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Cover images (from top): Protea longiflora *(NT)*; Hardy's Cottage *(Eric Chrichton, NTPL)*; Nymans *(Patsy Fagan, NTPL)*.

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UK Climate Impacts Programme

RHS

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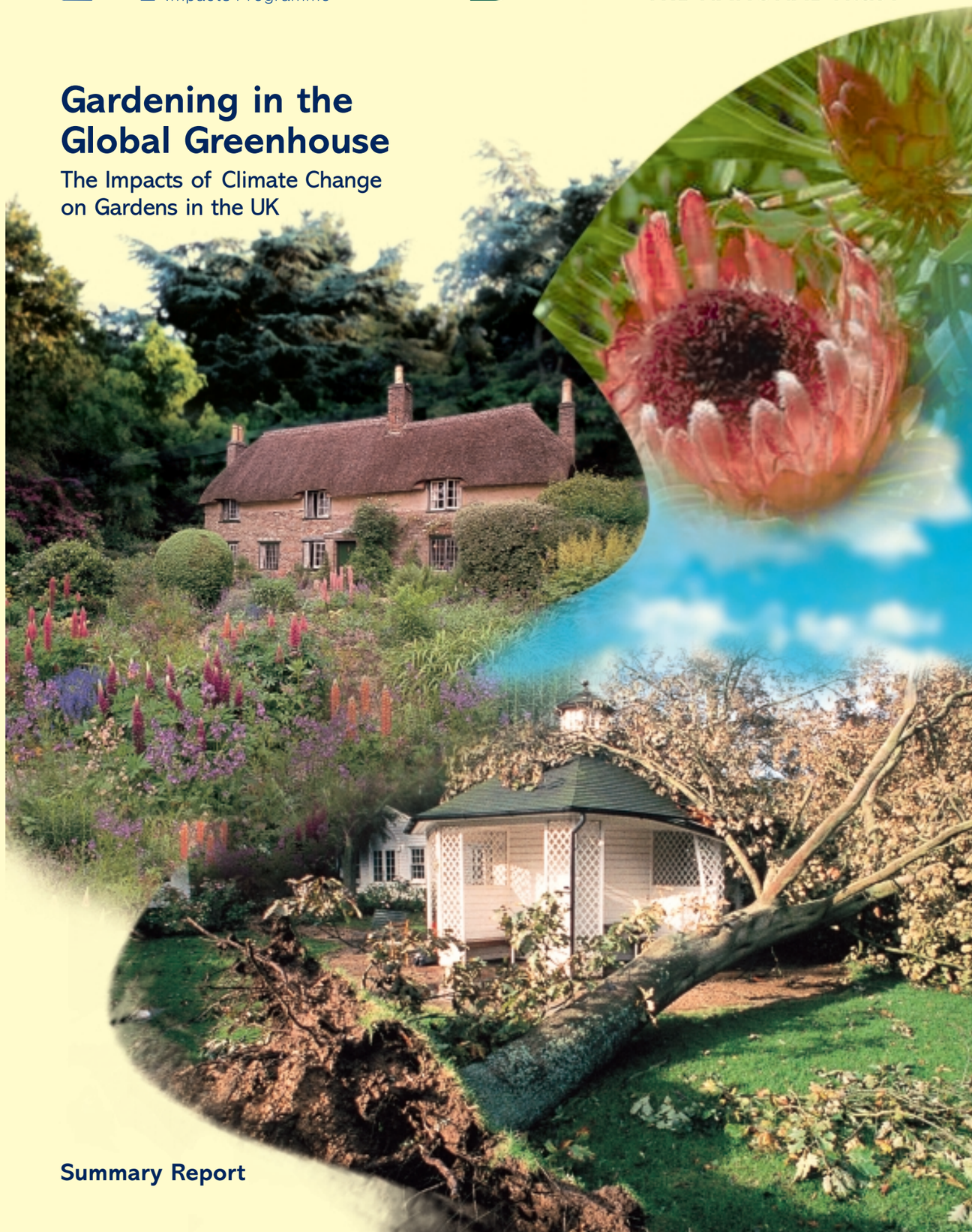
Gardening in the Global Greenhouse

The Impacts of Climate Change on Gardens in the UK



Summary Report

ST. JAMES'S PALACE

As a passionate gardener with a keen interest in both our national heritage and environment, I welcome this timely report on the potential impact of climate change on British gardens and the industry they support.

