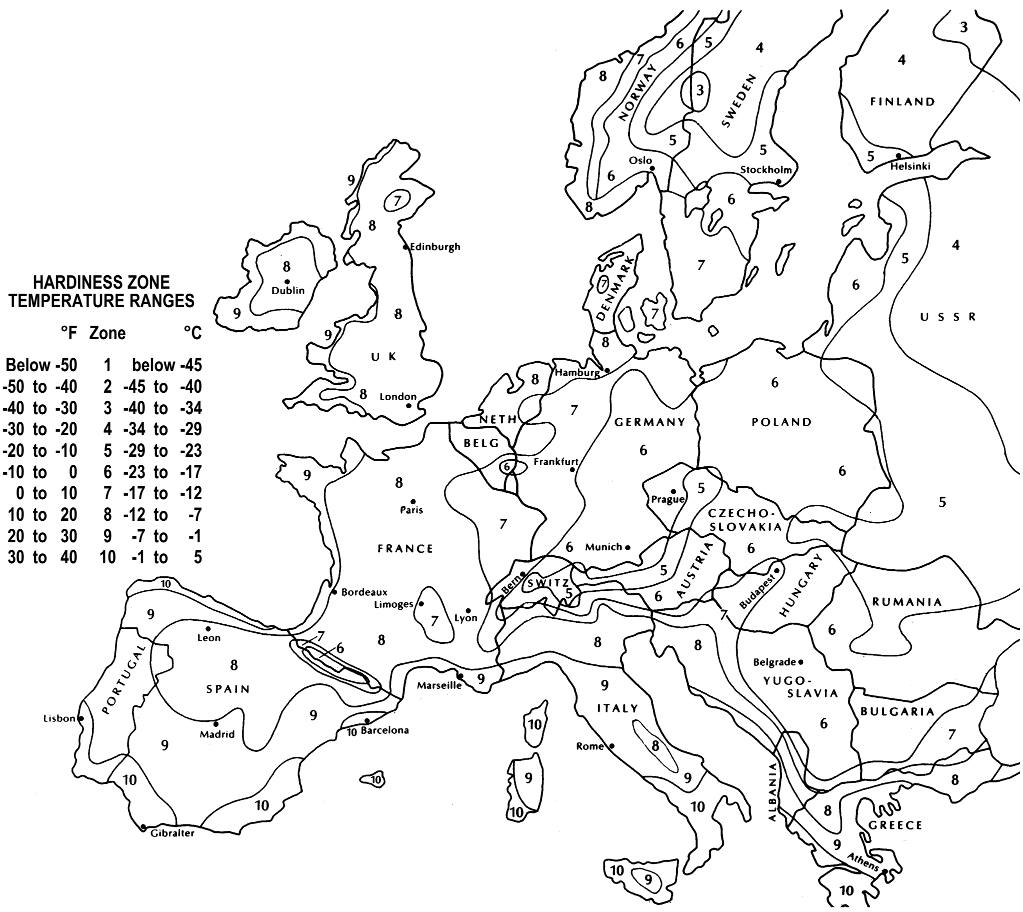

Figure 15: The USDA hardiness zones applied to Europe. *Source: Schacht and Fessler, 1990.*

Sukopp and Wurzel (2000) suggest that the heat island effect of major cities also lends support to the conclusion that many plants will adapt readily to the increasing temperatures predicted by the climate change scenarios. Native and exotic plants survive at least as well in cities, where the mean temperature is often 2-3°C warmer, than they do in surrounding rural areas.

The response to temperature is further complicated because the variations in microclimate within a single large garden are probably equivalent to the variation occurring on the macro scale across at least half of England. If there is a great desire to grow a particular plant, much of the change anticipated in plant tolerance as a result of climate change could, for several decades at least, be compensated for by moving plants to more sheltered or more shaded situations for example, though of course only if the plants are small enough and tolerant enough to be moved. This might also apply in special circumstances to heritage gardens where a particular plant needs to be conserved, but it would not apply, of course, if the particular plant had an historically determined particular place.

A scale of hardiness developed initially in the United States, from zone 1 (Alaska) to zone 10 (Florida), has also been adopted in Europe. On this scale, most of the UK falls into zone 8, with the Scottish highlands falling into zone 7, and the southern and western coastal fringe to zone 9. The average annual temperature change anticipated by the UKCIP02 low and high emissions scenarios by the 2080s is equivalent to about half a zone.

Hardiness and satisfactory growth and flowering are more complex than the ability to withstand a particular minimum temperature. Some North American plants, in particular, are tolerant of low temperatures, but will not grow well in Britain because of cool summers and an erratic transition from autumn to winter to spring. Climate change will favour the growth of some of these plants and will encourage good autumn colour in these and many other plants.

4.2.2 WATER AVAILABILITY AND GARDEN PLANTS

Although higher temperatures anticipated by climate change scenarios are, in themselves, unlikely to have a major impact on the garden flora, the relationship between temperature and water availability will be of critical importance to survival of many plants. If the expected climate changes were limited to higher temperatures and drier summers, it would not be at all difficult to find plants tolerant of the climate conditions suggested by the UKCIP02 scenarios for the 21st century. A rule of thumb of looking for parallels about 150km further south for each °C could be used (see Ciesla, 1995; van de Geijn, 1998).

However, most of the plants used in ‘dry’ or ‘water-wise’ or ‘xeriscape’ gardening are intolerant of the winter wet, and increased winter rainfall is a component of all the UKCIP02 scenarios. By the 2080s winter precipitation is likely to increase by 10-30% across the UK with regional variations. But increased winter precipitation will not necessarily lead to wetter soils. This is because the warmer, drier summers and autumns expected could substantially reduce soil moisture content before the onset of winter, particularly in the south and east where soils may become some 20-50% drier by the 2080s. By the 2080s, winter soil moisture contents are expected to increase by around 4% in parts of Wales and south west England, and by 4-10% in Scotland, while parts of south east and north east England could see a 10% reduction in winter soil moisture. Annual soil moisture content is expected to decrease by 10-20% across the UK by the 2080s with regional variations. The impacts of increasing winter rainfall may, therefore, not be as serious as the figures of precipitation change imply.

The local setting of the garden will be important in determining the impact of hydrological changes. Clearly, only coastal gardens or those in low-lying areas near the coast will be affected by increases in sea level, although gardens farther inland may suffer from increasing salt spray damage. Low-lying areas inland, such as the Bedfordshire Plain, may suffer from increasing flood risks in periods of heavy rain. Most larger gardens from the early 18th century onwards were consciously sited on eminences for the prospect which that afforded

(Bisgrove 1978), and so should be at lower risk of inland flooding as winter rainfall increases, though they will be at risk from summer drought.

Soil type will also be important. On light, sandy soils, increased winter precipitation is likely to be advantageous, replenishing the water resources depleted in hotter and drier summers. There will, though, be some increased leaching of nutrients from the soil. On heavier soils and in low-lying areas (the two situations are often linked, because clay deposits occur on flood plains and old lake beds), higher winter rainfall could lead to an increased risk of waterlogging. Improved soil drainage and careful positioning of plants (perhaps in raised beds) may assist in countering wetter winters but the effects of long periods of higher humidity, surface wetness and low light conditions will not be so easily remedied. Plants in raised beds will also be more susceptible to summer drought.

Another important factor in relation to increased winter rainfall is its intensity. A greater proportion of winter rain is expected to fall in more intense downpours. If the soil is capable of absorbing large amounts of water quickly, the garden will benefit fully from the higher rainfalls anticipated by climate change scenarios. If it is not, water will run off across the surface, causing erosion and possibly flooding, and it will be lost as a resource to the garden. Dawson *et al*. (2001) (using the UKCIP98 scenarios) suggest that by the 2050s run-off could increase by up to 20% in the winter and decrease by as much as 20% in the summer, with the largest changes in the south and east. Good soil husbandry will play a very important role in allowing plants and gardens to adapt to this aspect of climate change.

Given the continued survival of traditional gardening skills, it will be possible for the garden plants to survive fairly substantial changes in climate. Indeed, the lessons offered by long established garden maintenance techniques are being recognised increasingly as analogous to techniques which could be required in the wider aspects of landscape and nature conservation, if fragile habitats such as relict alpine meadows, lowland heaths and fens are to survive and adapt to climate change.

Winter precipitation is expected to increase across the UK. However, increased precipitation will not always lead to increased soil moisture content. By the 2080s, slight increases in winter soil moisture content are expected in south west England, Wales and Scotland, but annual soil moisture content may decrease by 10%-20%, with regional variations. Rainfall intensity is likely to increase in winter, increasing the risk of flooding. It may be difficult to find plants that will tolerate hotter drier summers but also survive wetter winter conditions, particularly in gardens with heavy soils.

4.2.3 CLIMATE AVERAGES VERSUS WEATHER EXTREMES

Although plants may survive significant changes in average temperature and average precipitation rates, it is important to realise that climate change will not come as a smooth gradient of change, but as the accumulation of a very large number of fluctuations about a mean. Weather will remain variable in future, and extreme conditions will occur. These would have more immediate impact on the garden than average changes in climate would. A week-long heat wave, a night of severe frost, drought, floods and very high winds, for example, will stress most garden plants and kill the more sensitive ones.

As part of this study, fourteen garden managers were asked to cite any examples of extreme weather events in the past five years that had affected their gardens. All ten respondents listed events ranging from heavy or prolonged rain (7 responses), through frosts and prolonged cold spells (5), high winds (5), floods (2), drought (2), variable rainfall (1), mild winters(1), very warm springs (1), unusually high/low temperatures (1) and deep snow (1).

Eight respondents thought that extreme weather events had become more frequent during their careers (two of these adding the qualification, “without doubt”). Another thought that extreme weather events were now so common that they no longer justified the term ‘unusual’. These responses do not constitute hard evidence for the existence of climate change: not all of the phenomena listed are necessarily associated with climate change and the recollections might well be biased by the freshness of recent events. However, they do offer some indication of recent climatic impacts on gardens and, by analogy, illustrate the effects and reactions which many of the components of climate change anticipated by the UKCIP scenarios are likely to create.

Climate change – long term changes in temperature and precipitation, for example – is the result of averaging widely variable daily, monthly and annual weather conditions. Short term weather events will have more immediate impact on the garden than will long term changes in climate.

Plants in gardens will be less vulnerable to climate change than plants in natural habitats, because of the management they receive. However, climate change will have significant impacts on garden plants and additional management inputs will be required to reduce adverse impacts.

Garden character and responses to climate change

The magnitude of climatic changes to which a garden is likely to be subject, will depend on its regional and local setting. Gardens in the north and west of the UK may be more vulnerable to flooding than those in the south and east. Gardens on hilltops are likely to suffer more from drought, while those in valleys or on flood plains will be susceptible to flooding. Only gardens on the coast or near sea level will feel the impacts of increases in mean sea level.

The significance, or impact, of those climatic changes will depend very much on the particular characteristics of the garden, on the ‘genius of the place’. The enormous diversity of gardens, and the reasons for this, has been outlined briefly in section 1.1. Within this great diversity though, and accepting that every categorisation has its misfits, it is possible to distinguish two main types of gardens: the small, private or domestic garden and the heritage garden. There are, of course, also many large private gardens. These have some of the characteristics of domestic gardens (a considerable degree of freedom to determine and modify the form and contents of the garden) and some of heritage gardens (availability of machinery, and usually trained staff to carry out large scale operations). The impacts of climate change on domestic and heritage gardens are examined in this chapter.

5.1 The domestic garden

In the domestic garden, the design and content of the garden result from a complex interplay between what is available and what is considered desirable. The garden layout often evolves and may undergo radical changes from time to time. Change – even complete change on occasions – is usually acceptable and will often be considered desirable.

Supply and demand interact in determining the form and contents of the domestic garden, but in complex ways. Such is the contrariness of the archetypal keen British gardener, that many will seek to grow some plants because they are difficult or not widely available and will reject other plants because they are easy and to be found in every garden centre. In cases where the garden is seen as a room outside rather than as a plot for cultivation, the gardener may be more inclined to follow fashion and to accept what is portrayed on television and readily available at the garden centre.

In both of these types of gardens, climate change will influence the ease of cultivation of some plants and the perception of what gardens are for, but it will be only one of many social, cultural, economic and environmental influences determining the progress of garden fashions. Cultivation of the currently popular *cannas*, tree ferns and other tropical looking plants may be made easier by climate warming, but it is very unlikely that climate change is the primary reason for their popularity.

For keen gardeners and for advocates of an outdoor lifestyle garden, climate change offers exciting opportunities and few threats. The main strategy for dealing with problems in the private garden has always been avoidance of the problem. If one plant fails for any reason, it will cease to be used by all but the most determined enthusiast, and more robust alternatives will be adopted; the range of plants available is so wide that it will not usually be difficult to find alternatives. Difficulties in the growing of particular plants, as a result of climate change or for any other reason, will be more or less indefinitely circumvented by changing to a different plant palette.

Keen gardeners have always enjoyed the challenge of growing marginally hardy plants, seeking sheltered corners of the garden and using a variety of protective covers in winter to increase the chances of success. Their gardens represent the limit of what is possible in that location. Climate change should allow such gardeners to succeed more frequently in growing plants which previously could only be grown in warmer areas. As successes increase, so will the demand. Sought after plants may cease to be the province of specialist nurseries, and may become available in garden centres and adopted by the wider gardening fraternity.

Challenges will arise for the more conservative gardener as a result of climate change. A luxuriant herbaceous border and an immaculate green lawn will be much harder to achieve in a hotter and drier climate. However, for those who insist on retaining such features, the expenditure in time and money to water plants, for example, and to mulch and feed, could be small in absolute terms because of the small size of the garden.

The domestic garden results from personal whim. It often changes from year to year as new ideas are tried. In many gardens the challenge of growing difficult plants is part of the excitement of gardening and the effort required to meet the challenge is focused on a small area.

For the domestic gardener climate change poses few problems and offers several opportunities. Lawns will be more difficult to maintain, but irrigation will often be practical, given their small scale. Plants needing cool, moist conditions could be moved to deeper shade. With warmer weather, climate change offers opportunities of using the garden more often and of growing a whole new range of plants.

5.2 The heritage garden

There are more than 3000 gardens in Britain regularly open to the public. Of these, over 1530 are registered for their special historic importance (English Heritage, 1998). The gardens range from small sites, like Barbara Hepworth's home in St Ives, to great landscaped gardens, like Stourhead, and from privately owned gardens to public parks and properties held in trust. The register includes many other types of designed landscapes and gardens, like allotments, town squares and cemeteries. A number of gardens and parks, like the magnificent water gardens at Studley Royal along with Fountains Abbey, are of such international importance they have been designated World Heritage Sites. Together, the UK's garden heritage reflects the evolution of garden design spanning the last 500 years, and illustrates the diversity of designed landscapes and gardens and plant collections, and their historic interest.

Gardens may be historically significant because of their design, their planting or their associations, or a combination of these. The garden at Audley End (Essex) for example, has a Victorian parterre, set in a Capability Brown landscape. The garden at Killerton (Devon) contains many plants introduced from Japan and elsewhere in the 19th century by James Veitch. The gardens at Down House and Chartwell (both in Kent) were developed by Charles Darwin and Winston Churchill respectively. Neither of these Kent gardens is outstanding in its design or planting, but each sheds light on the life of an historically important person. Gardens important for their plant collections alone are increasingly being acknowledged for their aesthetic, cultural, botanical and historical significance.

5.2.1 CONSERVING THE HERITAGE GARDEN

Heritage is a fragile and non-renewable resource (Farrar and Vaze, 2000), and the cultural heritage – especially heritage gardens – is disproportionately sensitive to change (Shackley and Wood, 1998) because it necessarily involves long time spans, during which extreme climatic events are likely to occur.

The fragility and uniqueness of the historic environment underpins the Government's own policy (DCMS and DTLR, 2001) on protecting and sustaining historic buildings, monuments, gardens and landscapes. In *A Force for Our Future* (DCMS and DTLR, 2001) the Government says: "If we fail to protect and sustain it [the heritage environment] we risk losing permanently not just the fabric itself, but the history of which it is the visible expression. It is therefore essential that decisions taken at all levels – national, regional and local – have regard to any potential impact on the physical remains of the past". The aim of conserving historic parks and gardens is to protect and maintain these landscapes, and the investment of resources and the skills that went into their creation over the centuries. The conservation approach is as diverse as the range of gardens, and individual to each one.

As well as sustaining the authenticity of the historic design, garden conservation seeks to sustain the character, qualities, traditions and the plant material of individual gardens. Many gardens have a long history of development and evolution, sometimes with different phases overlaying each other. The historic interest may relate to the designer, design ideas or the progression of designs, its period or rarity, associations with notable events or people, or the botanical interest of plants or plant collections, or a combination of all these factors.

English Heritage's criteria for gardens of special historic interest are:

- sites with a main phase of development before 1750 where at least a proportion of the layout of this date is still evident, even perhaps only as an earthwork;
- sites with a main phase of development laid out between 1750 and 1820 where enough of this landscaping survives to reflect the original design;
- sites with a main phase of development between 1820 and 1880 which is of importance and survives intact or relatively intact;
- sites with a main phase of development between 1880 and 1939 where this of high importance and survives intact;
- sites with a main phase of development laid out postwar, but more than 30 years ago, where the work is of exceptional importance;
- sites which were influential in the development of taste whether through reputation or references in literature;
- sites which are early or representative examples of a style of layout, or a type of site, or the work of a designer (amateur or professional) of national importance;
- sites having an association with significant persons or historical events;
- sites with strong group value (English Heritage, 1998).

In garden conservation, significance is determined by establishing the past history of a garden and its design influences, what survives today and how the garden has developed since first begun. Garden designs, whether formal or informal, rely on a precise relationship between structural features like avenues, hedges and groups of trees, and open spaces like lakes and lawns. Flower displays and plant collections add a rich decorative layer to the landscape designs. The original planting of the garden, the choice of trees, shrubs and flowers would have been governed by species availability, the garden's location and geology, and the skills and interests of the designer, owners and their head gardeners. In all cases, a garden's significance, historical precedent and traditions shape the policies for its conservation and the plants grown, and where they should be grown. Gardens may also be of interest for their artistry or horticultural styles, plant collections and scientific collections. The great tree collections of the 19th century, for example at Killerton (Devon), Westonbirt (Gloucestershire) and Sheffield Park (Sussex) were not simply collections but were arranged for aesthetic effect. Features may be of architectural, archaeological or wildlife importance too, and great educational value. These interests, and other new developments such as opening the gardens to visitors, also need to be embraced in planning the garden's future management.

5.2.2 CLIMATE CHANGE AND HERITAGE GARDENS

Climate change potentially poses an escalating range of threats for heritage gardens, from the impact on choice of plants grown, through to the long term sustainability of historic designs due to changing environmental conditions. The long term cumulative impact of repeated storm damage, drought, pest and diseases, flooding, lake siltation, sea level rises and so forth is likely to be of greatest significance. Within the next 50 years, some garden features may become vulnerable, and a few gardens may be at risk of complete destruction as a result of climate change, despite the best efforts to counteract its effects on a local level. This will be particularly the case where plants and plant schemes are close to their ecological and physiological limits, for example, moisture loving herbaceous borders grown on the thin gravely soils of the Thames and Chilterns, or ferneries in locations where drought and exposure might be a regular feature in future. However, the majority of plant species that are currently cultivated in historic gardens could be maintained by the use of suitable soil moisture conservation techniques and irrigation in summer, albeit at increasing cost.

Climate change is anticipated to be most marked in the south, and especially the south east, of the UK so clearly it will be most difficult to adapt garden management in these regions. In the north west temperature increases are expected to be less marked and several of the parameters of seasonal precipitation and cloudiness, for example, are not expected to change beyond the limits of present variability. The climate change impacts will be less dramatic, but this is not to say that there will be no concerns. Small changes in temperature and water availability may make the difference between survival and loss of a rare plant or a distinctive plant community, which may be an important factor in the uniqueness and significance of a particular garden.

5.2.3 POTENTIAL EFFECTS OF LONGER TERM EXTREME CLIMATE CHANGE

In the most extreme case, maintaining original, historically authentic trees species and varieties may not be possible. Recent storms in the north have resulted in the loss of many fine specimens and champions of Douglas fir (*Pseudotsuga menziesii*) at Cragside, Northumberland. This damage may have been due as much to the fact that the trees have grown to the limit determined by current gale incidence, as to increases in gales themselves.

Perversely, such events can have beneficial consequences. The 1987 and 1990 storms devastated many landscape gardens, by toppling the mature trees and overgrown features, but it also created opportunities to rejuvenate the gardens through carefully planned repair and restoration programmes. A body of expertise and skills on historic park and garden restoration has developed from the storm damage work. However, the cost implications of the storms for owners and the Government were significant. English Heritage, alone, released £4 million of grants for storm damage related repair programmes to historic parks and gardens (English Heritage, 1997).

Repeated and prolonged summer droughts, as are projected especially for the south, could turn large areas of parkland brown, threatening their aesthetic appeal, grassland flora and fauna, grazing regimes, and agricultural income. Longer-lived tree species may also be threatened, especially the beech (*Fagus sylvatica*), a characteristic and important component of many southern gardens and parks, such as Ashridge (Hertfordshire), on the thin chalky soils of the Chilterns. The serene verdant English parkland we have become used to could disappear.