For centuries, gardening has been part of the British psyche. Our own gardens are important to us as individuals, and our major gardens, many of which are of international importance, are a significant part of our cultural identity. With garden tourism and gardening now contributing substantially to the national economy, there is an urgent need to understand the implications of climate change for gardens and gardening so that we can prepare for the future.

Almost all scientists now agree that the British climate is likely to change significantly in years to come. The precise nature and scale of those changes is still uncertain, but it is both an alarming and sobering thought that some features of the nation's best-loved gardens might become unsustainable due to changing climatic conditions. Marked changes in seasonal temperatures and rainfall, together with extreme events such as drought, flooding and storms, will have major implications for all our gardens.

For domestic gardeners, climate change will bring challenges, but may also open up new prospects. Those who are willing to adapt to the changes will be able to draw on a wider palette of garden plants and pursue exciting new design opportunities. The prospect of gravel gardens replacing lawns and tropical planting replacing the traditional herbaceous border will certainly not please everyone. But it seems likely that some of the quintessential elements of the English garden will become increasingly difficult to maintain. Soil and water conservation will remain of paramount importance.

Reading the findings of this report should literally bring home the implications of climate change. Understanding the scale of the challenges we will face in our own gardens may perhaps help us to comprehend the wider implications of climate change for mankind. This, in turn, might encourage us to take responsible action to limit the damage by reducing emissions of carbon dioxide as rapidly as possible. Important though they undoubtedly are, a great deal more than our gardens is at stake.

Introduction: The British and their gardens

The British are noted for their love of gardens. As an art form, gardening is an essential part of our culture. It is one of the leading hobbies in Britain, with an estimated 27 million gardeners (41 per cent of the population) participating in some way. Gardeners sustain a multi-million pound horticultural retail industry. Our heritage gardens and their plant collections, representing 500 years of garden history, attract 24 million visitors each year, contributing an estimated £300 million to the tourism industry.

Drought dried out lakes and reservoirs in 1976
(Mike Sleigh, RHS)

Trees at Chartwell, Kent felled by the storm in 1987
(Peter Baistow, NTPL)

[1] *The UKCIP02 scenarios describe how the climate of the UK is likely to change over the course of the 21st century. They were produced for the UK Climate Impacts Programme by the Hadley Centre at the Met. Office and by the Tyndall Centre for Climate Change Research with funding from the Government's Department for Environment, Food and Rural Affairs.*

A wake up call from the weather

Gardeners are more aware than many how the weather affects them and their interests. Over the last four decades, extreme weather events have severely damaged many gardens and resulted in major economic losses. These events include:

- severe winter weather in 1962/63 that killed many hardy plants;
- drought in 1976, which weakened trees and dried out lakes;
- storms in 1987 and 1990 that felled millions of trees;
- torrential and prolonged rain leading to soil erosion, flooding and drowning of plant roots in 2000 and 2001.

These events highlight the vulnerability of gardens to the vagaries of weather and climate. A workshop was held in London in April 2000, attended by gardening organisations, commercial horticulturists, landscape consultants, the horticultural press, and representatives from local and national government, universities and research organisations, to consider how gardens would be affected by climate change.

Flooding at Westbury Court, Glos. in 2000/01 *(NT)*

The primary outcome of the meeting was the commissioning of a technical report, entitled 'The Impacts of Climate Change on Gardens in the UK', by Richard Bisgrove and Professor Paul Hadley, of the University of Reading (2002). The authors assembled and evaluated evidence on how plants and garden components respond to altered climatic conditions, and assessed the likely impact of the UKCIP[1] climate change scenarios on gardens in the United Kingdom.

This document summarises their report. It describes effects on garden plants, domestic gardens, nationally important heritage gardens, the landscape industry and the retail horticultural industry. It discusses aspects of gardening that might benefit from climate change and identifies techniques and practices that might reduce undesirable effects of climate change on gardens. It also highlights the important role that gardens can play in raising awareness of environmentally sustainable practices which can minimise the effects of climate change, and identifies areas for further research.

What is happening to our climate?

The current phase of climate change is part of a continuous warming of the climate recorded over the last 150 years and is being caused primarily by industrial activities that have raised levels of greenhouse gases which retain heat within the atmosphere.