In the longer term, there may well be situations in which, because of climate change, a whole garden is at risk of being destroyed by inundation as sea levels rise or by increasing incidents of flooding, if the frequency of heavy rainstorms increases. In such circumstances, 'managed retreat' will be the only viable option, and it will only be possible to 'preserve' the garden as an archaeological site, unless the garden is of such importance and the resources so freely available that defensive measures, such as a wall or earth bund are possible. The financial ramifications of such protection, especially if a lengthy stretch of river bank is involved, as is the case at Westbury Court on the River Severn (Gloucestershire), will be considerable; and the context of the historic garden will be altered. Social and economic considerations will also have to be considered, with some gardens in flood plains possibly being 'sacrificed' to ensure the protection of upstream urban communities. Conversely, there will be garden management issues like flood waters washing soil and nutrients into ornamental lakes, and creating algal blooms which can be damaging to human health or animal life, as well as being unpleasant, difficult and expensive to resolve.

Historically important plant collections, with original introductions from known collectors for example, pose a particular challenge if climate change threatens the survival of unique trees. Exact repetition of a planting scheme may not be possible, and anyway can be argued to be seldom desirable for, for example, plant hygiene reasons. Where accurate replanting is desirable, such as with a formal avenue, and where the tree species or varieties can no longer be grown easily, it will be necessary to rethink the conservation policies for these design elements of the garden.

Where a particular species is considered of the greatest importance, it may be propagated and replanted, if necessary in a more favourable position in the garden or even elsewhere in the UK (requiring coordination between owners and organisations). This is a sensible insurance against accidental loss, regardless of climate change. Where the particular specimen is important because of its age, position or historical associations, good cultivation (aeration of the soil, mulching, removal of competing grass, irrigation) may extend its life.

In very general terms, architectural gardens that rely on terraces, steps, balustrades and fountains for much of their drama will be less obviously affected by climate change, than will plantsman's gardens. Architectural garden features may suffer from settlement problems and cracking of walls and steps on some soils in hotter and drier conditions. Such damage will usually be much more expensive to repair, but the costs could be countered by reduced frost damage in winter. English Heritage has commissioned UCL's Centre for Sustainable Heritage to develop a method for understanding and assessing climate change risk for the historic environment, and to identify further areas of research.

5.2.4 BOTANIC GARDENS

Botanic gardens constitute a particularly interesting group, as most of the major botanic gardens in the UK are simultaneously heritage landscapes and outdoor laboratories, expanding our knowledge of plants – as is the case with the Royal Botanic Gardens, Kew. Many of the most notable plants are of great age and some have important historical associations, so climate change may have impacts on the heritage aspects of the garden. Historically, however, botanic gardens have had to be intensively managed in order to grow the widest possible range of plants in the living collections. The ethos and skills to deal with management challenges (including the potential challenges associated with climate change) already exists within these gardens, although there may be additional costs such as irrigation.

There will also be the advantage, for many botanic gardens, in being able to grow a wider range of plant than hitherto. Several gardens use the most sheltered corners of the garden (eg, narrow south-facing borders against the glasshouse range) – to grow the least hardy plants. With a general warming of the climate, these plants may be able to move into the open garden, releasing their locations for even more tender plants.

The advancement and dissemination of knowledge is another important aspect of the botanic garden, so development of the collections is important to the vitality of the garden. Climate change may offer new opportunities for the collections. After the 1987 storm the Royal Botanic Gardens, Kew extended their tree collection to include more species better suited to increasing temperatures. The botanic garden at the University of Cambridge has developed a dry garden as an example of 'waterwise' gardening.

5.2.5 MANAGING HISTORIC PARKS AND GARDENS THROUGH CLIMATE CHANGE

Garden conservation management plans are already extensively used as practical tools to develop conservation policies and to monitor ongoing management and maintenance. These plans could readily be used to appraise climate change impact risks, adjust conservation policies accordingly, and to measure cumulative effects. Managing the effects of climate change could also impact on the use of surrounding land, its character and landscape setting for individual gardens. Management agreements could be used to develop cooperative approaches to larger scale land management, to ameliorate climate change impact such as flood prevention schemes which, in turn, could bring benefits for individual gardens through the control of soil and nutrients being washed into lakes and streams. Specific measures, like silt traps for mirror lakes, will be an essential and incur additional costs to build and maintain.

Britain's historic gardens and parks were mostly developed during a climate that itself is becoming historic, therefore adaptation in future will be unavoidable. If anything of the original effects and layouts are to be conserved in perpetuity, changing and/or more intensive maintenance regimes will have to be introduced, accepting the cost implications arising. Greater coordination will be required between organisations and owners, to ensure the conservation of the country's valuable plant collections for future generations. In all cases, managing gardens is about managing natural processes, including the human desire for change. Extreme climate change will make such changes common place and so challenge the way we think about our historic gardens, what we expect of them and what we mean by conservation.

Garden management in a changing climate

In this chapter, the components of a garden are taken individually and the potential impacts of climate change on each are considered in relation to the domestic and the heritage garden. Some of the costs associated with managing the impacts of climate change in gardens are identified in Box 6.1 at the end of this chapter.

6.1 Climate change impacts on soil

While much attention has been paid to changes in the aerial environment in response to climate change, our review suggests there has been much less work on soil. Soil changes brought about by climate change will have a very profound influence on plant growth, and garden management and use. These issues are considered briefly here.

The total carbon content of world soils is nearly three times that of above ground biomass, and twice that of the atmosphere (Piccolo and Teshale, 1998) (Figure 16).

Soils under arable cultivation have only 15-20% of the humus content of forest or grassland soils. On a world scale, the conversion of forests and grasslands to cultivated arable has had a major impact in reducing soil carbon content, contributing significantly to the increased carbon dioxide levels in the atmosphere, and hence to climate change. The importance of the soil as a sink for atmospheric carbon (Lal, 2000; Pearce, 1998), the effect of climate change on the soil itself (Norby and Jackson, 2000) and the vulnerability of organic soils (Bragg and Tallis, 2001) and wetlands (Winter, 2000), have all been considered to some extent at the agricultural level and in natural ecosystems, but these topics apply equally in gardens.

Changes in atmospheric levels of carbon dioxide will, in itself, not have a significant impact on soils, because carbon dioxide diffuses from the soil into the atmosphere, rather than from atmosphere to soil. The higher temperatures resulting from climate change will be more important. As soil temperature increases, so does the rate of biological activity in the soil. Higher temperatures typically result in increased breakdown of soil organic matter, releasing available nitrogen in the process and thus increasing plant growth (Medlyn *et al*., 2000).

However, higher air temperatures will substantially increase evapo-transpiration by plants, thereby reducing soil moisture content. In experiments at Cambridge, a 3°C increase in soil temperature caused a 30% increase in evapo-transpiration (Jeffery, 2001) and a 25% decrease in soil moisture (Harte *et al*., 1995). The UKCIP02 scenarios all point to higher soil moisture deficits over increasingly longer periods across the UK in the future. In conditions of extreme drought, this will result in cessation of organic matter breakdown. However, for most of the time, soils will retain some moisture, and the combination of increased aeration (air replacing water in the larger soil pores) and increased temperature will accelerate loss of soil carbon by oxidation to carbon dioxide.

Loss of soil carbon, as organic material is broken down, also results in release and mobilisation of soil nitrogen. Intermittent wetting and drying in early autumn causes accumulation of soil nitrate and, when the soil is once again at field capacity, leaching of this nitrate is increased. Jeffery (2001) measured a 47% reduction in the volume of drainage from soils heated to 3°C above ambient, but a doubling of nitrate loss in drainage water. Imposition of a two month drought during the experiments increased nitrogen loss from the soil, when the drought ended.

The principal effects of climate change on soils will be to accelerate loss of soil organic matter and to release nutrients in increasing amounts. These increases in oxidation of soil organic matter and mobilisation of soil nitrogen cannot continue indefinitely. If not replaced by natural processes or during cultivation, carbon content and nutrient status of the soil will be diminished, causing loss of fertility. Broadmeadow (2002a) suggests that microbial breakdown of leaf litter with increased carbon:nitrogen ratios, as plants fix atmospheric carbon dioxide in a scenario of reduced availability of soil nitrogen, will result in further reductions of available soil nitrogen to the point that plant growth will be adversely affected.

Loss of organic matter will also result in loss of soil structure. The soil therefore becomes more susceptible to wind erosion in the drier summers anticipated by the climate change scenarios, and less permeable to water, leading to increased water erosion and run-off in the heavier downpours of wetter winters (Piccolo, 1998).

When mobilisation of soil nitrogen coincides with a slowing of plant growth in the autumn, much of the nitrate will be lost from the soil in drainage water, possibly causing problems elsewhere in pollution of streams, ponds and lakes and adding to the problems being caused by increasing levels of nitrous oxide present in the atmosphere (see section 6.2.2).

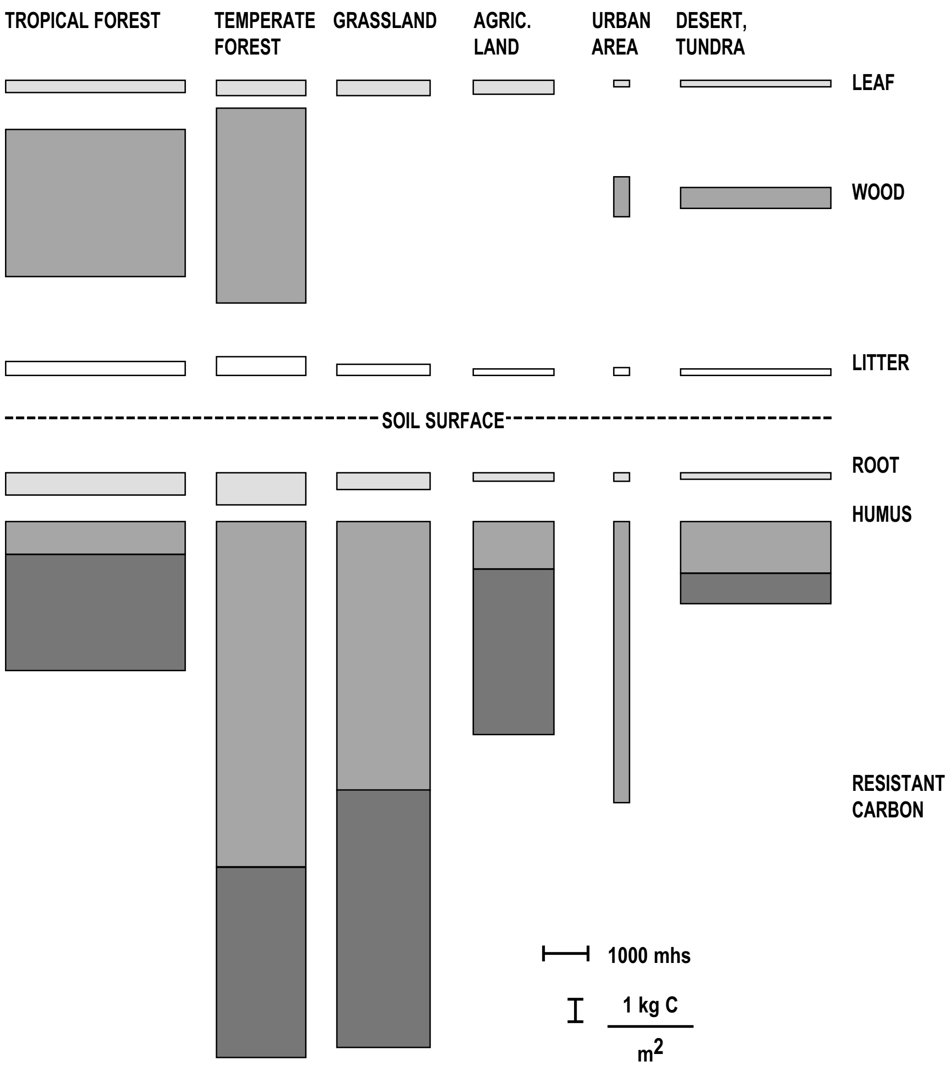

Figure 16: Carbon in the soil as compared to carbon stored in land cover. *Source: Piccolo, 1996.*

6.1.1 Climate change impacts on particular soils

The local effects of these changes on gardens will depend on soil type. In light, freely drained soils the increased biological activity in warmer and wetter winter months will lead to increasingly rapid loss of organic matter, and thus to increased susceptibility to erosion. Organic matter loss will also reduce waterholding capacity of the soil and further accelerate and exacerbate effects of summer drought as summer rainfall decreases.

Highly organic soils are at risk of rapid oxidation as the combined effects of increased evapo-transpiration and reduced summer rainfall lead to aeration of previously waterlogged profiles. The most dramatic example of this is in the East Anglian fens, where soil levels have dropped by tens of metres since the area was drained for cultivation in the 17th century. The loss, both by oxidation and wind erosion, is continuing to the extent that large areas will soon be unsuitable for commercial crop production.

A similar, though less visible, problem exists in upland areas where increasing oxidation of peat soils will not only affect the natural vegetation in SSSI and other designated areas, but may expose archaeological remains which are important cultural components of many parkland and garden landscapes (Farrar and Vaze, 2000).

Heavy soils may retain sufficient water and nutrients to sustain plant growth through the summer months, despite the drier regime, though on very retentive clay soils water available to plants will be much less than that held by the soil. However, these heavy soils may suffer from waterlogging in winter.

One obvious sensible response to climate change will be to work within constraints imposed by soil conditions. The need, also, to maintain or improve soil organic matter content, and hence its waterholding capacity, and to ensure adequate drainage, can not be over-emphasised.

i) Domestic gardens

The soil in the smaller, domestic garden is likely to have been much modified from the natural state during construction of the house and other built structures, such as drains, paths and driveways. There is potential for soil improvements to be made to minimise the effects of climate change. For example, the structure and nutritional status of soils can be improved by incorporating organic material and by mulching to reduce loss of organic matter as temperatures increase. Incorporation of grit or the construction of raised beds can counter the risk of waterlogging from heavy winter rains.

Such treatments will also ameliorate the impact of increased drought and increase the infiltration of heavy rainfall. The cost per square metre of these treatments, especially if materials are bought in small units at retail prices, will be very high, but the area to be treated will generally be small.

ii) Heritage gardens

There may be some scope for soil amendment and improvement in the intensively managed parts of heritage gardens, as in the domestic garden. The availability of leaf litter and other organic waste, and the availability of machinery for shredding, composting, transporting and incorporating organic matter will make handling relatively easier than in the domestic garden, though at considerable capital cost.

In less intensively managed areas, the prevention or reversal of soil deterioration will depend on maintenance of plant cover, retention of fallen leaves (perhaps using strategically placed plant groups to minimise wind-blow of leaves onto paths or lawns) and, where acceptable, return of lawn clippings to maintain organic matter levels and an open soil surface.

On slopes, it may be necessary to use interceptor gullies and soakaways to reduce soil erosion risks. Regular maintenance, perhaps upgrading and renewal of drainage systems will also be necessary.

Traditional gardening techniques have always been directed at maintaining fertile, water retentive, but well-aerated soil. The challenge in the 21st century will be to continue that tradition in the face of limited and often dwindling resources.

The reduction of soil carbon by clearing forests and ploughing grassland has been a major contributor to climate change. Soils are, in turn, significantly affected by climate change. Many factors interact in determining the soil's susceptibility to climate change.

Increase in temperature will increase the rate of loss of soil carbon by oxidation. This will lead to loss of soil structure and loss of permeability, so intense rainfalls may cause run-off (and therefore erosion and flooding) rather than the recharge of soil moisture reserves. Oxidation of soil organic matter also releases nitrates, which may increase plant growth, or leach out of the soil to pollute rivers and lakes.

Decreased rainfall will slow conversion of soil carbon to carbon dioxide, but the relationship is complicated and effect will differ from day to day. Usually, plants will cease to take up water (and therefore nitrates) from the soil before the soil has dried to the extent that organic matter breakdown stops. Nitrates will therefore accumulate in the soil and be leached out in heavy rains.

Highly organic soils, in fen and moorland areas, will be most susceptible to climate change and may lose their ability to support their characteristic vegetation.

Any action which increases soil organic matter will help to reduce all these problems and thereby will reduce the cause, as well as the impact, of climate change. Caring for and covering the soil will play a significant role in countering the adverse impacts of climate change.

6.2 Climate change impacts on water

Water exists in two forms in gardens: water supplies are used for irrigation; water features provide aesthetic, and often ecological and productive, benefits. In practice the two components are often linked. At the simplest level, a hosepipe (water supply) can be used to top up a garden pond, while the pond (a water body) can be used to fill a watering can. On a larger scale, a borehole might be used to fill a lake, while a lake or stream might provide a water supply for irrigation or domestic use.

The availability of water for use and its presence in water features is determined by the hydrological cycle. A very brief and much simplified description of the cycle is provided in Box 6.2, to set the important topic of climate change impacts on water into context.

6.2.1 WATER SUPPLIES

Water supply for human use may be obtained by taking water directly from rivers or by pumping it from underground aquifers. As river flows are uneven and demand is more or less even throughout the year, it becomes necessary to impound and store water in reservoirs, so that large flows in winter can be used to meet large demands through the summer. This is particularly the case in the more hilly and rocky parts of the country, where most water runs off the surface into streams rather than soaking into the soil, so stream flow is most variable.

Much of the water supply in the UK is provided from private water companies on a regional basis, but some users have their own private water supply, either directly from a river or, more commonly, by pumping from a borehole (Table 4). Such extractions require a licence.

Total water abstractions declined between 1971 and 1991 as a result of the closure of old, watercooled power stations and the decline of heavy industry (Table 4). Indeed the water table is rising under major cities in the UK as a result of this decline, threatening an increased risk of flooding and a danger of pollution of water supplies, as the water table rises through industrially polluted soils (Shackley and Wood, 1998). In the same period, public water supply increased from 14-18 billion litres per day, an increase from 34%-51% of total water abstractions, partly as a response to some increase in population, but mainly as a result of higher living standards.

The direct impact of climate change on overall demand for water is expected to be rather small. The main uses of water – for cooling of power stations in industry, and domestically for flushing toilets and washing clothes – will be little affected by climate change. The likelihood, though, of reduced supply as a result of climate change will present challenges in

Box 6.2 The Hydrological Cycle

The primary source of water supply is from precipitation. Water reaching the soil surface will either be absorbed into the surface or will run off. Water filtering down through the soil and underlying rocks will eventually reach an impermeable layer, above which it will accumulate to form an underground zone in which pores in the rock are more or less saturated with water. This natural reservoir is called an aquifer, and the level of water in the aquifer is the water table.

Because of inequalities in the soil and in the underlying rocks, this water table will sometimes reach the soil surface and the water will bubble out as a spring. For example, where a thick stratum of chalk (a very porous rock) overlies impervious clay, water will accumulate on top of the clay layer and emerge wherever the chalk/clay interface is exposed at the ground surface, to form a line of springs along a hillside. Water from the springs will flow down hill in streams. These streams meet each other and build into rivers, which make their way down to the sea.

It usually takes months or years for a drop of water arriving at the soil surface to filter down through the soil to the water table and then to emerge at the surface again, so short term fluctuations in precipitation are evened out and the output from springs is much less variable than is the input of rainfall. There will be a gradual increase of stream levels in winter, and a gradual decline in summer but day to day fluctuations are eliminated.

If water does not soak into the soil, but instead runs across the surface, it will flow down hill carrying with it soil particles. Trickles of water coalesce to form runnels, then streamlets and streams. Erosion of the land, as soil particles are carried down by the water, creates channels which determine the future course of the streams. As these channels become more clearly defined, the concentration of water increases and, with it, the ability to carry more sediment, including larger stones and rocks.

Surface run-off feeds into streams quickly, so the level and force of the stream will increase rapidly during periods of rainfall and decrease equally quickly when the rain stops. In heavy rains, the stream channel will be inadequate to carry the extra volume of water; the water will flood onto surrounding land, depositing most of the silt it carries and, in time, building up a flood plain. Some of the flood water will drain back into the stream as its level drops. Some will soak into the surface to replenish the water table. By eroding and depositing soil, the stream will gradually reshape the landscape.

In a natural ecosystem, rivers and streams will have a more or less steady base flow of water emerging from springs throughout the year, supplemented by short term increases of water from run-off after periods of rain or snow-melt. If the land surface is made less pervious, by compacting the surface or by covering it with concrete or tarmac, for example, infiltration and the steady base flow will be reduced, and the flash flows after rainfall will increase. The long term effects of this are to increase the risk of flooding, and to deplete groundwater reserves which feed the steady flow of streams and rivers.

Loss of groundwater is exacerbated by extraction for domestic, industrial and agricultural use. Decrease in surface permeability as a result of development also increases the sensitivity of the hydrological system to short term heavy downpours, and so greatly increases the risk of sudden floods in heavy rainstorms. Flooding is further exacerbated by channelling water into drains and river channels, which pass the problem more rapidly downstream. Every step in the process, from absorbent forest soil, to grassland, to bare arable soil, to tarmac accelerates and exacerbates the change from steady year-round flow of rivers and streams, to the sudden oscillations from spates after rainfall, to low base flows, and intensifies the problems of insufficient water supply to dilute pollutants. In the most extreme cases, streams will dry up completely in dry periods then turn into raging torrents for a few hours or days after heavy rainstorms.

Climate change is likely to intensify the hydrological cycle. Rates of evaporation will increase due to higher temperatures, variability of precipitation will increase (with increases in winter and decreases in spring, summer and autumn), as will variability of run-off owing to more intense rainfall. Water and soil management will be inextricably combined when protecting gardens and the wider landscape from the adverse effects of climate change. Increasing the humus content of the soil will help to reduce the vulnerability of soils to erosion, and to increase their capacity to absorb heavy rainfalls which might otherwise cause flooding.

Table 4: Licensed non-tidal water abstractions in England and Wales, 1971-1991. *Source: Herrington, 1996*

Year	Public Water Supply		Industry		Spray Irrigation		Agriculture		Electricity Generation		Fish farming and watercress production		Total
	Ml/d	% of total	Ml/d	% of total	Ml/d	% of total	Ml/d	% of total	Ml/d	% of total	Ml/d	% of total	Ml/d
1971	14345	33.60	9214	21.58	68	0.16	170	0.40	18896	44.26			42693
1972	14797	34.97	9162	21.65	63	0.15	170	0.40	18118	42.82			42310
1973	15252	36.41	8658	20.67	58	0.14	156	0.37	17767	42.41			41891
1974	15155	40.55	7080	18.94	78	0.21	76	0.20	14988	40.10			37377
1975	15360	42.86	6560	18.30	111	0.31	94	0.26	13714	38.27			35839
1976	15009	42.72	6655	18.94	161	0.46	96	0.27	13211	37.60			35152
1977	14747	41.72	6958	19.68	116	0.33	120	0.34	13406	37.93			35347
1978	15828	44.94	6626	18.81	81	0.23	150	0.43	12539	35.60			35224
1979	16267	45.20	6762	18.79	106	0.29	140	0.39	12710	35.32			35985
1980	16186	46.87	5034	14.58	92	0.27	133	0.39	13087	37.90			34532
1981	16105	48.05	4973	14.84	117	0.35	111	0.33	12208	36.43			33514
1982	16331	48.21	4729	13.96	139	0.41	117	0.35	11587	34.21	970	2.86	33873
1983	16224	48.06	4093	12.13	171	0.51	118	0.35	12179	36.08	971	2.88	33756
1984	16402	49.05	3892	11.64	199	0.60	122	0.36	11757	35.16	1066	3.19	33438
1985	16641	50.95	3939	12.06	137	0.42	130	0.40	10711	32.79	1105	3.38	32663
1986	16592	47.69	4114	11.83	167	0.48	125	0.36	12744	36.63	1048	3.01	34790
1987	17244	49.16	3712	10.58	102	0.29	122	0.35	12806	36.51	1089	3.10	35075
1988	17597	51.21	3901	11.35	144	0.42	120	0.35	11787	34.30	815	2.37	34364
1989	18205	51.64	3654	10.36	298	0.85	115	0.33	12189	34.57	794	2.25	35255
1990	18336	50.66	3795	10.49	378	1.04	129	0.36	12612	34.84	946	2.61	36196
1991	18181	50.78	3800	10.61	365	1.02	134	0.37	12430	34.72	895	2.50	35805

meeting even a modest anticipated increase in demand. The UKCIP02 scenarios all point to greater water deficits in summer and autumn months.

In terms of impact on overall demand for water, the horticultural industry, gardens and golf courses are, and will continue to be, of minor importance.

Water used by farmers and commercial growers for irrigation increased erratically from 68 million litres per day (Ml/d) in 1974 to between 100-200 Ml/d in the period 1974-1988 then rose rapidly to 365 Ml/d in 1991. This increase was a result of general intensification of farming, and the demand from the new supermarkets for regular and predictable supplies of high-quality vegetables, as well as the need for increased irrigation in hot, dry summers. It is not possible to separate out the effects of increased sophistication of production systems from increased need to match higher evaporation levels resulting from climate change, but the total increase represents a change from using 0.16% of the public water supply for irrigation in 1974 to using 1% in 1991. This is a very small proportion but a six-fold increase.

Domestic use in the south and east of England for lawn sprinkling increased from 0.1 litres per capita per day (l/c/d) in 1976 to 4.3 l/c/d in 2001 and, ignoring any effect of climate change, is estimated to rise to 8.7 l/c/d by 2021 (Table 5). The statistics for other garden uses are 1.1, 4.8 and 7.2 l/c/d respectively.

This rapid rise is associated with increased ownership and use of sprinklers, but the extent to which this reflects climate change impacts, as distinct from a general increase in the standard of living (ability to afford sprinklers and time to use them) and in appreciation of gardens, is again uncertain. While the change from 1.2 l/c/d in 1976 to 9.1 l/c/d in 2001 and 15.9 l/c/d in 2021 for lawn and garden watering represents a very large proportional increase it is, and will remain, less then use for personal washing (33.5, 46.5 and 61.6 l/c/d) and represents a change from 1% (1976) to 4.3% (1991) to 8.9% (2021) of total domestic demand in the south east, the driest part of the country.

In his analysis of domestic demand components of water supply for non-metropolitan south and east England 1991/2021, Herrington (1996) calculates that, with a 1.1° rise in temperature by 2021, water use for lawn sprinkling will increase by 35% and for other garden uses by nearly 20%.

Golf courses, with their need to create smooth greens and the current cultural insistence on a lush green setting, are conspicuous consumers of water but, in a national context, not highly significant. An

Table 5: Domestic demand components of water supply for non-metropolitan south and east England in 1981 and 2021 incorporating climate change. *Source: Herrington, 1996*

Component	**1991** **Climate standardised**	**2021** **No climate change**	**2021** **+1.1°C warming**
WC use	35.5	33.6	33.6
Showering	5.3	24.0	26.8
Other personal washing	41.2	37.6	37.6
Clothes washing	21.7	22.0	22.0
Dish washing	11.8	11.0	11.0
Waste disposal unit	0.4	1.5	1.5
Car washing	0.9	1.5	1.5
Lawn sprinkling	2.5	8.7	11.8
Other garden use	3.8	7.2	8.6
Miscellaneous use	23.9	31.3	31.3
Total domestic use	**147.0**	**178.4**	**185.6**

average golf course using the public water supply uses 2.7 million litres of water annually (Table 6). Assuming some increase in the number of golf courses, Herrington (1996) estimates that water demand in the south east for irrigation of golf courses might increase from 3.3 Ml/d (1992) to 4.8 Ml/d (2021) in the absence of climate change.

A 1.1°C increase in temperature by 2021, and a 2.1°C increase by 2051 (similar to temperature changes projected under the UKCIP02 medium high emissions scenario) is expected to add 4% (by 2021) or 8% (by 2051) to the requirements which would be expected in the absence of climate change. This 8% increase compares with estimates of 11.8% increase for agricultural irrigation, and 37.5% increase for air-conditioning. The total of 5 Ml/d estimated water use by golf courses in the south east in 2021 with moderate climate change, represents less than 0.1% of domestic water consumption and is therefore insignificant in terms of the total amount of water used.

These various horticultural uses of water are not large in relation to overall consumption then, but when seasonality of water supplies and peak demands in water use are taken into account, a very different picture emerges.

Not only are the levels of demand increasing rapidly, but the maximum demand for water for horticultural use occurs when water is least available. In a hot year, a golf course increases its water consumption by 40% over use in an average year (Herrington, 1996). Calculations of garden use of water in the Thames and Lee Valley catchments, suggest that public water supplies will need to increase by 1.2% to meet increases in demand related to climate change by 2050 on an annual basis, but this represents a 3-4% increase in demand for the six months April-September, or 7-8% for June-July. In East Anglia, 3% of annual water use in an average household was used in the garden in the wet year of 2001 (Chivers, *pers. comm.*). This figure was 6% in the dry year of 1996. Concentrated in the two driest months, the peak demand may rise to 25% above the average level of water use.

The situation is made worse by the fact that water applied to gardens, unlike water used in washing machines, baths and other household uses, is not returned quickly to replenish river flows. Although in the long term, water for horticultural (and agricultural) use is recycled *via* the hydrological cycle, replenishing the water table by infiltration or recharging clouds by evaporation from plants, substantial extraction of water for irrigation will lead in the short term to falling river levels.

The impacts *of* gardens *on* water demand as a result of climate change will, therefore, be a modest increase in total demand for water, but a very marked increase in peak demand in hot, dry summers. As climate change continues beyond 2050, and as expectations of gardens continue to rise, water use for gardens may cease to be a minor proportion of total domestic demand. Sales of garden watering equipment have risen from £21 million to

Table 6: South and east England golf course water use in 1992 and 2021, without and with climate change (numbers of courses and demand for water). PWS = Public Water Supply; DA = Direct Abstraction.
Source: Herrington, 1996

	1992 No climate change	2021 No climate change	2021 With climate change
PWS only	368 @ 2.70 Ml	546 + 55 @ 2.70 Ml	546 + 55 @ 2.81 Ml
DAs only	288 @ 3.64 Ml	427 + 43 @ 3.64 Ml	427 + 43 @ 3.79
Ml Mixed: PWS	144 @ 1.35 Ml	214 + 22 @ 1.35 Ml	214 + 22 @ 1.40 Ml
Mixed: DAs	144 @ 1.82 Ml	214 + 22 @ 1.82 Ml	214 + 22 @ 1.89 Ml
Total no. of courses	800	1187 + 120	1187 + 120
Water use: PWS	1188 Ml = 3.3 Ml/d	4.8 + 0.5 Ml/d	5.0 + 0.5 Ml/d
Water use: DAs	1310 Ml = 3.6 Ml/d	5.3 + 0.6 Mld	5.5 + Ml/d

£61 million in the past four years but ownership in the UK is still considerably below that of France and Germany, despite the higher proportion of people living in flats in those countries (Ofwat, 2002).

To adapt to these changes, either demand will need to be suppressed, by hosepipe bans or pricing structures, for example, or supplies will need to be increased, mainly by the construction of increasingly expensive reservoirs and in the face of increasing environmental opposition.

The impacts *on* gardens as a result of increasing deficits of natural water supply will come both directly, as a result of reduced rainfall and increased evaporation within the garden, and indirectly as a result of reduced availability or increased cost of water in the public supply system. Water shortage is likely to be the most serious single impact of climate change on gardens. In addition to damage to plants, especially to mature trees, summer drying or serious depletion of lakes in landscape parks is an increasingly frequent phenomenon, usually with serious ecological consequences as well as loss of visual amenity.

Deficits in natural supplies will occur in a context of decreasing availability to the water suppliers and increasing demand for water for other uses, primarily as a result of increased living standards. Gardeners could respond to these deficits in a number of ways. Planting schemes could be adapted to incorporate drought tolerant species (see sections 3.4, 4.2 and 6.3-6.8). Irrigation could be applied, although water for irrigation is likely to become more expensive and perhaps increasingly stringently controlled. Water could also be stored during wet periods to compensate for times of shortage

Water storage could take the form of improved water retention in soil, by mulching and increasing organic matter content, or by installing rain water butts, recycling of 'grey' water from baths and washing machines or, on a larger scale, by building reservoirs. Increasingly, users of large volumes of water (farmers, golf courses, nurseries) are building private reservoirs so that they can store (and in the case of nurseries recycle) water for use in times of shortage. Farm reservoir capacity nearly doubled between 1984 and 1995, from 33 million to 64 million cubic metres. This provides about 40% of the current water supply needed for irrigation. A further 30 million cubic metres of storage capacity would cost between £13 million and £73 million depending on individual site conditions (Orson, 1999).

Most such reservoirs are purely functional, regular in shape, steep sided and often fenced for safety. If the land and resources are available, there is no reason why they should not be designed as visually attractive ponds and lakes that could also look attractive (or at least acceptable) when the water level drops during peak extraction periods. The investment might well be worthwhile in large gardens threatened by water shortage. A 45,000m^3 reservoir has recently (September 2002) been completed in The Royal Horticultural Society's garden at Hyde Hall (Essex) as the central feature of a new environmental area.

Although the use of water butts in domestic gardens might seem a trivial response to climate change, the widespread application of such conservation measures could have a significant impact in reducing peak demands for water. This dispersed storage could also be more economic than centralised provision of expensive and environmentally sensitive reservoirs (Entec, 2000).

Irrigation systems are already being installed in many public and private gardens and are considered to be an essential feature of any new golf course. Irrigation to reduce the impact of water deficits will be subject to availability of sufficient water resources. Continued climate change is likely to result in increasingly stringent control of extraction – perhaps even in the withdrawal of extraction licences – higher cost of water, and the possibility of restrictions on garden use in prolonged droughts, when water is most urgently needed. Trickle irrigation systems and leaky hose, or other surface and sub-surface systems, will economise on water loss by evaporation. But, reducing dependence on external water supplies and prioritising key areas of the garden which most need irrigation, will be increasingly important responses as climate changes intensify.

While reduced precipitation in the summer months will cause increasing shortages of water during the growing season, higher precipitation rates in winter may cause unwanted surpluses. A recent flash flood at Wallington (Northumberland) for example resulted in the collapse of a 17th century garden wall. The sudden release of floodwaters built up behind the wall, then caused severe erosion of paths and borders in the garden. On a wider scale, extensive floods in the winter of 2000/01, which filled news bulletins for many weeks, caused huge losses of property and widespread damage to gardens. The increased volume and intensity of winter precipitation anticipated by the UKCIP02 scenarios is likely to increase flood risk in future. The scale of damage caused by recent flooding events suggests that it would be wise to prepare for similar future events, while the experience gained is still fresh in the mind.

Adaptations might include physical protection of the garden, where possible, by earth mounding or, during Environment Agency flood alerts, preparing sand bags. Safety measures include ensuring that power points, water and gas taps, mower fuel and garden chemicals are installed/stored above anticipated flood levels. Any measures which will slow the flow of water through a garden (encouraging infiltration rather than run-off), or channel water to areas where it will cause least damage, will be worthwhile especially if the surplus can be stored for future use. Where parts of a garden flood regularly, terracing or decking above expected flood levels will allow access through the garden without treading on saturated lawns. Ensuring that drainage systems (open or piped) are in good condition and that the soil is in good physical condition to absorb water and resist erosion, are sensible aspects of garden management, even if floods are not anticipated. Reclamation of the garden in the aftermath of flooding is usefully described in the Environmental Agency booklet *Flooding in Gardens* (Environment Agency, 2002).

Modification of the long term composition of the garden in response to flood threats will usually not be advisable, except in those situations in which serious flooding has occurred in the recent past and there is some evidence that the frequency of flooding is increasing. Most plants which are tolerant of flooding are not tolerant of dry conditions, and drought as a result of climate change poses a much more serious threat to gardens than does flooding.

Water will be less available in summer, when it is most needed to sustain plant growth, and more abundant in winter. If water extraction increases (for domestic use and for irrigation) the water table will drop and steady river flows will be reduced. The likely impact of climate change will be lower summer flows in streams and rivers but sudden increases in water level after heavy rain. This trend will be exacerbated by urbanisation, and the damage resulting from it will be increased if houses and gardens are established on flood plains.

Although, as yet, a very minor component of total water demand, water demand for irrigation of gardens and golf courses will increase rapidly (it increased six-fold between 1974 and 1991), and concentration of demand into the hottest, driest months may increase peak demands by 25% in the south east. Where demand can not be met, the result will be reduced pressure, or restrictions in use and, in the longer term, higher costs to pay for new water supply infrastructure.

6.2.2 WATER FEATURES

Water in the garden, whether a bird bath in a tiny courtyard or a lake in a Capability Brown landscape, is a very attractive feature, both in itself and in the wildlife which is attracted even to the smallest water feature. Water features require a reliable supply of water, natural or piped.

The main impact of climate change on all water bodies will be increased evaporation from the surface. This will result in the need to top up water levels, by hosepipe or by borehole if permissible. A secondary effect of using tap water to refill a pond, is that the nitrate content of the water will encourage unwanted weed growth. Ponds and lakes relying on a natural water supply to keep them full will be at risk of drying out in hot, dry summers.

Higher summer temperatures present a further problem, because oxygen is less soluble in water as the temperature increases, but the demand for oxygen from aquatic organisms increases with temperature. Biological oxygen deficiency therefore increases sharply with temperature. In a balanced ecosystem this de-oxygenation would normally be compensated for by higher rates of photosynthesis in submerged plants, releasing oxygen into the water. However, when higher summer temperatures are combined with excessive nitrates (from accelerated breakdown of soil nitrogen, from increased leaching and erosion of agricultural soils and from increasing atmospheric pollution with nitrous oxides), the vigorous growth of a surface blanket of algae shades out submerged aquatics. As the algae exhaust the nutrient supply and die, breakdown of the dead mass rapidly depletes dissolved oxygen supplies and the water will become eutrophic – stagnant, unhealthy and foul-smelling. The 1990s droughts in Sheffield Park (Sussex), combined with an accumulation of silt, built up from leaf litter and part caused by soil washed off surrounding farmland in heavy storms, led to serious algal blooms. The cost of dredging to rectify the problem amounted to £40,000 (Calnan, *pers. comm.*; Owen, 2002).

Management of water bodies is a complex matter. Shading of the surface by tree planting will help to reduce surface temperatures, which could become warm enough in future to kill fish populations. But autumn leaf fall from the trees could be detrimental, increasing the amount of organic material falling into the pond or lake. In natural, unlined, ponds, trees will also extract water and exacerbate the fall in water level.

Management of the edge to achieve a gentle gradient and a shelving beach, or transition from marginal vegetation (reeds for example) to deep water, will disguise changes in water level, and the latter especially will add to the biodiversity of the pond. Care will then be needed to ensure that the vegetation itself does not encroach too much on the water surface. Where blanket weed growth and eutrophication become important problems, surface skimming of the water to remove algae will result in immediate improvement, though at considerable effort on any substantial scale. Oxygenation of water using fountains or cascades, or air pumped through submerged porous pipes where decorative treatment of water is considered inappropriate, will improve water quality.

Running water bodies – streams and rivers – are also at risk of falling water levels in periods of reduced precipitation and high evaporation rates. The River Pang near Reading has dried out completely in recent, hot summers because of reduced rainfall and increased abstraction, spoiling the appearance of gardens through which it runs, but with much more serious loss to fish and other life.

On a garden scale, the problem of reduced water volumes is not easy to counter, except by pumping from elsewhere – usually at substantial cost and often at the risk of depriving other areas of much needed water. Reshaping of the stream bed, or construction of weirs so that the stream forms a chain of small ponds as water levels drop, will provide some refuge for water life until such time as rainfall restores the natural water flow.

Water bodies may also have to cope with periods of excess supply. Increases of water volume, through more intense and more prolonged rains, may cause scouring of the stream bed, overflow of banks or dams, loss of marginal plants and fish, and flooding of adjacent land. There is also a risk that flooding of garden ponds could release exotic water plants into adjacent streams, and thus into the wider landscape. Water flooding across farmland, the overflow of 19th century combined storm and sanitary sewers, and the flooding of septic tanks, can cause pollution of the water and contamination of water supplies.

The more natural the stream profile, with meanders, shallows and abundant marginal vegetation, the more able it will be to withstand fluctuations in water throughput. Engineering efforts to clean out the stream, to straighten and deepen the channel and to engineer the banks by removing vegetation, may solve a local problem but only by moving the problem even more rapidly downstream. Impeding water flow and diverting surplus water into areas which can safely be flooded temporarily (holding areas, silt traps and balancing ponds), will provide a far more effective and durable response. Such areas can usually be designed to increase biodiversity and visual interest.

The whole strategy of coping with the impacts of climate change, and especially in its effects on water supplies and water bodies, will need to rely on learning lessons from nature rather than trying to overrule it. Response to these alternating deficits and surfeits of water will require careful management of water flow and water quality. Techniques might include impounding run-off, recycling irrigation water and using grey water where possible, combined with land contouring, improving soil structure and better drain maintenance

6.2.3 WATER MANAGEMENT

i) Domestic gardens

The impacts of climate change on water supply to the domestic garden will be significant, but can be reduced by sound water management using methods described in section 6.2.2. Shortage of water in the summer can be made good by irrigation, preferably using stored water, and concentrating on the most important plants in the event of a prolonged hosepipe ban. Irrigation after dusk, using a timer or by staying up late, and irrigation using seep hose or trickle irrigation, will reduce evaporative losses.

In well managed gardens, surplus water in winter should infiltrate into good garden soil and run off drives, paths and patios onto lawns or borders, or into drains if levels are suitably designed. However, flood risk can be expected to increase in some areas in future (Hulme *et al*., 2002). Advice on how to cope with excess water in the garden is provided by the Environment Agency (2002).

In the long term, it will become advisable to adapt planting schemes to the new climatic regime of the particular area. It would certainly be wise, for example, to replace any plants which consistently suffer from summer drought, but fluctuations of weather will be more important than climate change in the domestic garden, so major changes in planting from year to year as a result of last year's weather damage, would be unwise.

Water bodies in domestic gardens will usually be small in scale, most typically a garden pond. Reduced rainfall and the increased evaporation resulting from higher temperatures will necessitate topping up of the pond. If this can be done using stored rainwater, it will avoid the secondary problem of nutrient enrichment which results if mains water is used. Some reduction of evaporation may be possible by ensuring that about 50% of the water area is shaded by surrounding vegetation.

ii) Heritage gardens

The principal dilemma in managing water supplies in heritage gardens is in deciding how closely it is necessary to adhere to the *status quo*. Key areas of the garden may justify irrigation, in which case a balance must be struck between the high capital cost of a sophisticated and automated system, and the high running costs of a hosepipe or watering can.

As in the domestic garden, maximum use of stored water – water butts, underground water tanks such as those in many old greenhouses or, where development is permissible, surface ponds or reservoirs – may be used.

Reference has already been made (in section 6.1.4) to the possible need for gullies and soakaways to direct excess surface water. Flooding, especially frequent flooding, is not often a problem in heritage gardens of the 18th century onwards as their creators usually built above flood level. Where flooding is occurring more frequently as a result of climate change or changes in land use, the only remedy is costly intervention to accommodate floodwater, by improving drainage ditches, or to divert it from the most vulnerable areas with earth bunds or other techniques, including perhaps pumping. Regular maintenance of drainage channels is an essential part of garden management. Upgrading of the drainage and flood defence systems may be called for in particular instances where increased flood risk is evident.

The problem of water bodies in heritage gardens as a result of climate change impacts is considerable because, as attractive features, they usually occupy key locations in the landscape. Falling water levels in summer may necessitate a pumped water supply. Barley straw is sometimes effective at reducing algal blooms. Oxygenation by pumping air through perforated hoses on the lake bed can improve water quality and save fish stocks. When appropriate, the creation of wetlands (such as reedbeds) or beaches, will buffer the visual impact of fluctuating water levels, increase the absorption of excess water into the water table and localise the deposition of silt in areas where it can be more easily and cheaply removed than from the lake itself.

Water surplus may result in overtopping of lakes. It is, therefore, very important to ensure regular inspection of dams, sluices and spillways to conform to the requirements of the Reservoirs Act (1974), so that the excess does not cause a threat to life or property.

Decreasing natural flows in summer will result in falling water levels in watercourses, ponds and lakes. This will affect the appearance of the landscape and have more serious consequences for the environment and for fisheries. Average water supplies may increase in winter, and major floods will remain a risk.

Increasing temperatures will also affect water bodies, decreasing dissolved oxygen levels and increasing the risk of algal blooms. Water bodies will, therefore, require more management in future.

6.3 Climate change impacts on trees

As the largest and longest-lived plants in a garden, trees are most vulnerable to the stresses induced by climate change. As complex and long-lived organisms they experience climatic impacts over a long time, sometimes centuries, and any impacts of the benefits or injuries imposed by long term climate change or short term fluctuations in the weather, will be reflected with compound interest as time passes (Ceulemans, 1998).

Root suffocation of cedars in the National Trust's garden at Osterley Park (Middlesex), drowning of beech trees in the lower part of the Royal Horticultural Society's garden at Hyde Hall (Essex) and the loss of fifteen million trees across the south of England in the storm of October 1987 are conspicuous reminders of the value of trees and of the threats facing them. The one night of 16th October 1987 saw a loss of trees equivalent to fifty years of natural tree decline (Rich, 1988).

Fire hazards, especially in coniferous windbreaks or woodland, will increase sharply as temperatures increase and summer droughts extend, although here many factors will interact. Evidence in recent years is that fire risk, not surprisingly, increases in hot, dry summers. The number of outbreaks also increases with increases in visitor pressure (also related to hot, dry summers), as most fires are started accidentally by cigarettes or picnic fires. However, although the number of fires in recent dry summers has increased, the damage caused has declined, because outbreaks are reported and dealt with more rapidly since the advent of the mobile phone.

The most serious threats facing trees are summer drought, possibly winter waterlogging and high winds. There is widespread concern, in particular, about the future prospects for beech (*Fagus sylvatica*). Beech is native to southern England and, under conditions of climate change the natural distribution would be expected to move north and east (Berry *et al*., 2001; Broadmeadow, 2002a, b; Harrison *et al*., 2001) (see Figure 14a in section 4.1). It was, however, extensively planted in the Chilterns and on the North and South Downs following the enclosure of downland in the early 19th century and the abandoning of arable cultivation after 1850 (Piggott, 1988).

Unfortunately, it is unable to tolerate the increasing water stress associated with climate change on these light soils and hilltop situations. There is a strong negative correlation between reduced rainfall in July, and crown density of beech in the following year (Cannell and Sparks, 1999), but the underlying causes of this correlation are complex. Low rainfall (and therefore high light intensity) in one summer, stimulate the beech to produce a heavy crop of seed (mast) in the following year. Whether this seed production is the plant physiological equivalent of a panic response to drought, or a result of high carbohydrate levels in the sunny year enabling the tree to invest in reproduction in the following year is uncertain, but the combined effects of drought stress in one year and the drain on resources of fruiting in the following year is manifest in a thin canopy of small leaves. The tree can take several years to recover and, if another dry summer occurs before this recovery is complete, the tree will go into long term decline.

The impacts of summer drought can be overcome to some extent by irrigation and soil improvement, and especially by replacing highly competitive grass with protective mulch beneath the canopy of the tree. The cost of this on a large scale, for scattered parkland trees or long avenues, for example, would be astronomical and the visual change from trees in grass to trees in large mulched circles will not always be acceptable.

Winter waterlogging can also be reduced by good soil care and drainage. In most instances, drainage of wet sites will improve the tree's root system, especially its depth of rooting, and make it more, not less, tolerant of drought. A particular problem will arise in gardens in which higher winter rainfall is likely to result in root death, making the tree less able to withstand reductions in summer rainfall. Careful attention to drainage will be needed in such situations.

To minimise the impacts of high winds gardeners will need to ensure good establishment of young trees and good shelter. In particular, planting open-ground stock rather than container grown trees, and planting trees as transplants, or even as seed, rather than as larger standards, will assist in the development of a wind-firm root system. Pit planting (in a prepared planting hole), rather than slit planting, has been shown in forestry planting to result in much higher stability of trees (Broadmeadow, 2002a). Improved drainage to reduce waterlogging will also reduce susceptibility to wind-throw as soil strength and root anchorage are greatly reduced at high soil moisture contents.

However, the main strategy for protecting trees from the adverse effects of climate change must lie in developing long term management and replacement programmes. Storm damage in 1987 was much higher in over-aged trees and in single-species plantations. Maintaining a good age structure and, where appropriate, using a mixture of species, will insure against massive storm damage. If historical precedent and historical significance do not constrain tree choice, there is much scope for regenerating tree plantings with more resilient species, as is already being carried out at Sheffield Park (see section 6.3.1 below, and especially Tables 3 and 4). Although old and decaying parkland and woodland trees are of great importance in conservation of biodiversity, it is important to remember that the population of 'veteran' trees depends, in the long term, on a flourishing population of young trees which will become veterans in centuries to come.

There will be many instances in which historical precedent and the visual delight of a lofty, single-age and single-species avenue, for example, prevail against a mixed-age, mixed species approach but in such cases it will be necessary to be aware of the

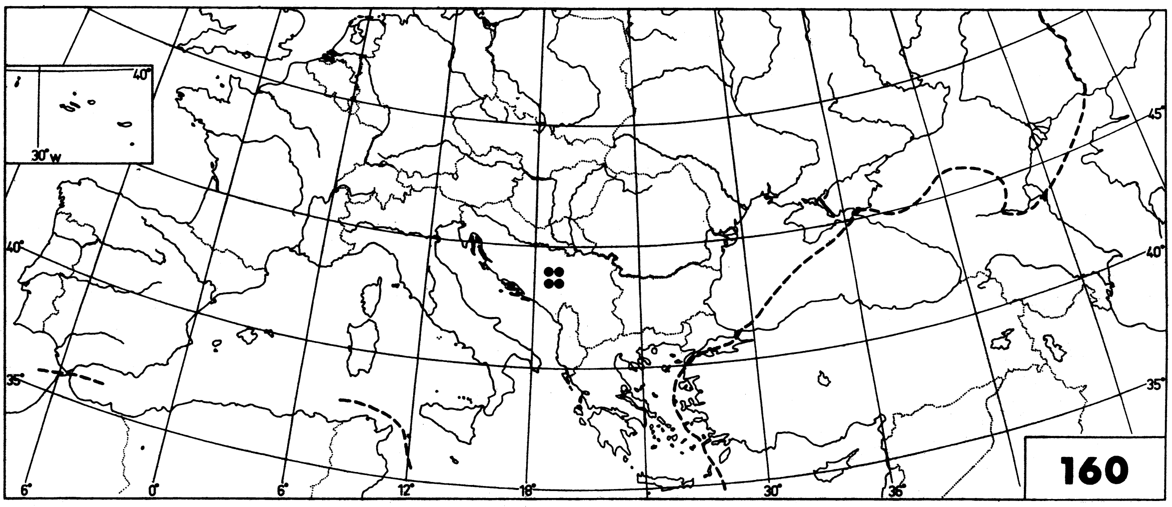

Figure 17a: Natural distribution of Serbian spruce (*Picea omorika*). *Source: Tutin et al., 1964.*

additional risks inherent in such situations, and to have in place a policy for replacement when the avenue declines, as it inevitably will.

6.3.1 TREE SELECTION

In Britain, in contrast to many other parts of the world, there are virtually no natural forests. Ancient woodland has been managed over centuries, sometimes millennia, to provide fuel, building materials and a habitat to attract deer and other animals to be hunted for food (Rackham, 1993). Much of our current tree stock has been planted, usually for a combination of economic and aesthetic reasons. Changes in social awareness and changes in agricultural land use have provided opportunities for tree planting in recent years. The shift away from planting monoculture of fast growing (many coniferous) species, to planting mixed woodland species (White, 1994), initially for ecological and amenity reasons, will be useful in insuring against total loss of a woodland if a particular species proves unable to survive climate change.

In deciding on suitable species for long term planting, natural distribution maps of plant species are of limited use as indicators of how plants might survive in gardens as the climate changes. Serbian spruce (*Picea omorika*), for example, has a very limited distribution in the wild (Figure 17a) but is described in *Hillier's Manual of Trees and Shrubs* (n.d.) and by Bean (1976) as one of the most adaptable spruces in cultivation.

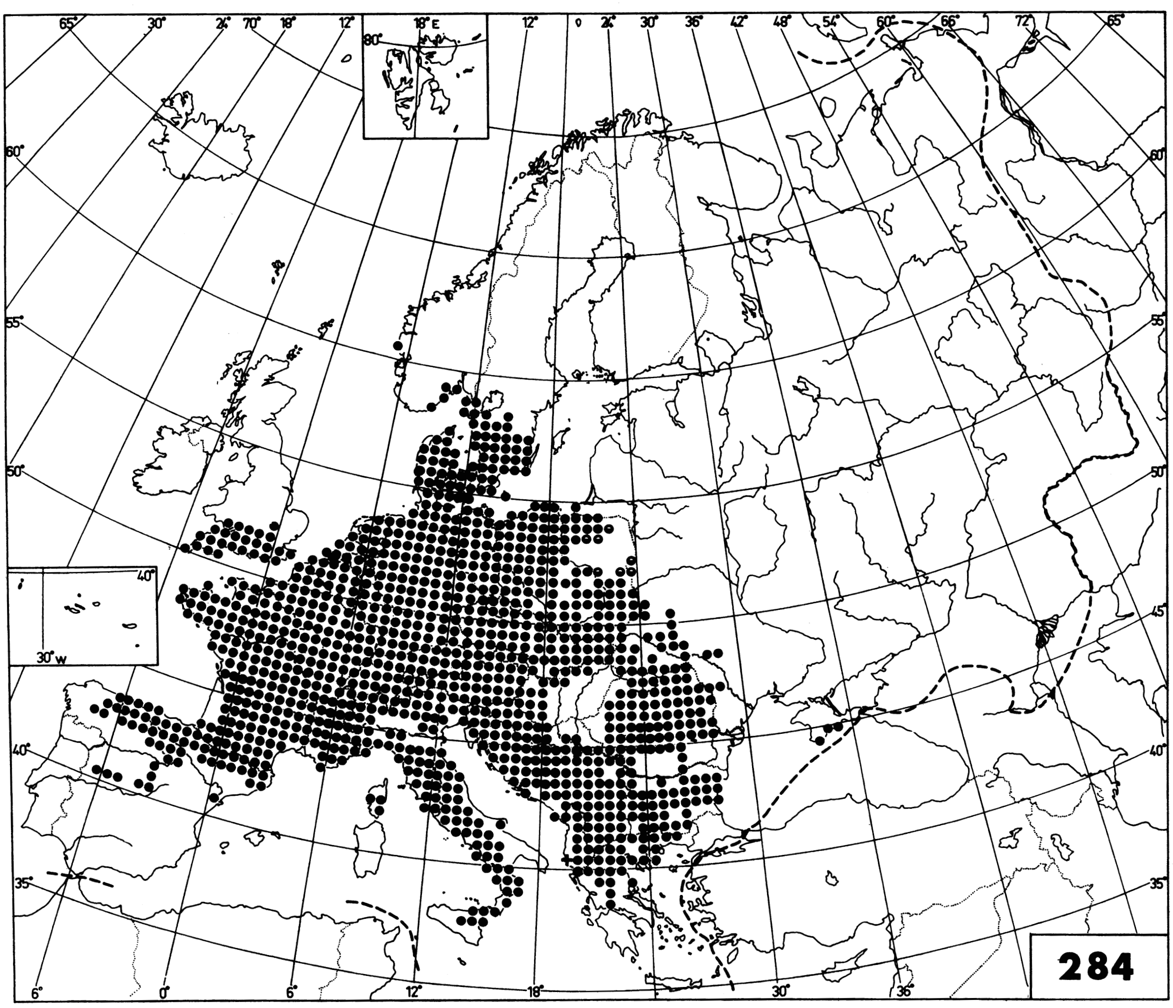

Figure 17b: Natural distribution of Beech (*Fagus sylvatica*). *Source: Tutin et al., 1964.*

Beech (*Fagus sylvatica*), on the other hand, has a very wide distribution from southern England to Sicily (Figure 17b), but is found only at increasingly high altitudes towards its southern limits, and then only on the well watered northern slopes of mountains. Survival of beech in Sicily, therefore, is clearly no guarantee that it will survive at low altitude on the hot, dry chalk soils of the Chilterns.

The distribution of pedunculate oak (*Quercus robur*) is even wider, from the north of Scotland to Sicily but this, too, is a result of differing altitudinal distribution, occupying higher altitudes in southern latitudes. There is also wide phenotypic variation within the oak population. Oak seeds collected from different zones and germinated or grown in one site show wide variations in dates of leaf emergence, leaf drop, rate of growth, degree of branching and other characteristics. Clearly it will be possible to find 'oaks' (in the broad specific sense) which, if planted today, will tolerate the climate of Britain in a hundred years time, but these may not have the form that is currently associated with the traditional English oak. Conversely, a particular phenotype of oak growing well in England now will probably not grow well after a century of accelerating climate change.

Similar problems arise with lime (*Tilia x europea*), a tree which exists in gardens as several distinct clones, each of which imparts its own particular character to avenues, parks and gardens. It may be necessary to consider whether limes failing as a result of climate change should be replaced by other clones of lime, which may have different forms, or to use another species of more similar silhouette.

Phenotypic variation will, however, be of some use in selecting tree provenances with greater tolerance of climatic changes. Such selection already forms part of the policy for redevelopment of the tree collections at Kew following the loss of many mature trees in the 1987 storm.

In a garden context, it is also necessary to distinguish between climatic tolerance and usefulness. Birch (*Betula pendula* and other species) is amongst the most tolerant of trees to a range of environmental stresses, but they respond to drought by losing their leaves. A near-leafless birch may survive increasing summer droughts, but will not make an effective aesthetic contribution to the landscape.

Table 7: Quality timber trees that should benefit from extra warmth in Britain. *Source: White (1994).*

Acer saccharinum	Silver maple
Carya cordiformis	Bitter nut
Cladrastis lutea	Yellow wood
Corylus colurna	Turkish hazel
Cupressus glabra	Smooth Arizona cypress
Cupressus sempervirens	Italian Cypress
Eucalyptus delegatensis	Woollybutt
Fagus grandifolia	American beech
Juglans nigra	Black walnut
Ligustrum lucidum	Tree privet
Liriodendron tulipifera	Tulip tree
Paulownia tomentosa	Foxglove tree
Platanus acerifolia	London Plane
Prunus serotina	Black cherry
Pyrus pyraster	Wild pear

Table 8: Trees that are resistant to storm damage. *Source: White (1994).*

Acer pseudoplatanus	Sycamore
x Cupressocyparis leylandii	Leyland cypress
Magnolia (tree species)	Magnolia
Ilex aquifolium	Holly
Metasequoia glyptostroboides	Dawn redwood
Robinia pseudoacacia	Black locust
Sequoiadendron giganteum	Wellingtonia
Taxus baccata	Yew

Table 7 lists trees which should benefit from higher temperatures in the UK, and Table 8 trees which are resistant to storm damage.

6.3.2 FRUIT TREES AND BUSHES

As discussed in chapter 4, many fruit trees and soft fruit bushes have a winter chilling requirement to break dormancy before flowering (then fruiting) can occur. Higher winter temperatures could pose a serious problem to fruit growers. Problems are already occurring with the blackcurrant crop after unusually mild winters (Carew, *pers. comm.*). The problem may be overcome in the short term by substitution of cultivars with smaller chilling requirement and, in the longer term, by breeding or by changing crops, from apples, pears and cherries to peaches. Clearly, this would represent a major investment requiring long term planning and having a significant impact on commercial fruit growers.

In heritage gardens, a particular problem may arise in growing historical cultivars of fruit trees. Many of these were selected and grown originally because of their close adaptation to local climatic conditions, so additional care in cultivation will be required when these conditions cease to exist.

6.3.3 TREE MANAGEMENT

i) Domestic gardens
Trees in or near smaller gardens will inevitably be near to property, so great care is needed in their management. It is very difficult to balance the visual and ecological value of a large oak on a housing estate, with the real or perceived danger of branch loss or toppling in strong winds. The presence of a house or houses will exacerbate the impact on large trees of high temperatures, summer drought and gusting winds, so it may be necessary to feed or water trees to maintain their health. All operations connected with tree care in confined spaces are expensive.

With newly planted trees, management is less complicated. The most important management consideration is to match the choice of species to site conditions. Most owners will plant small, ornamental trees with limited lifespans, so long term considerations of adaptation to climate change will not be an important factor in the choice of species. Large species are nevertheless important features of our urban landscapes and future planting policies need to perpetuate and enhance tree cover and ensure good management.

ii) Heritage gardens
A very different situation applies to the management of trees in large gardens, and especially in those heritage gardens which include parkland and ornamental woodlands.

The average unit cost of dealing with trees damaged by weather extremes or weakened by climate change, using skilled forestry or garden staff from the estate, will be much less than the cost of dealing with a tree in the urban setting of a domestic garden using external contractors, although of course the total cost of dealing with large numbers of trees (or with a large cedar in a courtyard) will be very much higher.

Because of the generally high levels of knowledge and skill in heritage gardens, the need to attend to trees will be recognised and measures such as soil aeration, irrigation, feeding and mulching are more likely to be undertaken to arrest decline.

On average, again, a higher level of stress imposed damage and decline may be tolerated in heritage gardens if the tree is seen at a distance, is unlikely to create a serious hazard, or is one of many trees. Veteran trees are of historic and wildlife importance, and they are often an intriguing feature.

Given the long term nature of heritage gardens, more attention will be given to the systematic replacement of the tree population than to firefighting treatments on individual trees. The main response to climate change impacts on trees in heritage gardens will need to be directed at ensuring a balanced age range and, where possible, diversity of species, including species chosen to tolerate the anticipated climate changes for the next century. The long term advantages of using small planting stock will usually prevail over the need to create an instant impact with large trees which, when moved from the nursery, will have difficulty in establishing and in surviving hot, dry summer conditions.

Trees constitute the most vulnerable and most visible component of the garden to face the impacts of climate change. They are long -lived, so face the longest period of exposure to climate change and the highest risk of damage by infrequent events.
They also have the largest sail area exposed to the elements. Beech will be especially vulnerable on light soils and in dry areas of the south east, areas where it has been extensively planted, is least suited to, and which will suffer the largest degree of climate change.

It will not be difficult to find trees suited to the climates anticipated by the scenarios for the 2050s or even the 2080s. Planting young trees from open ground stock rather than container grown material, and planting in autumn rather than spring, on well prepared sites, will maximise the trees' chances of surviving climatic stresses. However, planting in anticipation of continuing healthy growth for centuries will not be possible, unless the rate of climate change is abated.

6.4 Shrubs and sub-shrubs and climate change

6.4.1 SHRUBS

Like trees, shrubs are vulnerable to summer drought, waterlogging and wind damage, although they are less susceptible to toppling by winds. The enormous range of shrubs, such as roses, means that it would not usually be difficult to substitute one species for another where such substitution is acceptable. The life span of a shrub is such that climate change during its lifetime is unlikely to shorten its useful lifespan. A particular problem can arise, as at the National Trust's Sheffield Park (Sussex), when the canopy of mature trees is lost or thinned by storms, leaving shade demanding shrubs exposed to full sun and to the competition of vigorous weed growth in the wake of disturbance.

6.4.2 SUB-SHRUBS

Sub shrubs such as *Fuchsia*, *Indigofera*, *Penstemon* and some *Ceanothus* may become increasingly useful with climate change. Many are marginally hardy because they originate in regions where the climate does not require adaptation to a cold season, and so allows more or less perpetual flowering. Given increasing temperatures in the UK, and especially the anticipated reduction in frost, sub-shrubs may make a major contribution to the garden of the future. They are, though, often rather brittle and will, of course, suffer badly in exceptionally severe winters. Most are not tolerant of waterlogging.

6.4.3 SHRUB AND SUB-SHRUB MANAGEMENT

i) Domestic gardens

The domestic gardener is likely to view shrubs as part of a changing garden population. If a shrub is killed by severe drought or by flooding, it will be replaced, perhaps with something more tolerant but more probably with something more interesting or novel. The main factor determining the fate of shrubs in domestic gardens is their size. As they encroach too far beyond bounds they may be pruned, or removed and replaced. Shrubs are unlikely to be in place long enough to experience any adverse impact of climate change.

High standards of husbandry – feeding, watering, pruning – will reduce impacts of adverse weather within the smaller domestic garden, but the more permanent the plant, the less likely it is to be recognised as needing or benefiting from such treatment.

Sub-shrubs have a promising role to play in domestic gardens as mean temperatures increase. Long flowering seasons and, in many species, some tolerance of drought, make them useful substitutes for the more demanding annuals. Many are also more decorative than the majority of shrubs.

ii) Heritage gardens

As with other aspects of heritage gardens, the impacts of climate change will depend on the degree to which the status quo is considered important. In most heritage gardens carefully thought through management plans have had the effect of making systematic pruning and/or replacement of shrubs the norm, rather than allowing the structure of the garden to be swamped by excessive growth, then trying to rectify the damage by wholesale clearance, perhaps prompted by widespread losses following drought, flood or storm damage. Where some freedom of interpretation is acceptable, shrub replacement may reflect conditions resulting from climate change. Otherwise, high standards of husbandry will be needed to retain authentic planting until it becomes impossible.

If there is scope for innovation, then the potential for use of sub-shrubs will be as for domestic gardens.

> **Shrubs will be affected by climatic change in the same way as trees but to a lesser extent because of their smaller size and generally shorter lifespan.**
>
> **Sub-shrubs may play an increasingly important role in gardens. Their long flowering season is an advantage and their marginal hardiness will become less of a hindrance to use as temperatures increase.**

6.5 Herbaceous perennials

The range of herbaceous perennials is such that it is difficult to generalise on their responses to climate change. The Beth Chatto garden in Essex, where conditions range within a few metres from dry gravel to heavy clay, and where the plant range varies accordingly, is one of the best examples of this diversity (Chatto, 1994).

Many of the denizens of the traditional herbaceous border will not adapt well to climate change, and especially to water stress in summer. This is especially so for the most highly developed herbaceous perennials such as aster (eg, *Aster novi-belgii*), delphinium (*Delphinium x cultorum*), lupin (Lupinus x regalis) and phlox (*Phlox paniculata*) which have been selected and bred for garden use, on the assumption that soils will be deeply cultivated and well supplied with nutrients and water (Martineau, 1913; Roper, 1960). There is also a problem in selecting plants tolerant both of summer drought and winter wet. Old cultivars of iris, for example, are tolerant of dry summer conditions but will be killed by waterlogged conditions in winter.

As with most other plant forms, good soil cultivation will help to ameliorate the adverse components of climate change. Improvement of soil drainage and raising the soil level even by 10-15cm will improve the chances of survival of plants intolerant of wet conditions. Recent trends in the adoption of Dutch and German ideas in naturalistic planting of herbaceous perennials (von Schoenaich, 1994) and gravel gardening or dry gardening are already becoming popular in the UK. They may be tailored to suit a particular suite of climatic conditions by appropriate plant choice, with modifications to the landform where necessary to improve drainage.

One characteristic of herbaceous perennials is that most establish very quickly, usually within a season and certainly by the second year. If planting schemes in general are increasingly threatened by regular swings from summer drought to winter floods, a scenario which greatly exaggerates the changes anticipated by UKCIP02 scenarios, increasing reliance on herbaceous perennials, provides one attractive strategy for rapid reparation of the damage – as always, within the bounds of what is acceptable in any particular garden.

It is possible that the need to stake plants will decline if summer rainfall intensity declines and average wind speeds drop, as plants may also be more robust as a result of higher carbon dioxide levels. However, the uncertainties associated with storm predictions and the potential impacts of these events are such that inherently unstable plants should continue to be supported.

6.5.1 HERBACEOUS PERENNIAL MANAGEMENT

i) Domestic gardens
The domestic gardener will have the freedom to choose from a very wide range of perennials having the ability to cope with conditions created by climate change in a particular place. The usual balance will have to be struck between increasing maintenance inputs to grow particular plants, or choosing plants suited to a particular situation.

ii) Heritage gardens
The need to retain the essence, and perhaps the detailed composition, of a traditional herbaceous border will impose some management difficulties in heritage gardens. However, given the high

inputs needed in the past in soil cultivation, regular lifting and replanting, staking and other operations, the additional effort of adapting to climate change will not be as great as with more permanent forms of planting.

Herbaceous perennials are a very diverse group so it will not be difficult to find some which will grow in altered conditions. They are more or less short-lived so will not need to adapt to any significant degree of climate change in the course of their life. Because they mature quickly, they could play a useful temporary role where shrubs and trees have had to be replaced either in phased renewal or as a result of storm or flood damage.

6.6 Bulbs

Spring bulbs are strongly influenced in their development by temperature (Rees, 1972). The general pattern is that they require low temperature (i.e. winter) to stimulate root development, rising temperature (spring) to stimulate leaf expansion and flowering and, in some cases, such as tulip, high temperature (summer) to stimulate flower formation in the newly developing bulb for the following year. Actual temperatures controlling this development vary from one genus to another, usually reflecting closely the natural climatic conditions within which the particular genus evolved.

Many spring bulbs are already flowering much earlier as a result of warmer winters and springs than they were 20-30 years ago and may continue to do so. However, if winters become too warm, root initiation may fail and the plant may be severely weakened or killed. It will then be necessary to lift and store bulbs in refrigerated stores (as is already done to force early flowering in tulip and narcissus), rather than using them as permanent garden plants. Increasing soil and air temperatures may also upset the synchronised development of the bulb, for example by causing leaves of hyacinths to expand more quickly than the flower spike, thus reducing the visual impact of the flower. Spring displays of carpets of naturalised bulbs, like daffodils and crocus may disappear as a garden feature.

Some spring bulbs (tulip, some crocus) are intolerant of flooding while others (many *Narcissus*) are more tolerant, and others (*Camassia*) will grow in very wet soils. The natural distribution of the bulb gives a very good indication of its tolerance or intolerance of flooding.

Most summer and autumn flowering bulbs will flourish in higher temperatures. Temperature increases anticipated in the UKCIP02 scenarios may permit an increasing range of these late flowering bulbs (including bulbs, corms, tubers and other plants with fleshy rootstocks) to be grown as permanent inhabitants of the garden. They may also be grown more widely across the UK, but only if spared wet winter conditions, to which most summer bulbs are exceptionally sensitive.

Bulbs are strongly influenced by temperature so climate change will affect their timing and sometimes their healthy development. Most summer and autumn flowering bulbs flourish at high temperatures and will respond positively to dry summer conditions. They will become increasingly useful, and increasingly hardy as winter temperatures increase, but are very intolerant of wet winter conditions.

6.7 Annuals and tender perennials

Many annuals, especially hardy annuals, will exhibit accelerated development and/or suffer from water stress, given the higher temperatures and reduced summer precipitation expected with climate change. They will flower, seed and die earlier, thus reducing their garden-worthiness. On the other hand, higher spring temperatures will permit earlier planting of half-hardy annuals and higher winter temperatures will permit an increasing number of annuals to be grown as hardy, rather than half-hardy annuals, and will permit an increasing number of hardy annuals to be sown in autumn for an earlier summer display. Many tender perennials, especially the *Pelargonium*, are well adapted to hot dry summers and will flower more freely in such conditions. All are removed at the end of the summer season, so tolerance of winter conditions is not an issue.

Spring flowering biennials such as wallflower (*Cheiranthus cheiri*) and forget-me-not (*Myosotis sylvatica*) will benefit from higher winter temperatures. In northern areas, where spring planting has been the norm for wallflower, it will be increasingly possible under conditions of climate change to move to autumn planting, and the quality of overwintered plants should improve in most areas. Wallflower, in particular, is not tolerant of wet soils. In areas in which increased winter rainfall is anticipated and the result is likely to be poor winter drainage, it will be necessary to avoid its use or to improve soil conditions by cultivation or, more usefully, by raising soil level.

Strategies of response to climate change might include improved cultivation (especially irrigation where possible), a change in the garden flora (replacing short-lived hardy annuals by the more durable half-hardy annuals – which will become less half-hardy as temperatures increase) and perhaps moving in the mildest areas from twice-yearly replacement of spring then summer bedding, towards a permanent planting of plants previously considered to be tender perennials (Owen, 2002).

In warmer parts of the world, such as the southern United States and Japan, it is common to use three bedding schemes per year – in spring, summer and autumn -, instead of two, where summer bedding is expected to flower until late autumn. As summer temperatures in the UK rise and summer drought causes premature senescence of summer annuals, this practice could be employed in southern areas (Shaddick, 2000). This obviously has major cost implications if carried out on any substantial scale, but for most domestic gardens the extra cost is likely to be lower because of the smaller areas involved. Autumn bedding presents significant opportunities for nurseries and garden centres to stimulate sales at what is currently a very quiet time of year (see Chapter 8).

Overall, the advantages of climate change in relation to cultivation of annuals might outweigh the disadvantages: the opportunities to experiment with new half-hardy plants which may eventually become hardy as temperatures increase, are legion (Shaddick, 2000). The great risk with annuals is that, if weather conditions in a particular season are unfavourable to the plants being used in that year, the effect may be disastrous. On the other hand, if the planting does fail to produce the planned-for result, there is no permanent loss to the garden. Good ground preparation and, where possible, the availability of irrigation as a precaution against excessively dry summers, will maximise the likelihood of favourable results.

Annuals and other short-lived and temporary plants will obviously not need to adapt to climate change in their own lifetimes. Many hardy annuals will flower earlier but seed and die more quickly in hot, dry summers. Half-hardy annuals and tender perennials will be favoured by higher temperatures but most will need adequate water supplies to sustain lush growth and free flowering. On balance, climate changes will favour the exciting uses of annuals and other ephemerals.

6.8 Lawns and other grass areas

Grasslands are very characteristic of large areas of the UK's landscape and a very important component of many gardens. A long history of grazing animal husbandry and what has been a very equable climate, has led to much of the countryside being clothed in grasslands. These habitats often exhibit great species diversity. Visual delight in this greenness encouraged the cultivation of lawns which could be maintained with relatively little effort compared with most other parts of the world, and are much admired by overseas visitors.

The image of the UK as a 'green and pleasant land' is an important factor in encouraging tourists to visit, and it may be an increasingly important factor in encouraging UK citizens to holiday at home instead of travelling to increasingly hot, dry destinations abroad. It is our view that the image could be damaged if, as seems inevitable in some parts of the UK, climate change leads to summer browning of the grass. There is a more direct economic impact for large gardens and parks in which the grass is used by grazing animals. Lower stocking rates and greater conservation of grass as hay or silage may be necessary. On a regional scale, changes in farming practice in response to climate change, such as the conversion of grassland to arable cultivation or the replacement of wheat by sunflowers (Wade *et al*., 1999), will also have impacts on the setting of the rural garden.

6.8.1 THE DIVERSITY OF GRASS AREAS

The lawn, meadow or parkland represents a particular type of plant community created by regular defoliation of the vegetation, by grazing animals or by cutting. Over many years (centuries in some instances), the species composition adapts to local soil and climatic conditions. Many grasslands contain a rich diversity of species. Some surviving fragments of species-rich grasslands have been designated as Sites of Special Scientific Interest (SSSIs) supporting a wide range of insects and other invertebrates, as well as many species of plants. Old garden lawns, such as those at Chatsworth (Derbyshire) or Charles Darwin's garden at Down House (Kent) which have been regularly mown, can also be of considerable ecological significance.

On the other hand, it is possible to manage the lawn to favour only a small range of the finest-leaved grasses and to eliminate especially the broadleaved plants, in order to achieve a fine, rich green lawn of bowling green quality. It is also possible to modify the lawn, by heavy feeding and careful attention to drainage, to make it tolerant of heavy wear, whether from sports activities or from casual use by garden visitors.

As a general principle, the shorter the grass, the greater the desire for uniformity (especially the absence of weeds), and the smaller the area of the lawn, the more effort will need to be invested in it. A first class bowling green may require mowing every day, brushing, spiking, feeding at frequent intervals and irrigation, if dry weather persists for more than a few days. At the other extreme, a large expanse of grassland serving mainly as a green setting might, if not grazed, be cut once a year (even less, on a poor soil) and receive no other treatment, but still continue to serve its purpose well.

As lawns are almost invariably maintained using mowers powered directly or indirectly by fossil fuels, they constitute a visible contributor to climate change. Calnan (*pers. comm.*) has calculated that the National Trust uses 82,000 litres of fuel each year to mow 30 square miles (77 sq km) of lawn at a cost of £136,000. In the context of the 70,000 litres of fuel required to power a Boeing 747 on a single journey across the Atlantic, this annual consumption is insignificant, but if the principle of reducing fossil fuel use by changes in management (see section 6.8.3) can be demonstrated in National Trust and other heritage gardens, the message may be picked up more widely.

6.8.2 CLIMATE CHANGE IMPACTS ON THE GROWTH OF GRASS

The traditional smooth, closely-shaved lawn of UK gardens will be disadvantaged by higher summer temperatures, drier summers and wetter winters.

Increasing temperatures, in particular, will lead to temporary and long term changes in the composition of the grassland community. Jeffery (2001) found that annual meadow grass (*Poa annua*) decreased when turf temperature (and indirectly air temperature) was increased by 3°C, while clover (*Trifolium repens*), yarrow (*Achillea millefolium*) and browntop bent (*Agrostis tenuis*) increased. In Australian research, extreme but short term temperature increases decreased the proportion of cool season grasses, such as fescues and increased the presence of warm season grasses, such as Bermuda grass, but the effect was temporary (White *et al*., 2000).

Water deficits result in reduced growth. The productivity of grassland is inversely proportional to July and August temperatures and directly proportional to summer rainfall (Sparks and Potts, 1999). This is not usually a disadvantage in itself in gardens, but it can cause severe problems in parkland, where the grass is a food supply for grazing animals as well as a visual amenity. Deficits also eventually result in discoloration of the grass. This in itself causes long term damage only in very extreme circumstances. After the summer-long drought of 1976, for example, it took just ten days for lawns in the University of Reading's teaching garden to return to a satisfactory state of greenness. However, the immediate damage in visual terms is very serious for ornamental lawns. Water stress will be especially serious on close-mown areas, as continuous close mowing restricts root development (Bisgrove, 1980).

Summer saturation of lawns after very heavy downpours poses a potentially bigger problem, in that the grass will be very susceptible to compaction and this will cause long term damage to the lawn, unless extra effort is expended on aeration and other intensive maintenance practices. At Hidcote Manor (Gloucestershire), the cost of lawn repairs and reinforcement is currently £3000 per annum and it is still necessary to close important grass paths at times, to prevent more serious deterioration from visitor pressure after heavy summer rains. Compaction problems may also arise in warm, dry summers as visitor pressure can be damaging when the soil is dry.

Increasing mean temperatures, a longer growing season and increased rainfall during increasingly frost-free winters will result in greater productivity and more mowing, probably throughout the winter in the mildest areas. This has resource implications, but also poses management problems, in that mowing into the winter, combined with expectations of higher winter rainfall, means that the risk of soil compaction by mowing equipment will be increased, and permanent damage to the grass root system is likely.

Increase of soil and air temperatures will almost inevitably also lead to higher incidence of pest and disease outbreaks in lawns, because of the general increase in biological activity. Moss is only a major problem on most lawns in early spring when the mosses, with their lower temperature thresholds for growth, are able to flourish in the absence of actively growing grasses. In many regions, moss will probably become more prevalent but paradoxically, also less of a problem. Higher temperatures will allow the moss to grow over a longer period in winter, but earlier growth of grass in the spring will conceal and suppress the mosses.

6.8.3 GRASS MANAGEMENT

In order to explore potential responses to the impacts of climate change on lawns and other grass areas, it is necessary to understand firstly that grassland results from regular defoliation and secondly, that management inputs increase as the need for a short and uniformly green surface increases.

One possible response to adverse climate impacts would be to accept different standards and thus to permit altered maintenance methods. A very likely impact of climate change will be increasing drought stress and temporary discoloration of the lawn. Coping with the browning of lawns in dry periods will require decisions as to whether to tolerate the discoloration (to the visual detriment of the garden and perhaps the displeasure of paying visitors) or to irrigate using increasingly scarce water resources. Raising the height of cut, and returning clippings to the lawn, could increase the resilience of lawns to drought, reduce the period and degree of discoloration in summer and often reduce the incidence of moss in spring (Bisgrove, 1980), but may lead to an increase in thatch problems. In parts of the United States, lawns are sprayed with green dye to disguise the browning which occurs as a result of low temperatures in winter or drought in summer.

In large gardens, the owner or manager could contemplate greater development of more naturalistic 'meadow' areas (Owen, 2002) with less frequent cutting, bearing in mind that long grass may pose increased fire risk in dry summers and may eventually harbour ticks and other undesirable wildlife, if temperatures continue to increase (see section 7.1).

There is a further complication in decision-making in relation to frequency of grass cutting, in that a rotary mower uses much more fuel to cut a given area of lawn than does a cylinder mower. Any change in mowing regime which results in the need to change from cylinder to rotary mower (in order to tackle longer grass), will not give the savings in fuel consumption or time that one might initially expect, although it may produce a more resilient turf.

In small gardens, gardeners might respond to more frequent browning of lawns by applying more irrigation and fertiliser), or by replacing grass with paving, gravel or ground cover.

Increasing variability of weather conditions will also complicate management. Routine mowing of lawns during a summer of alternating drought, when growth ceases, and heavy rain, when growth is rapid but soil conditions unsuitable for mowing, could become questionable. The need to mow grass in increasingly warm but wetter winters becomes increasingly probable. In long, wet periods it will be necessary to decide whether to mow the grass and risk soil compaction or to accept greater variability in height and tackle longer grass intermittently in the drier periods. Mowers could be developed to help gardeners manage lawns through predicted milder winters.

If mowing is done in-house (and especially in domestic gardens where the owners are 'the staff'), a more flexible regime may be possible, switching between mowing and other operations on a more *ad hoc* basis, but the management of lawn areas by contractors will be more difficult to specify and therefore more costly. In any case, management will be more complex.

Some respite from increasing temperatures may be achieved by using newer cultivars of turf grasses developed in the United States, though these usually have the disadvantage of being bred for golf courses and other highly managed landscapes, so require high nutrient and irrigation inputs.

Very substantial increases in temperature may eventually necessitate the replacement or reinforcement of the current range of cool temperate (C3) grasses with warm-temperate and subtropical (C4) grasses, as in much of the southern United States and southern Europe, but this is very unlikely to be necessary by the 2080s even under the high emissions scenario. Cool temperate grasses have an optimum air temperature for growth of 15-24°C and an optimum soil temperature of 10-18°C, compared with 27-35°C and 24-29°C respectively for warm season grasses (Ward, 1969), and warm season grasses discolour badly at sub-optimum temperatures. Such substitution would represent a very major change in the quality of lawns in the UK as warm season grasses are generally coarser and less tolerant of close mowing. Very considerable inputs in terms of irrigation, fertiliser application and disease control would then be required to maintain the fine textured, short and soft turf which has been the hallmark of the UK lawn.

i) Domestic gardens

In a small domestic garden, intensive management of lawns is possible because of the small scale, even to the extent of using bath water for lawn irrigation in times of hosepipe bans. More commonly, most domestic gardeners are accepting and moving to lower standards of maintenance, slightly longer grass cut by rotary rather than cylinder mower, and with some acceptance of weeds and summer discoloration. Because of the regular time commitment imposed by lawns, perhaps combined with problems resulting from increasingly frequent summer droughts, small lawns in particular are being replaced by gravel, paving or decking.

ii) Heritage gardens

The specific character of different parts of a heritage garden will call for particular standards of maintenance which may vary from bowling green to rough meadow. The skills are available for sensitive, appropriate and varied maintenance. An extensive armoury of equipment for mowing, aeration, irrigation and other operations is available, though at a cost, and the scale of the garden may merit investment in a range of such equipment.

Particular problems of compaction caused by mowing in wet weather or by increasing visitor numbers after wet weather may require sports turf type management, but the cost may be justified by increased visitor capacity.

There may be some scope for conversion of fine grass surfaces to lower maintenance meadows, especially in those gardens where excessively high maintenance is a recent departure from earlier conditions. In grazed areas, the problem of balancing stocking rates with varying productivity of parkland grass will need to be addressed.

The lawn is a very characteristic feature of UK gardens and is very likely to be adversely affected by climate change. The more the lawn departs from a natural meadow community towards a highly managed, very short and weed-free green carpet, the more vulnerable it will be to climate change impacts.

High summer temperatures and reduced precipitation will reduce grass growth, sometimes completely, and cause the lawn to go brown. In winter, increasing temperatures and rainfall will stimulate grass growth throughout the winter, particularly in the southern UK. The mowing season may shift with year-round mowing possible in the mildest areas. The need to mow when the soil is wet and therefore susceptible to compaction will be difficult to manage.

Adaptation to climate change will require cultural modifications (increased height of cut, timely application of fertilisers, or acceptance of brown summer lawns), or technical responses (irrigation and perhaps new mowing equipment) or a combination of these. Sensitive and responsive management will be increasingly important.

6.9 Paths, walls and garden structures

6.9.1 PATHS AND WALLS

Paths will need to be designed, constructed and maintained to prevent washing out in storms and to avoid large volumes of water being discharged from paved surfaces onto erosive soil during heavy rainstorms. It may also be necessary to choose path and paving surfaces to avoid (or facilitate the treatment of) algal growth, especially if gardens are opened to the public early in the year as the flowering and garden visiting season advances.

6.9.2 GARDEN BUILDINGS AND STRUCTURES

Wind and sun damage to fabric, and increased wetness from driving rain are likely to be the main problems associated with garden buildings (Jarman, 2001). Deterioration of fences, pergolas and other wooden structures will probably accelerate if high summer temperatures dry the timber excessively, leaving gaps for penetration by winter wet and fungal decay organisms. Higher standards of construction (including larger gutters and downpipes) and maintenance, and more use of durable timbers from sustainable sources where appropriate, will assist in overcoming these problems. There will be cost implications though, and limitations to such adaptations in listed and other important buildings. Antique statuary may require special protective covers in winter to prevent damage from extreme weather events.

Above and below ground, archaeology may also be vulnerable to climate change impacts, such as ruins in gardens exposed to flash floods. In recent years, flash flooding episodes have become more frequent at Studley Royal (Yorkshire), causing particular concern for the surviving structure and foundations of one of the garden’s picturesque ‘eye-catchers’ – Fountains Abbey.

Good ventilation of greenhouses and adequate shading will be necessary to avoid excessive build-up of heat in summer, for the benefit of the plants and of the gardeners looking after them.

On the positive side, glasshouse heating costs in the winter should be substantially lower in warmer winters, and frost damage to stone and brickwork, sculpture and other features of ‘hard’ landscapes will be reduced.

High summer temperatures, heavy downpours and driving rain, sun and wind damage, and increased pest activity may accelerate deterioration of garden structures. Higher standards of construction and upkeep, and improved techniques of decay prevention will be required to maintain garden structures. On the other hand, frost damage and glasshouse heating costs could decrease as a result of climate change.

6.10 Garden staff

Those faced with the maintenance and management of gardens in the 21st century will face a more challenging task in dealing with climate change. Physical working conditions should improve throughout much of the year as temperatures increase in winter and rainfall decreases in summer, but very hot or very wet conditions will make work more difficult at times. Care will be needed to prevent dehydration in high temperatures and more consideration will be needed in choosing protective clothing suitable for use at high temperatures. Care will be needed, too, to guard against the effects of higher UV light levels in summer.

Coping with climate change may involve more work and more stress, especially for those who have invested years of their lives in establishing and caring for their gardens. Maintenance (especially mowing) will be less predictable. Dealing with storm, flood or disease damage to the garden is likely to be mentally stressful as well as physically demanding. The additional ameliorative or remedial work required to respond to the impacts of climate change, such as soil cultivation, irrigation, mulching, more complicated mowing and more active intervention to ensure a healthy age range of trees, are all likely to add to the cost of managing gardens.

6.10.1 PERCEPTIONS OF CLIMATE CHANGE BY GARDEN MANAGERS

When garden managers were asked about their perceptions of the potential impacts of climate change, most respondents saw a mean temperature rise of 2-5°C as an advantage as the range of plants which could be grown could be extended, and heating costs in glasshouses could be reduced. More extreme changes – a threefold increase in the number of days above 27°C – could enable arid zone plants to be grown in the garden and might increase visitor spend in shops, if they seek relief there from the outdoor heat. These comments indicate the diversity of factors which garden managers need to consider.

Generally agreed negative aspects included the need for increased watering, the possibility of new or increased pests and diseases, the need for increased mowing and the possible loss of visitors to the coast in sunny weather. The prospect of 5-10 days each year with temperatures in excess of 40°C was seen by all respondents as a negative impact, as it could lead to plant damage, severe problems under glass, the need for irrigation and a probable reduction in visitor numbers.

In other respects there was an obvious regional influence in the perceived impacts of climate change. A longer growing season and a substantial reduction in the number of frost days were considered to be beneficial, especially in northern gardens, but pest, disease and mowing problems were raised.

Responses to the prospect of a 20% increase in winter rainfall were more varied. One respondent in the east of England saw a potential benefit in improved tree health, but others saw only disadvantages resulting from waterlogging, saturated lawns, more damage, a reduction in available working time and decreased visitor numbers.

The prospect of a decrease in summer rainfall received equally varied responses. Several respondents identified the need for increased irrigation as the main potential disadvantage, with possible damage to lawns and some plant loss as secondary concerns. Interestingly, the respondent from the driest garden saw no problem as the challenge was already present, but saw the possibility of growing more plants from semi-arid regions as an advantage. The respondent from one of the wettest gardens also saw possible advantages of reduced summer rainfall in improved summer weather for visitors, and in creating better meadows.

Not surprisingly, the likelihood of more variable rainfall with more frequent droughts and heavy rainstorms was viewed as an entirely undesirable aspect of climate change, making planning of events and operations more difficult. However, three of the ten respondents suggested that uncertainty was already a normal feature of their operations and that any further change would make little difference. The possible increased incidence of strong winds was also seen as wholly undesirable with the potential for damage to plants and buildings, tree loss and increasing the need for safety audits.

The prospect of a 50cm rise in sea level was considered irrelevant to most respondents except the one manager gardening on the coast, whose garden had been under water for several months in the previous winter. He noted from first hand experience that sea level rise would be devastating in its effects on plants and visitor numbers.

The threat of new pests, salt damage, ultra-violet light damage and managing the uncertainty of change were also identified as potential difficulties or challenges. The potential inability to grow the existing plant range was also raised as a problem by one gardener, as additional management input would be required to design new planting schemes. The fact that this point was raised just once suggests that managers are either confident of their ability to grow plants under future climates, or that other problems associated with climate change, were considered more pressing.

When asked if actions were being taken to adapt to or mitigate climate change, six interviewees replied that they were engaged in or planning measures to reduce the environmental impact of their operations, including recycling, minimising carbon dioxide emissions and reducing greenhouse heat losses. A seventh had installed a new irrigation system to counter drought. No actions were planned by the other three respondents – in one case because none was affordable.

A majority of the responses to the individual questions suggested that climate change would be disadvantageous. Of the hundred individual responses (ten respondents with ten questions), 51 indicated disadvantages, 27 advantages, 12 a balance and 10 no impact. Paradoxically, though, when asked what the overall effect of these possible changes would be, four replied "advantage", three "balance" and three "disadvantage"

6.10.2 RESPONSES OF GARDEN STAFF

i) Domestic gardens

In domestic gardens, the impacts of climate change and responses to it will depend on the nature of the owner/gardener. The owner may choose to garden at different times of day (in the cool of the late evening), or to postpone maintenance in wet weather. They may also choose to exploit climate change with more adventurous planting, to battle against it using more intensive management, or to avoid its impacts by adopting low maintenance features.

ii) Heritage gardens

In heritage gardens, the impact of climate change will depend on the nature of the garden. There may be some sense in changing working practices, for example an earlier start or later finish and longer midday break in very hot weather, but the manager will need to operate within the constraints of employment law and contractual obligations. The most difficult situation will apply when maintenance operations are contracted out, a situation which often applies in relation to grass maintenance. A horticulturally sensible approach of cutting grass when it needs cutting and when soil conditions are suitable for mowing is more difficult to write into a standard contract than is the specification of a routine mowing regime. If such a specification is produced, the contractor will almost inevitably increase their quote to protect themselves against the uncertainties within the task.

One of the important and costly impacts of climate change on heritage gardens is that staff will need to be increasingly highly trained to be able to contend with impacts of change on the garden itself. Many of the operations described above, although an integral part of good garden management, will need to be carried out more often and with greater thoroughness, so increasing staff levels will be required if standards are to be maintained.

Climate change will have some benefits for garden staff in terms of their working environment in generally warmer and drier springs, summers and autumns. Very high temperatures in summer and wetter winter conditions will need to be contended with.

Coping with the uncertainties and adverse impacts of climate change and with damage caused by extreme weather events may increase job stress for gardeners. Most respondents to the questionnaire felt that climate change presented a mix of advantages and disadvantages with their responses being influenced by the geographical situation of their garden. When asked about the overall impact of climate change on their garden, responses ranged very evenly across the spectrum of "advantage" to "no overall impact" to "disadvantage".

Box 6.1 Cost implications of climate change for gardens

It is impossible, in a study of this scope, to deal in detail with the costs of climate change in each and every type of garden, and for each garden operation. However, the costs associated with managing the impacts of climate change on gardens fall into six broad categories.

Plant growth. Higher growth rates over a longer season will result in a greater mass of vegetation. The removal and disposal of surplus growth, whether lawn mowing or shrub pruning, will involve increased costs.

Plant failures. Removal and replacement of plants damaged by extreme weather events or by gradual failure over a sequence of dry summers will be very costly. Experience of past events suggests that restoring gardens after major storms or floods could mop up normal maintenance budgets of public gardens for several years.

Pest, disease and weed problems. Managing these problems will become increasingly resource intensive, particularly as environmental concerns and tougher legislative requirements are reducing the available range of approved pesticides.

Reducing negative impacts. The equipment and resources required to reduce the impacts of climate change will have significant costs. Irrigation water itself is likely to become more expensive, if it is available at all in times of severe drought.

Insuring for damage. Greater care will need to be taken to protect buildings and other garden structures against damage and decay. This may involve increased maintenance, the use of more expensive building methods, and increasingly rigorous safety inspections of trees and dams. Insurance cover against severe weather damage will be important, but may be increasingly costly or difficult to obtain. Insurers are already taking steps to withdraw protection from some flood risk locations, unless policy changes are made. Greater financial reserves may be required to cover loss.

Managing negative impacts. A major weapon against the adverse impacts of climate change will be sensitive management with long term strategies for the care and phased repair and regeneration of all components of the garden. The increasing complexity of dealing with climate change impacts will require more highly skilled staff, who may demand higher rates of pay if such staff are forthcoming.

Climate change and garden visitors

There are two distinct but related aspects to the interrelationship between gardens and people: the effect of climate change on people, including their propensity to visit gardens, and the effect of people on gardens as climate changes.

7.1 Impacts of climate change on garden visitors

Visitor numbers to gardens will be influenced by many factors, of which climate change is only one. A recent press release from the English Tourist Council (26 August 2002) indicates that visitor numbers to tourist attractions in England have decreased by 2% in the past year, in part as a result of the destruction of the World Trade Centre on September 11 2001 and the aftermath of the outbreak of Foot and Mouth disease. Visitors to many rural attractions decreased by 25% or more. Visits to theme parks and gardens increased, however, after several years of static or slightly declining numbers of garden visitors. A recent survey of National Trust visitors confirmed that nearly 60% came solely to visit the gardens, such is their popularity.

Scenarios of social change point to an ageing population, increased leisure and increased mobility. Such changes could result in increasing numbers of people with the inclination and ability to visit gardens. A swing away from the foreign package holiday, concerns over safety and the environmental impact of air travel might discourage travel abroad. As hot areas of the world become hotter still, there may be further disinclination to travel. If these deterrents are combined with improvements in UK facilities (cleaner beaches, refurbished holiday resorts, higher standards of catering and more visitor facilities in gardens for example), there could be a positive swing towards holidays at home. The UK market could also benefit from an increase in short holidays.

If, however, pensions are reduced and living standards fall, and measures to limit private car use are implemented without a commensurate improvement in public transport services, visitor numbers could be expected to decline.

Predicting the number of visitors to gardens is further complicated by competition or synergy from other attractions. The increase in visitor attractions as a result of Millennium Commission funding and a general increase in the provision of leisure facilities has made it difficult to maintain visitor numbers at older attractions, but there is potential for synergy if nearby attractions cooperate in advertising. This is clearly demonstrated in the success of the Cornish Gardens consortium. More recently the Eden Project, one of the most successful Millennium Commission funded projects, has demonstrated its success in attracting visitors to Cornwall and feeding them on into other Cornish gardens. The benefit to the local economy of the Eden Project in its first year of operation, was £11 million (Kendle, *pers. comm.*).

Climate change, although only one of many factors, can be expected to influence visitor numbers in several ways. Improved weather should attract more visitors to gardens. Evidence suggests that good weather, especially in spring, boosts visitor numbers (Entec, 2000) and that bad weather, especially at Easter, the traditional start of the gardening and garden visiting season, dramatically reduces visitor numbers to gardens and garden centres.

In the early and late parts of the year, the ‘shoulders’ of the holiday season, higher temperatures and a longer growing season should encourage visitors (Entec, 2000). Spring temperatures and early flowering are already encouraging many gardens to open earlier in the year. The UKCIP02 scenarios all point to a 10-20% reduction in autumn rainfall. Unless plants suffer from premature leaf fall because of summer drought, the higher autumn temperatures, sunnier conditions and the contrast between high day temperatures and cool nights which results from clear skies, should favour the development of autumn colour and further encourage visitors. The pattern of daily visiting hours may also alter with climate change, as visitors may prefer to visit in the early morning and evening to avoid the heat of the day.

The effects of climate change on the incidence of pests and diseases on plants have already been discussed in Section 3.5, but the possible impacts of climate change are not limited to plant pests and diseases. As summer temperatures increase, ticks, which are vectors of Lyme Disease in humans, and perhaps mosquitoes, could become more common (Department of Health, 2002). If the public perceive the risk of exposure to such insects to have increased, they may be less inclined to wander through meadows or to picnic. This could negatively influence visitor numbers.

There are clearly many factors that influence visitor numbers to gardens, and each major garden will have its own set of parameters determining its catchment area and the likely threats and opportunities arising from climate change. Climate change will undoubtedly affect all gardens in the UK to a greater or lesser extent. However, the most important influence on a garden's attractiveness to visitors and on visitor numbers will be marketing in its broadest sense. If gardens can continue to offer the high quality environments that the public seek, they should succeed in maintaining and increasing visitor numbers.

Climate change is only one of many factors which may influence visitor numbers to gardens. Warmer weather could lead to increased visitor numbers, but there may also be increased competition from the beach and other destinations. Warmer and drier springs and autumns, may stimulate visitor numbers, but very high summer temperatures may discourage visiting.

Gardens will need to respond to changing climatic conditions by providing, for example, adequate visitor facilities to mitigate against the adverse effects of poor weather. Ultimately, marketing in its widest sense will be the most important factor influencing future visitor numbers.

7.2 Impacts of visitors on gardens in a changing climate

The need to attract visitors is a very important factor having an impact on heritage gardens in particular. When garden managers were asked to identify the main directions of development of their gardens and the main influences on forthcoming changes, visitor facilities were central in replies to the questionnaire. The main categories of response were:

- to upgrade and/or expand facilities for visitors;
- to increase visitor numbers, the range of visitors and the visitor season;
- to increase the educational value and use of the garden;
- to increase the diversity of the garden;
- to increase operational efficiency.

Four of these five relate directly to increasing visitor numbers and visitor satisfaction. Other objectives included expansion of the garden (offering more to visitors), raising standards (making it more attractive to visitors), integration into the surrounding landscape and expanding the scientific basis of the (botanic) garden.

Most responses also reflected the need to meet budgets (increase income) and to justify the existence of the garden by increasing educational provision, linking plants with science, and attracting more visitors over a longer season.

Of the ten responses to the question "What is your next major development?" five referred to new planting schemes, one to the replacement of existing planting (a hedge killed by flooding), two to buildings (visitor facilities), one to the reopening of an historic garden route, and the tenth to a lake for water conservation. None of the planting schemes reflected any explicit or obvious direct response to, or awareness of, climate change, though the replacement of a hedge killed by flooding (too much water) and the lake to store water for irrigation (too little water) indicate the range of problems which might arise from climate change.

One effect of climate change is that significant increases in visitor numbers might be expected at those times of the year when the weather is most uncertain and potential damage to gardens most severe: a sunny weekend in February after a week of rain could see large numbers of visitors arriving at rain saturated gardens, causing major problems of soil compaction and major discomfort in muddy car parks and on muddy or slippery paths. This has already occurred at Nymans in Sussex, for example.

Weather will remain highly variable in future, so investment in weatherproof facilities such as garden shelters, glasshouses and other indoor visitor attractions may be needed to sustain visitor numbers and to encourage repeat visits.

Visitor expectations are equally difficult to predict. Expectations of high material standards such as green lawns and air-conditioned restaurants may increase the difficulty of adapting to impacts of climate change. On the other hand, visitor expectations of high ethical standards with respect to sustainable management of gardens may make it easier to introduce some modifications, such as accepting browner lawns, and more difficult to introduce others, such as irrigation systems, made necessary by climate change. Visitor education and interpretation, and the conspicuous implementation of good environmental practices, will be critical so that people may understand, accept and hopefully, adopt for themselves, a more sustainable way of gardening.

All the garden managers responding to the questionnaire survey indicated that increased visitor numbers were important to the funding of the garden and, in some, to meeting the educational objectives of the garden. Higher visitor numbers will exert greater physical pressures on gardens. Grass was seen as especially vulnerable. Climate change may result in an increasing number of days on which the weather is suitable for garden visiting but when the ground is wet or exceptionally dry. Both circumstances can lead to severe soil compaction beneath lawns. Intensive management techniques developed initially for sports turf can assist the garden manager to cope by invigorating, reinforcing, protecting (in exceptionally wet weather), or replacing grass. Such techniques are already widely used in heavily visited gardens. There are cost implications and environmental implications in, for example, mowing heavily fertilised grass or replacing grass with paving, but if increased visitors bring in increased income, the solutions may be self financing.

It is evident that gardens are useful small models of the environment as a whole, and that some of the challenges presented by climate change occur in, and can be remedied on, a garden scale. The ability of a garden to demonstrate good practice in its response to climate impacts may engender increasing support for gardens. Many gardens with an educational aim are focusing on sustainability as the major thrust of their activities. Gardens which have not in the past developed this role may be able to boost visitor numbers and income, by implementing sustainable practices and marketing them as exciting and educational attractions.

Increasing visitor numbers will have impacts on gardens. Shelters, wet weather facilities and air-conditioned restaurants may be required and may change the character of the garden – for better or worse. Gardens could be most severely affected by increased visitor numbers when the soil is too wet or too dry to withstand compaction. Increased management and maintenance inputs, and perhaps changes of design, will be needed to reduce impacts. Changing climate could also impact on staff and staffing. In a hot, dry summer for instance, the garden may be at its best in the early morning or evening, but opening the garden at these times would have significant impacts on staffing.

Climate change and garden related industries

Climate change will have significant impacts for garden-related industries such as nurseries and garden centres in relation to two aspects: operational effects and market opportunities.

8.1 Impacts on operations

Insofar as these enterprises are growers of plants, they will meet the much the same type of opportunities and risks as those facing gardens.

Higher mean temperatures will allow a wider range of plants to be grown (see Table 9, page 110), but extreme weather events may cause more damage. This damage will be exacerbated where plants are grown in plastic tunnels or glasshouses, which are themselves vulnerable to hail storms and strong winds, and in containers. Container grown plants with their root systems confined, often in a black container, are more susceptible to root damage from exceptionally high or low temperatures, than are established plants in gardens. Notcutt (*pers. comm.*) has pointed out that there has not been an exceptionally severe winter since 1962/3, at which time container plant production was in its infancy. A severe winter now that container plant production is the norm, could have devastating consequences for nurseries and garden centres.

Reduced availability of water in the summer will have major implications for nursery stock production. Even if not rationed, the cost of mains water is likely to increase as will the cost of boreholes, reservoirs and water treatment plants which may be necessitated by tighter regulation of water supplies. Container grown plants are much more susceptible to moisture stress in hot, especially windy, conditions than are plants in the open ground, so a reliable water supply is essential regardless of cost. Water conservation, recycling and adoption of more efficient irrigation systems will help to offset the increasing cost and decreasing availability of water. Novel work by Horticulture Research International, East Malling, uses restricted water supply to improve the quality of container grown plants (Cameron, *pers. comm.*). Reduction of wind speed on the nursery, using natural (hedges and trees) or synthetic windbreaks, will also reduce water loss.

Although not strictly a result of climate change, the increasing legislative and societal pressures arising out of general concern for the environment, and therefore stimulated by debate about climate change, will also pose challenges in terms of pesticide and other chemical use, restrictions on peat use, taxation of fuel, recycling of waste materials and tighter safety regulations, all of which will be reflected in higher production costs. Working conditions will deteriorate on very hot days, especially in polythene tunnels and glasshouses, possibly necessitating a midday rest for staff and improved clothing for spray operators or structures with increased ventilation.

More unsettled conditions arising from climate change will also have impacts on plant production. Container grown trees and shrubs, in particular, are inherently unstable and will fall over in high winds or heavy rain. Although a nursery will not usually face the type of wind-blow risk which faces the owner of a garden with mature trees, young trees will be damaged if containers are blown over. The cost of setting trees upright after a gale, or of staking to prevent blowing over, or of writing off damaged stock is considerable. More attention to shelter will reduce wind damage. Howard's Nursery in Norfolk uses living windbreaks of *Miscanthus sacchariflorus*, which also has some potential as biomass for fuel. Increasing the weight of compost, although introducing other problems, would make plants more stable, and probably better able to adjust from the nursery to more normal, mineral soils. Container design could also be developed to improve stability.

Nursery infrastructure will also be affected by climate change. A hailstorm at Notcutts nursery in August 1987 caused damage to polythene tunnels and glasshouses, as well as to plants, with costs exceeding that of all frost damage in the past 50 years. Notcutts garden centre in Peterborough was flooded at Easter 1998 causing widespread loss to property and stock, and a flood during the same period at the National Trust's Bodiam Castle (Kent) destroyed the gift shop's entire stock.

Indirect losses as a result of adverse weather conditions can be even more devastating. The flooding at Notcutts Peterborough centre resulted in loss of trade at a crucial time of year for sales. At present, 50% of garden centre sales are concentrated into a few weeks of spring and early summer. Hilliers Nurseries sell two-thirds of their stock in March, April and May (Woodhead, *pers. comm.*) Drought also reduces interest in gardening and has a major impact on the purchase of plants, lawn mowers and other equipment.

Perhaps the most significant implications of climate change for garden industries will arise from extreme weather events, such as droughts and floods. These events may affect garden industries more severely than they affect gardens. The loss of trees in a storm will be a devastating but temporary setback in the lifespan of a garden, incurring extra costs and reducing visitor numbers during closure, but the garden has considerable cultural momentum. Suitably informed, visitors might be encouraged to visit in larger numbers to see the devastation from a safe vantage point and to support repair efforts. The loss of stock or of structures on a commercial nursery engenders no such sympathy and, without adequate reserves or costly insurance, there is a serious risk of bankruptcy.

The key to survival will be adaptability and management of risk. Irrigation equipment may be necessary as temperatures rise and summer rainfall declines but it may be less acceptable as water shortages become more severe. A company which continues to produce only hosepipes might run into trouble. One which diversifies into water butts, grey water treatment and mulch mats would probably flourish.

To survive, businesses will need to understand that the only constant is change. For instance, plants were grown in non-peat composts for centuries before peat became widespread less than half a century ago. Among the benefits of historic garden conservation has been the rediscovery of more sustainable methods of production and the realisation that it is possible to make a profitable enterprise out of demonstrating these methods. The use of sun frames rather than sophisticated mist units in plant propagation, traditional techniques of composting and organic production, and biological control of pests, have all led to more sustainable plant production systems and often reduced costs of production. In addition to the direct advantages which these developments produce, the success of demonstrating such techniques at the 'Lost' Garden of Heligan (Cornwall), for example, shows the commercial advantages of adopting them.

Growers will be affected in the same way as gardens will be by very high temperatures, water deficits and other climatic changes, but because the nursery stock and garden centre industry relies on rapid throughput of plants, it will be particularly vulnerable to extreme weather events. Awareness of the risk climate change poses is important. Coping with risks will require business decisions, balancing reserves against increased profits or increased investment, as much as any physical response. The costs, savings and benefits of climate change adaptations should be calculated in relation to the costs of increased productivity or decreased damage.

8.2 Impacts on marketing opportunities

The warmer temperatures that should result from climate change may stimulate the enthusiasm for gardening and the use of gardens. The sale of garden products, such as garden furniture, tools and equipment for an outdoor lifestyle, may therefore increase.

Climate change also offers the opportunity for introducing new exotic species onto British patios and possibly even the open ground, benefiting both suppliers and customers. However, successful establishment of exotics depends crucially on adequate hardening off. For example Citrus 'Meyer's Lemon' has been cultivated outdoors in the UK for several years. The plant is grown by UK raisers under glasshouse conditions, but needs careful hardening off if it has a reasonable chance of surviving outdoors. Many retailers are importing exotic new species from warmer countries. Without suitable hardening off, it is likely that such imported plants may not survive the transition from growing in a warm climate to a cool one.

Similarly for many potential new garden species, there exist in the UK selected clones which have demonstrated their hardiness. If the same species are obtained from abroad it is likely that less hardy clones will be selected with the resulting poor establishment. Clonal selection of exotic species for growing in the UK is therefore important.

As gardeners become more adventurous, the loss of garden plants from drought, floods or late frosts should potentially be beneficial for the garden industries if they can themselves manage to escape the worst effects of extreme weather events.

Some idea of what may be possible in terms of planting in warmer conditions can be seen in gardens such as Tresco on the Isles of Scilly, or in many Cornish gardens, which enjoy exceptionally mild climates. Nurseries such as Hilliers are expanding their range of Mediterranean plants and palms (Woodhead, *pers. comm.*) and others are exploring the boundaries of what is possible in relation to the introduction of exotic new species into British gardens (Emmett, *pers. comm.*).

A sophisticated international network of breeders and growers is feeding new plants into UK garden centres, especially half-hardy bedding container, and hanging basket plants from Australia, California, Germany and elsewhere. Decrease in size of new gardens, an increasing emphasis on outdoor leisure and disinclination to struggle to maintain small lawns is leading to an explosion of demand for decking and containers.

Encouragement to change the contents of containers several times each year could stimulate an increase in year-round sales of plants and perhaps reduce the risks currently incurred in heavy dependence on spring sales. Indeed, autumn planting in general may become more popular. Before the advent of container plant production the majority of planting in UK gardens was carried out with bare root plants in October, November and December. The availability of container plants has shifted the main planting season to the spring when more pleasant planting conditions usually prevail. A trend to warmer, drier autumns and increasingly mild winters could regenerate interest in autumn planting, a move which would also reduce the risk of losses of newly (spring) planted material in summer droughts. A particular opportunity for nurserymen will arise, as summer temperatures increase and summer rainfall decreases, of focussing customer attention on autumn gardening as a sign that the heat of summer is over in much the same way that spring sales reflect delight in the end of winter. This will require research and development of new crops and crop schedules and a considerable marketing effort, but potential rewards are substantial.

Table 9, overleaf, indicates species that have potential as new garden plants in the future conditions of climate change.

Quite often it is not the ability to survive winter cold that limits the introduction of new species into UK gardens, but their ability to tolerate wet conditions. For example many cactus species can tolerate temperatures well below freezing, but will not tolerate wet conditions. Retailers may introduce new species which are cold tolerant, but may be quite intolerant to the wet conditions which inevitably occur during UK winters. As well as the possibility of introducing new exotic species into gardens many 'less exotic'species are likely to do better under conditions of climate change. For example, cyclamen will thrive in milder winters and drier summers.

Climate change is likely to alter and expand the range of plants which can be grown in the UK. There is potential to encourage gardeners to use their gardens more and to invest in them more, whether on new outdoor furniture, new exotic plants or water conservation equipment.

As with impacts of climate change on garden visitors, so with impacts on garden expenditure, there will be some direct and obvious effect of climate change but marketing will be the main factor in shaping the garden industry market.

Table 9: Plants likely to perform better in a warmer climate. *(Source: Emmett [pers. comm.])*	
The following genera (listed by family) are currently of interest to enthusiasts of exotic gardening because they contain species that are currently on the borderline of cold/wet tolerance in milder regions of the UK.	
Agavaceae	*Agave*
	Cordyline (Torbay palm)
	Yucca
Aizoaceae	*Carpobrotus* (Hottentot fig)
	Delosperma
	Drosanthemum
Aloaceae	*Aloe*
Araceae	*Alocasia*
Arecaceae	*Chamaerops*)
	Trachycarpus) Palms
	Phoenix)
Bromeliaceae	*Fascicularia*
	Puya
Cannaceae	*Canna* (Indian shot)
Crassulaceae	*Aeonium*
	Crassula
	Echeveria
	Sedum
Musaceae	*Ensete*
	Musa (Banana)
Myrtaceae	*Callistemon* (Bottle brush)
	Metrosideros
Oleaceae	*Olea* (Olive)
Proteaceae	*Banksia*
	Leucadendron
	Grevillea
	Protea
Restionaceae	*Elegia*
	Restio
Zingiberaceae	*Hedychium* (Ginger)

Research and further actions

This desktop study has brought together material from a wide range of sources to explore the potential impacts of climate change on gardens. Of necessity, its focus has been wide more than deep, and in many areas its conclusions have raised as many questions as they have provided answers.

One of the main objectives of this report was to identify gaps in our information on the impacts of climate change on gardening, heritage gardens and the garden industry and, from these gaps, to define a future research agenda. While this is not an exhaustive list, several areas for further investigation have been identified. These are outlined below.

9.1 Climatological research

9.1.2 CLIMATE CHANGE SCENARIOS

Climate impacts on particular gardens will be strongly influenced by their regional climate. Scenarios at a higher spatial resolution would facilitate climate impacts assessments for gardens.

9.2 Horticultural research

9.2.1 FROST SENSITIVITY

There is some doubt as to whether plants will be more or less damaged by frost with climate change. Further research is required to establish whether plants will be more likely to suffer damage as a result of frosting of precocious growth, or less likely to suffer damage because of reduced frequency and severity of frosts.

9.2.2 THE EFFECTS OF WARMER WINTERS ON DORMANCY AND PLANT DEVELOPMENT DURING DORMANCY

There is a substantial literature on dormancy, but the impacts of higher winter temperatures on growth, flowering and fruiting of garden plants needs more attention, as does its effects on winter hardiness. The possible interactions with elevated carbon dioxide concentrations also merits further study. Defra is looking towards funding research in this area.

9.2.3 AUTUMN COLOUR

Summer drought may result in premature leaf senescence and higher autumn temperatures in delayed leaf fall. The potential impacts of climate change on these precursors of winter dormancy have not been studied in any detail, unlike spring emergence from dormancy, but they could have considerable implications for the appearance of gardens in the autumn.

9.2.4 PLANT HARDINESS

Hardiness is determined not just by innate tolerance to freezing temperatures, but also by the conditioning of the plant in the previous summer or autumn. More refined maps of hardiness zones would enable informed judgements to be made on appropriate adaptations to climate change.

9.2.5 CARBOHYDRATE CONCENTRATIONS IN PLANTS

The effects of increasing carbohydrate concentrations in plants on flowering, autumn colour, and susceptibility to pests and diseases needs further investigation.

9.2.6 PESTS AND DISEASES

The incidence and virulence of pests and diseases in future, needs further investigation, with particular emphasis on phenology, monitoring and environmentally sensitive control.

9.2.7 WEEDS AND POTENTIAL WEEDS

The introduced plants which are currently causing concern in the UK, notably Japanese knotweed (*Fallopia japonica*) and *Rhododendron ponticum*, were in cultivation for a century or more before they became problems. It is important to understand why this should be, to review the various causes of exotic plant infestations in other parts of the world, and to establish which plants have the propensity to become problems in the UK as a result of climate change.

9.2.8 THE RELATIONSHIP BETWEEN PLANTS AND SYMBIOTIC SOIL FUNGI AND BENEFICIAL MICRO-ORGANISMS

Climate change may have significant impacts on mycorrhizal and other symbiotic associations, both directly and indirectly by influencing the host plant. A greater understanding of these relationships may result in the ability to offset adverse effects of climate change on trees, for example, by increasing mycorrhizal activity.

9.2.9 LAWNS

Lawns already receive considerable research input, mainly because of the importance of grass surfaces for sports. Most of this research is focused, however, on highly managed surfaces such as golf greens and football pitches. More research is needed, and the results of previous research on agricultural grassland and ecologically important grassland communities need to be reinterpreted, to meet the needs of gardeners seeking to adapt to the particular conditions imposed by climate change. Ways of managing lawns in wet conditions during late autumn, winter and early spring require specific investigation.

Mower manufacturers would do well to look at possible changes in mowing technology, to reduce compaction risk and perhaps to reduce the impacts of mowing on the environment.

9.3 Research on soils and water

9.3.1 SOILS

Soil is, in every sense, fundamental to the garden. Research into the fluctuations and fate of soil nitrogen and the dynamics of the relationship between nitrate release and uptake by plants or loss by leaching will have far reaching implications for gardens. Research into the dynamics of gain and loss of soil organic matter should also be considered a priority.

Mitigation of climate change is not within the scope of this present study, but it must not be forgotten that management of soil carbon (as organic matter) will have impacts on mitigating the effects of climate on gardens *and* on the mitigation of climate change itself.

9.3.2 WATER SUPPLY AND DEMAND

Further analysis of the potential demand for water in gardens on a regional basis will highlight problems of supply, and foster examination of possible methods of reducing or meeting water demand

Further research and dissemination of good practice is also needed to prevent loss of water quality in ponds and lakes as a result of climate change and to explore the possibilities of storage and recycling of rain and ‘grey’ water in domestic gardens.

9.3.3 WATERLOGGING

Amelioration and/or remediation of winter waterlogging and its effects on the growth of mediterranean plants requires further investigation. Predicted warmer winters and hotter, drier summers will encourage gardeners to grow more mediterranean plants, which are increasingly popular, but wetter winters will pose problems for these plants, which are generally intolerant of winter waterlogging. The suggested topic is a particular aspect of the wider issue of water management and one which is a practical issue for amateur gardeners, who will want to exploit the opportunities to grow a wider range of exotic plants in an environment of increasingly variable water supply.

9.4 Economic research

9.4.1 GARDEN VISITOR PATTERNS

Greater awareness is needed of visitor behaviour in a garden, so that gardens may better cater for visitors’ needs. Better understanding of the factors influencing visiting is also required to inform marketing strategies in present and future climates.

9.4.2 INDUSTRY RELEVANT RESEARCH

Technical investigations into improved production systems, including improved water management, ventilation or cooling systems for greenhouses, management and timing of production of novel crops, is required. Market research is also needed to gain a better understanding of customer behaviour and requirements.

9.4.3 HERITAGE SECTOR

More research on climate change effects for heritage gardens and landscapes is needed. English Heritage has commissioned UCL's Centre for Sustainable Heritage to undertake a scoping study to investigate likely risks and potential mitigation and adaptation strategies for the historic environment. The scoping study will be published in 2003. Climate change impact monitoring is also identified in the heritage sector's forthcoming annual *State of the Historic Environment* report.

Specific heritage garden research will also be needed to identify resources and level of investment required to maintain the quality and integrity of these gardens and the criteria for the management of significant plant collections on a national basis. The National Trust, for example, plan to assess the climate change risks facing its own parks and gardens. The value of conservation management plans as tools for managing change needs to be promoted; and the training and education of professional gardeners needs to supported to ensure the availability of skilled staff to manage these sites in the future.

9.5 Networks

9.5.1 A GARDEN NETWORK

The literature reviewed for this study suggests that the outcomes of much of the research outlined above will be varied and dependent on complex interactions. Interdisciplinary research at the level of the whole plant and plant community is needed. More needs to be understood about the role of gardens and parks in relation to biodiversity, nationally and internationally and how they might provide 'connectivity', in the form of green corridors, to ensure wildlife migration as climate zones shift.

A garden network is needed to exchange and coordinate observations, ideas and actions, and to communicate the effects of climate change on gardens widely. The network should highlight solutions to management problems and identify areas for further research relating specifically to the impact of climate change on gardens.

9.5.2 TOWARDS A *HORTUS EUROPEUS*

Flora Europea (Tutin *et al*., 1964) maps the natural distribution of plant species in Europe (see Figure 17 for examples). The parallel development of distribution maps for selected garden plants as a basis for (and result of) phenological mapping would provide a valuable resource in determining the actual and potential response of garden plants to climate change. It would also facilitate studies of plant hardiness and refinements to the concept of hardiness zones referred to in section 9.2.4 above.

There is clearly scope for, and great benefit in, relating garden plant phenological records with those of native plants, many of which contribute to gardens as well as to the wider landscape. Links with the International Phenology Garden Network, established in 1957, would be particularly useful in enabling comparisons with countries which currently have climates similar to those anticipated for the UK by the UKCIP02 climate change scenarios.

Data on responses of garden plants to changes in weather and climate are continually collected by UK gardeners. Systematic gathering of even a small proportion of this information through professional organisations would add significantly to our understanding of what will grow, and where.

9.5.3 AN INDICATOR SPECIES LIST

A list of genetically uniform plants which can be grown in a wide range of gardens should be developed to monitor the effects of climate change in gardens. The survival (tolerance of low and perhaps of high temperatures) and phenological data of these species should be collected. Plants which might not be expected to survive the winter in many situations should be included in the list to investigate hardiness.

9.6 Policy development

The garden network (above) should be used to disseminate an understanding of the importance of gardens in the national culture, so that they receive a rightful place in policy formulation. Nature conservation is achieved by a range of statutory designations and controls, but garden conservation does not receive such attention. The environmental and cultural benefits inherent in sensitive management of the garden heritage underline the importance of gardens in responding to the impacts of climate change. It is, therefore, important to ensure that gardens in all their diversity receive proper attention when matters of national and European policy are being developed.

Conclusions

Climate change is not something about to happen. It is something which is already here and is accelerating at a rate not previously experienced in the Earth's recent history. Current concerns about the potential effects of climate change on gardens have arisen not out of a theoretical possibility of change, but because we are already facing the consequences of climate change and extreme weather events.

The great storm of October 1987 marked a watershed in thinking about trees and gardens, with the realisation that nothing is immortal. Plant populations in gardens require constant management, development and renewal if they are to survive. The timespan within which major decisions need to be taken in gardens, will result in climate change becoming a significant factor in determining the direction and objectives of management inputs. With the exception of historically important gardens with closely prescribed planting schemes, gardens will be able to adapt to climate change and some will benefit, but the cost of adaptation may be considerable.

In discussing the impacts of climate change on UK gardens, it is important to distinguish between long term trends and the occurrence of sudden extreme events. The two main trends are steady increases in mean temperature and a reduction in annual precipitation, particularly in the summer, but the scale of change varies by region across the UK. The combination of heat and drought will be most damaging to large trees growing on light soils in the south of England, but its effects will be felt to a greater or lesser extent throughout the UK. In the north, for example, more rapid growth of vigorous annual weeds will threaten gardens where slow growing plants are particularly susceptible to competition, and gardens on steep slopes with shallow rocky soils will be very susceptible to drought.

The more dramatic impacts on gardens come from extreme weather events, particularly droughts, gales and floods. These are unusual and unpredictable events but they help to emphasise the importance of sustained management of the garden heritage, of not allowing a garden to slip into senile decay, in which condition it is vulnerable to even a modest gale.

The symbol of a garden as Paradise, a Garden of Eden, is an ancient but still a powerful one. The image of the UK as one large garden, a green and pleasant land, is a source of pride, pleasure and healthy exercise for many of its inhabitants and a magnet for tourists. Our garden heritage is a valuable national resource and warrants continued investment.

The role of gardens and parks as innumerable components in a green web, supporting and at times replacing the fragile network of natural ecosystems, has been little explored in this report. However, these millions of landscapes, large and small, will have a vital role to play in reinforcing a system of ecological corridors through which wildlife can migrate in response to climate change.

Lastly, the beneficial effects of good soil management and maintenance of a healthy plant cover in coping with climatic extremes in gardens provides a model which, if followed on a national and international scale, will do much to slow the pace of climate change and to reduce its impacts.

Adapting gardens to the impacts of climate change will incur additional expense and labour. However, by investing in gardens and by adopting good gardening principles on a wider scale, the UK will be able to address the implications of climate change for our gardens, and give future generations the opportunity of experiencing the pleasure of sitting under a tree that is some 200-300 years old.

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Appendices

Climate change questionnaire

The questionnaire below was sent to fourteen gardens. Replies were received from:

Nick Jarvis
Alfriston Clergy House, Sussex
Professor John Parker
Cambridge Botanic Garden
David Lock
Chirk Castle and Garden, Wrexham
Professor Charles Stirton
National Botanic Garden of Wales, Llanarthne
Peter Hall
Powis Castle and Garden, North Wales
Chris Bailes
Rosemoor, Devon
Dr David Rae
Royal Botanic Garden, Edinburgh
Dr Nigel Taylor
Royal Botanic Gardens, Kew, Surrey
Sarah Cook
Sissinghurst Castle Garden, Kent
Barry Champion
Trelissick, Cornwall
Jim Gardener
Wisley, Surrey

Climate Change and Gardens
1. What is the planning time-frame within which you operate? How far ahead do you plan for the garden?
2. What are the general objectives of any forthcoming changes? Expansion, upgrading of facilities, increased diversity of facilities, to attract more visitors, to widen visitor base, more economy /efficiency of operation, increased historical authenticity etc
3. What are the major influences on forthcoming changes? Budgetary restraints, need to attract visitors, difficulties in staff recruitment, new historical evidence, increasing emphasis on education etc.
4. What is your next major development?
5. To what extent does sustainability feature in your planning? Please tick one: a. Central driving force b. Important consideration c. Of some importance, but other factors more important. d. Minor importance e. No importance
6. To what extend does the need to respond to climate change feature in your planning? (Please tick one) a. Central driving force b. Important consideration c. Of some importance, but other factors more important d. Minor importance e. No importance
7. Can you cite recent (past 5 years) examples of extreme weather events which have affected your garden?
8. In your experience, are extreme weather events more or less frequent than they used to be? *Continues overleaf*

9. Below are some predictions about climate change over the next 20-50 years based on the UKCIP98 climate change scenarios. What positive and/or negative effects on your garden do you anticipate from these predictions if they prove to be true?
    a. A mean temperature rise of 2-5°C. (giving the south of England a climate similar to that of Bordeaux, and the north of England a climate similar that of Surrey).
    b. A 3-fold increase in the number of hot days (above 27°C or 80°F)
    c. 5-10 days each year with temperatures above 40°C or 105°F
    d. A longer growing season – perhaps ten days earlier start and later finish
    e. Substantial reduction in number of days with frost (to near nil in parts of Southern England).
    f. 20% increase in winter rainfall
    g. 20% decrease in summer rainfall
    h. Increasing uncertainly of rainfall: alternation of droughts and heavy rainstorms
    i. Increased incidence of strong winds
    j. 50cm rise in mean sea level
    k. Any other direct impacts of climate change
10. Do you see an overall benefit, an overall deficit, a balance of advantages and disadvantages or no impact for your garden in each of these scenarios? (Please write "ben", "def", "bal" or "no" as appropriate below.
    a. A mean temperature rise of 2-5°C (giving the south of England a climate similar to that of Bordeaux, and the north of England a climate similar that of Surrey).
    b. A 3-fold increase in the number of hot days (above 27°C or 80°F)
    c. 5-10 days each year with temperatures above 40°C or 105°F
    d. A longer growing season – perhaps ten days earlier start and later finish
    e. Substantial reduction in number of days with frost (to near nil in parts of Southern England).
    f. 20% increase in winter rainfall
    g. 20% decrease in summer rainfall
    h. Increasing uncertainly of rainfall: alternation of droughts and heavy rainstorms
    i. Increased incidence of strong winds
    j. 50cm rise in mean sea level
    k. Any other direct impacts of climate change
11. Would the overall impacts on your garden of the climate change phenomena described above be beneficial, damaging or neutral?
12. Are you (or are you likely to be) taking any steps in your garden to adapt to anticipated impacts of climate? If so, what steps?
13. Are you (or are you likely to be) taking any steps to reduce the causes of climate change?
14. Do you maintain records of;
    a. climatic data?
    b. phenological data?
    c. visitor numbers?

Many thanks for your time. The results of this questionnaire will be published, as part of a report on the impacts of climate change on gardens, in 2002.
Richard Bisgrove

Glossary

Acclimation: literally "becoming adapted to", as when plant response to higher carbon dioxide concentrations decrease because the plant has adapted to the new situation. **Acclimation** is used in plant physiology in preference to "acclimatisation" which strictly means "becoming used to a new climate".

Albedo: reflectivity of a surface. A surface (for example a dark soil) which has an albedo of zero absorbs all the light falling on it. A surface with an albedo of one (for example, fresh snow) reflects all the light falling on it.

Arthropod: animals (usually small animals) with segmented bodies and jointed limbs. Arthropods include insects, mites and millipedes, for example.

Assimilates: in the context of plants, materials such as carbohydrates and proteins, which the plant synthesises and then incorporates into its tissues.

C3/C4 plants: photosynthesis in **C3 plants** (most plants from temperate regions) involves 3-carbon molecules building into sugars. Some (mainly tropical) plants have a different mechanism involving 4-carbon molecules, with the advantage that they are able to store then release carbon dioxide within the leaf so that photosynthesis can take place while stomata are closed. These are referred to as **C4 plants**. A full explanation cannot be given in simple terms. The topic of C3/C4 plants has been referred to only in passing in the text, because temperatures much higher than those anticipated in the UKCIP02 scenarios would be needed to make significant use of C4 plants in UK gardens.

Clone: a population of genetically identical plants (and now animals). Clonal plants are produced asexually, by vegetative propagation, rather than from seed.

Development: see **Growth**

Dicotyledon(ous plant) (abbr. **Dicot**): there are two major divisions in the plant kingdom. Those which emerge from the seed with two seed-leaves (cotyledons) are known as **dicotyledons** or **dicots**. Most of these have broad true leaves. Those which emerge from the seed with one cotyledon are known as **monocotyledons** or **monocots**. Most of these, such as grasses and bulbs (narcissus, crocus, lily) have narrow leaves.

Dry matter: the substance (including carbohydrates and proteins) of plants as measured after drying the plant in an oven to remove all water. Dry matter includes the assimilates (q.v.) within the plant and the structural material of the plant.

Evaporation: conversion of (liquid) water to water vapour. Evaporation from plant leaves is often termed **transpiration**; the combination of evaporation from soil and leaf surfaces, and transpiration from within the leaf is termed **evapo-transpiration**. The amount of water which could theoretically be evaporated in particular climatic conditions is the **potential evaporation**, or **potential evapotranspiration**. Actual evaporation is usually less than potential evaporation because the amount of water available for evaporation is reduced as the soil dries and plants become stressed.

Growth: the increase in size of the plant. **Development** refers to changes of state within the plant, such as the production of leaves, the formation and expansion of flowers or the onset of dormancy.

Legume/leguminous plant: a plant of the family Leguminosae, with pea or bean-like flowers. Legumes include herbaceous plants such as sweet pea, shrubs such as broom (Cytisus) and gorse (Ulex), and trees such as Robinia and Laburnum. Legumes have root nodules in which symbiotic bacteria (q.v.) live. These are capable of converting atmospheric nitrogen into nitrates.

Monocotylendon(ous **plant**) (abbr. **Monocot**): see **Dicotyledon**

Mycorrhiza (plural **Mycorrhizae**): fungi which live in association with plants (especially many trees). The fungus receives assimilates (q.v.) from the plant roots and supplies the roots with minerals obtained from the soil through its extensive hyphae. Mycorrhizae are especially important in very acid or very poor soils as they are capable of extracting minerals which would be unavailable to the tree itself.

Multivoltine: having several generations each year.

Nematode: eelworm. A microscopic, worm-like creature. Some nematodes are harmful to plants, causing deformation of roots, stems or leaves. Others are beneficial, attacking pests such as vine weevil.

Phenology: the study of organisms as affected by climate, especially the timing of seasonal phenomena such as leaf emergence or flowering of plants, or seasonal arrival of migrant birds and butterflies.

Phenotype: the observable characteristics of a plant or animal produced by the interaction of its genetic make-up and the environment.

Photoperiod: length of the light period, usually in relation to a 24 hour day. ‘Long-day’ plants will respond (for example by flowering or emergence form dormancy) to photoperiods above a critical value. ‘Short-day’ plants will develop in response to short or declining photoperiods.

Pneumatophore: a woody outgrowth on the roots of swamp cypress (*Taxodium distichum*) which grows above the surface of water or wet soil to conduct oxygen down to the root system. Pneumatophores are commonly called ‘knees’.

Potential evaporation: see **Evaporation**

Ppm(v): parts per million. Gas concentrations are usually measured as parts per million by volume (**ppmv**) while concentrations of substances in solution or in mixtures of solids are measured in parts per million by mass (**ppmm**).

Precipitation: the amount of water reaching the soil surface, whether as rain, hail, snow or settlement of water droplets from mist and fog. A more inclusive term than ‘rainfall’.

Provenance: the location from which seed is obtained. Provenance is important because there can be wide variations within a species as a result of evolution in different climatic zones. Spruce trees from seed obtained from a population in Alaska, for example, will be much slower growing and have a shorter growing season, but be much more cold tolerant than seed collected from the same species in more southerly regions when both are grown in the same place.

Sink: plant physiologists use the term **source** to refer to the sites within the plant where assimilates (q.v.) (especially products of photosynthesis) are formed and **sink** to refer to the sites to which assimilates are transported for use. The presence of an active **sink** in the plant (such as actively growing tips or developing flower buds or seeds) will stimulate the plant to photosynthesise more rapidly.

SSSI: Site of Special Scientific Interest. A statutory designation of land, sometimes an extensive area of a particular habitat and sometimes a small area containing a rare plants or animals.

Stoma (plural **stomata**): small pores in the plant leaf (and to a lesser extent on other surfaces), through which water vapour and gases such as carbon dioxide and oxygen diffuses into and out of the plant. The stoma is bordered by guard cells which open and close the pore in response to changes in water vapour and carbon dioxide concentration. **Stomatal aperture** is the size of the pore.

Symbiosis: coexistence for mutual benefit. Mycorrhizae (q.v.) and trees have symbiotic relationships, as do the bacteria in root nodules of leguminous plants (q.v.) with their host plant.

Synchrony: (= same time). Two events which are organised so that they happen together are said to be synchronous, or to exhibit synchrony. In biology, synchrony evolves to ensure that a food source is available in suitable condition to sustain another organism, as when the hatching of a caterpillar is synchronised with the emergence of the leaves on which it needs to feed.

Thermal growing season: the longest period within a year that satisfies the twin requirements of (i) beginning at the start of a period when the daily average temperature is greater than 5.5°C for five consecutive days and (ii) ending on the day prior to the first subsequent period when the daily average temperature is less than 5.5°C for five consecutive days. The actual growing season will depend on the type of plant, on its emergence from dormancy and other factors but **thermal growing season** provides a precise meteorological measure of the way in which growing conditions vary from year to year.

Thermal time: the ‘amount of heat’ received by a plant. Thermal time is the product of the number of days and the number of degrees above a particular minimum for the process under consideration. The timing of many plant growth responses, such as breaking of dormancy or initiation of flowers, is determined by thermal time.

Transpiration: see **Evaporation**

Xerophyte (adj. **Xerophytic**): a plant adapted to very dry conditions, by its compact form, thick, waxy leaf surface or other characteristics.

Xeriscape: the use of xerophytic plants to create gardens which have low water requirements. ‘Dry gardening’.

Examples of climate change scenarios for three case study gardens

In the main report, the impacts of climate change are dealt with component by component, and in terms of regional scenarios. What matters in a garden is the combination of factors at a particular spot. In order to give some feel for these local impacts, three locations have been chosen, in the north, east and south west of the UK. For each location, basic meteorological data for 1961-90 are presented (Wheeler and Mayes, 1997) and changes anticipated by the medium high emissions scenario for the 2080s estimated by reference to the UKCIP02 scenarios (Hulme *et al*., 2002).

To choose a representative site for the north of the UK, in Scotland, is impossible because the deeply indented coastline and generally steep topography mean that the local influence of the sea and of changing altitude is always present, as anyone who has travelled the 24km (15 miles) from the cold rocky summit of Ben Eighe National Nature Reserve to the palm filled garden at Inverewe will appreciate. However, Ardtalnaig, south of Ben Lawers on Loch Tay has been selected as an inland site at low altitude on the southern edge of the highlands. Its climate is moderated by Loch Tay, which is of sufficient depth that it never freezes, but in other respects it is as 'average' as it is possible to find in this varied landscape.

Cambridge is in the driest part of England, but its climate is representative of a broad swathe of eastern England.

Torquay is a coastal location, but has been chosen as more representative of the south west as a whole than would be a more westerly site. It is also more characteristic of the gardened south west than are places farther inland, where the high moors, thin soils and atypically severe climate impose their local limitations on gardening.

Tables A3.1, A3.2 and A3.3 show January and July data for temperatures and precipitation at each location, and the changes to these which are anticipated by the UKCIP medium high emissions scenario for the 2080s. Current January and July precipitation figures are added to give some indication of changes in annual rainfall (data have not been calculated separately for every month of the year) and the ratio of January to July precipitation is presented to give some indication of the change in seasonal distribution of rainfall.

To avoid tedious repetition of qualifications, in the following descriptions the terms "now", "currently" or "at present" are used, slightly incorrectly, to refer to 1961-90 baseline conditions. References to future conditions throughout the text apply to the UKCIP02 medium high emissions scenario for the 2080s.

A3.1 Ardtalnaig, Loch Tay, Central Scotland

In Ardtalnaig the winter temperature, currently not dissimilar to that of Cambridge, is anticipated to rise by 2°C. The minimum may also increase from an average of 0.4°C, barely above freezing, to 2.4°C, somewhat cooler than Torquay now. In much of Scotland temperature rise could result in mean minimum temperatures changing from negative (below freezing) to positive.

Present July temperatures are 2-3°C below those of Cambridge and Torquay. With an anticipated rise of about 3°C, July temperatures in the 2080s in Ardtalnaig would be warmer than are Cambridge and Torquay at present.

In common with most of the western half of the UK, precipitation in Ardtalnaig falls mainly in the winter months. Current January precipitation is more than twice that of July. With an anticipated 20% increase in precipitation in an already wet winter, but a 35% decrease in a relatively dry summer, total precipitation (currently 50% higher than Torquay and 250% higher than Cambridge) would be little altered but the January:July ratio could change from 2.3:1 to 4.2:1.

Although the magnitude of these changes is less than in the east or south west, the decrease in precipitation in an already dry summer, combined with increasing temperatures, is likely to have a significant impact, especially in gardens on steep slopes and with shallow, rocky soils, where continuous throughput of water is necessary for the growth of the drought sensitive plants which are characteristic of Scottish gardens.

Whether increased winter precipitation is a bonus (replenishing soil moisture depleted in summer) or a problem (saturating soils and causing erosion or flooding) will depend on the management of water within the garden. The total amount of water is likely to be virtually unchanged but the amount available to plants will diminish because of higher evaporation rates at higher temperatures. The need to conserve winter supplies in order to compensate for summer deficits will therefore be very important.

A3.2 Cambridge, Eastern England

In Cambridge, January temperatures, and especially January minima, are currently similar to those in Ardtalnaig. An increase of about 2.8°C in winter temperatures by the 2080s would result in January temperatures higher than those currently experienced in Torquay.

Current July temperatures are similar to those of Torquay, though as a result of slightly higher maximum temperatures and slightly lower minimum temperatures in Cambridge's more continental climate. An increase of 4.5°C in summer tempera-

Table A3.1: Ardtalnaig, Loch Tay, Central Scotland

	1961-90 mean	Change in med high scenario for 2080s	Estimated figures for the 2080s
January		**Winter**	
Max temp (°C)	5.2		7.2
Min temp	0.4		2.4
Mean	2.8	+2°C	4.8
Precipitation (mm)	159	+20%	190
% of annual total	12.7%		
July		**Summer**	
Max temp (°C)	18.6		21.9
Min temp	10.0		13.3
Mean	14.3	+3.3°C	17.6
Precipitation (mm)	69	-35%	45
% of annual total	5%		
Precipn: Jan+July	**228**		**235**
Precipn: Jan:July	**2.3**		**4.2**

tures will not change that comparison. In terms of temperature, Cambridge and Torquay will be similarly affected.

In common with much of the eastern half of the UK, precipitation is distributed evenly throughout the year. July, with 8.7% of the annual precipitation, is slightly wetter in terms of precipitation than January, with 7.8%, although much higher evaporation rates with high summer temperatures mean that water is less available to plants in July.

By the 2080s, winter precipitation is anticipated to increase by 25%, but this could only mean an 11mm increase and would be insufficient to compensate for increased evaporation, given the mean temperature change from 3.65 to about 6°C. Summer precipitation would be nearly halved. Total annual precipitation decreases by a small total amount, but the ratio of winter:summer precipitation could increase from 0.9:1 to about 2:1.

The combination of higher temperatures and reduced precipitation will result in severe drought conditions in many years and accentuate the mediterranean climate which Cambridge already experiences to some extent.

What is not shown in the table of climate data is the fact that much of Cambridgeshire, Norfolk and Lincolnshire is very low lying, some of it at or below sea level. The landscape, and especially water resources, have been intensively managed for agriculture. However, as fertile peat soils have been lost by oxidation or wind-blow and as sea levels rise, land use and nature conservation policies have moved to planned retreat from the most vulnerable areas.

A3.3 Torquay, Devon

Torquay has a mild climate, several degrees warmer in winter than Cambridge and Ardtalnaig. Minimum January temperatures in Torquay are similar to mean

Table A3.2: Cambridge, Eastern England

	1961-90 mean	Change in med high scenario for 2080s	Estimated figures for the 2080s
January		**Winter**	
Max temp (°C)	6.5		9.3
Min temp	0.8		3.6
Mean	3.65	+2.8°C	6.45
Precipitation (mm)	43	+25%	54
% of annual total	7.8%		
July		**Summer**	
Max temp (°C)	21.5		26.0
Min temp	11.7		16.2
Mean	16.6	+4.5°C	21.1
Precipitation (mm)	48	-45%	26.5
% of annual total	8.7%		
Precipn: Jan+July	**91**		**80.5**
Precipn: Jan:July	**0.9**		**2.0**

January temperatures in Cambridge. In summer the differences are much less. Maximum July temperatures are lower than in Cambridge, though the mean is very slightly higher.

An anticipated 2.5°C rise in winter temperatures (compared with about 2.8°C in Cambridge) represents some closing of the difference but Torquay remains 2-4°C warmer than the other two places. Anticipated summer increases of about 4°C would result in 2080s summer temperatures again very similar to those of Cambridge.

As in Ardtalnaig, precipitation in Torquay falls mainly in the winter months. January, with 114mm, has 2.5 times the July precipitation of 46mm. A 20% increase in anticipated winter precipitation would result in an extra 23mm of rain, but increased evaporation would mean that soil moisture content in winter may increase by only 0-4%. July precipitation in Torquay is similar to that in Cambridge and, as in Cambridge, the 2080s scenario anticipates nearly halving this amount. Soil moisture deficit could increase by 40-50%.

The overall effect of moderate decrease in the relatively high winter precipitation and a substantial decrease in the much smaller summer precipitation is to leave the total unaltered, but the ratio of winter:summer precipitation could increase from 2.5:1 to 5.5:1. On thin, shallow soils and free draining slopes especially, water shortage in summer will be severe. In the past, lack of major aquifers or rivers to supplement precipitation and the extra demand on supplies caused by a marked increase in summer population of holiday makers has often led to water shortages. The building of new reservoirs has been strenuously opposed because of their impacts on a beautiful landscape. These problems can only increase as climate change continues.

One positive aspect of climate change in the south west is that soil moisture content is expected to increase by only a very small amount, perhaps 0-

Table A3.3: Torquay, Devon

	1961-90 mean	Change in med high scenario for 2080s	Estimated figures for the 2080s
January		**Winter**	
Max temp (°C)	8.8		11.3
Min temp	3.4		5.9
Mean	6.1	+2.5°C	8.6
Precipitation (mm)	114	+20%	137
% of annual total	12.7%		
July		**Summer**	
Max temp (°C)	20.6		24.8
Min temp	13.1		17.3
Mean	16.85	+4.2°C	21.05
Precipitation (mm)	46	-45%	25
% of annual total	5.1%		
Precipn: Jan+July	**160**		**162**
Precipn: Jan:July	**2.5**		**5.5**

4% above current levels. Soil saturation which has been a feature of recent exceptionally wet winters and which has led to root rot of many plants, especially magnolias, seems unlikely to become the norm. Gardeners will not be facing a losing battle if they improve soil drainage to contend with the problems caused by what should be infrequent very wet winters.

Another possible advantage is that the summer climate, although posing serious challenges for the cultivation of gardens, will improve the prospects of the south west as a holiday destination and improve the prospects for major gardens relying on tourism for their livelihood.

A3.4 Summary

In all three locations, the main challenge will be in coping with much drier conditions in the summer. In the north, higher winter rainfall will assist in overcoming the problem if the winter surplus can be stored. In the east, precipitation will decrease throughout the year and higher evaporation rates will exacerbate water shortages. In the south west, annual precipitation will be little altered by climate change but higher evaporation rates will reduce the amount of available water. If the UKCIP02 scenarios are reasonable approximations of climate change, it is unlikely that excessive winter wet will be an increasing problem, although there will, of course, be some very wet winters (and indeed some very wet periods in some summers) as in the past.