There is overwhelming evidence that the rate of warming is increasing, although projections for the rate and extent of warming vary, depending on predictions of economic growth, human population levels and compliance with international agreements to regulate emissions of carbon dioxide, the most important greenhouse gas.

In the UKCIP02 high emissions scenario, with rapid economic growth in developed and less developed countries and a market driven reliance on fossil fuels, by the 2080s average temperatures are likely to rise by 2°- 4.5°C, at a rate of between 0.3°- 0.5°C per decade. This is between two and three times faster than the current rate of temperature increase.

Traditional scenes such as this at Bodnant, Gwynedd will become a rarity *(Christopher Gallagher, NTPL)*

Droughts will become more frequent *(NT)*

In the low emissions scenario, at the current rate of 0.1°- 0.3°C rise per decade annual average temperatures will increase by 1° - 2.5°C by the 2080s. This lower rate of increase would depend on the use of clean and efficient technologies, reduced use of natural resources that generate carbon dioxide, and global solutions to problems of social and economic stability and equity between developed and developing countries.

Climate change is already occurring and further change is inevitable, with common consequences for climate in the UK. These are:

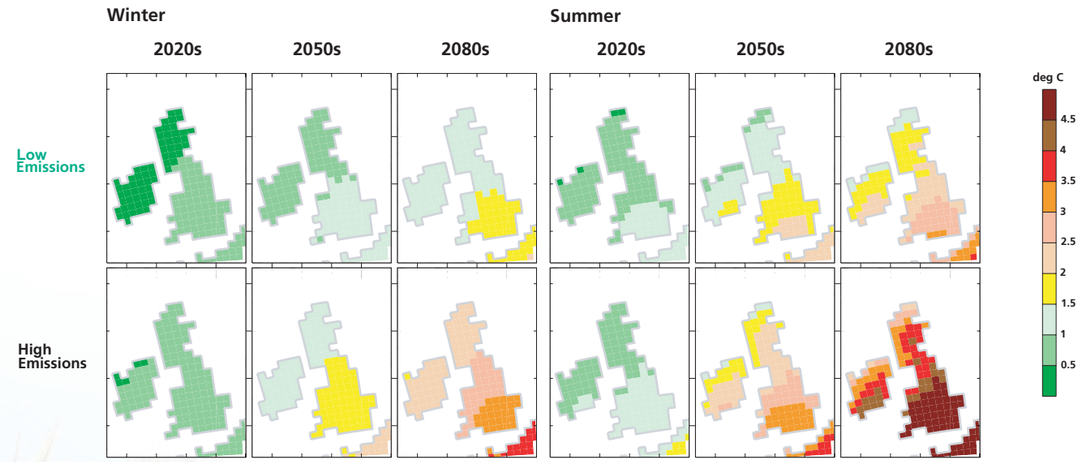
- higher mean annual temperatures, which will increase the length of the growing season for many plants. A 1°C increase in mean temperature will increase the growing season by three weeks in south east England and by 10 days in the north west;
- greater warming in summer and autumn than in winter, with summer maximums rising faster than summer minimums, leading to increased frequency of hot summer days. By the 2080s temperatures may exceed 42°C about once per decade in lowland England;
- winter minimum temperatures rising faster than winter maximums, leading to milder winters with a reduced temperature range and fewer frosts. In many parts of the UK, especially in the south west, frosts will be rare and might occur in Cornwall only about once every 10 years by the 2080s, although local variations will occur. Snowfall will decrease everywhere in lowland and coastal regions by as much as 90 per cent by the 2080s, and by 60 per cent in high snowfall areas such as the Scottish Highlands;
- mean annual rainfall may decrease by 10-20 per cent, but with 10-30 per cent more falling in winter and 20-50 per cent less in summer by the 2080s. Rain will tend to fall with greater intensity;
- by the 2080s summer droughts will be more frequent, as will very wet winters, but autumns will be drier. Higher temperatures and less cloud cover in summer will lead to greater evaporative loss from soils and leaves, worsening drought conditions;
- although predictions for extreme weather events are less certain than for temperature, weather patterns are likely to become more erratic, with greater frequency of torrential rain, temperature extremes and storms.

Within these overall trends there will be pronounced regional differences, with the lowest rainfall and highest temperatures occurring in south east England. The reduction of soil moisture will therefore be greatest in areas where water supplies are already low.

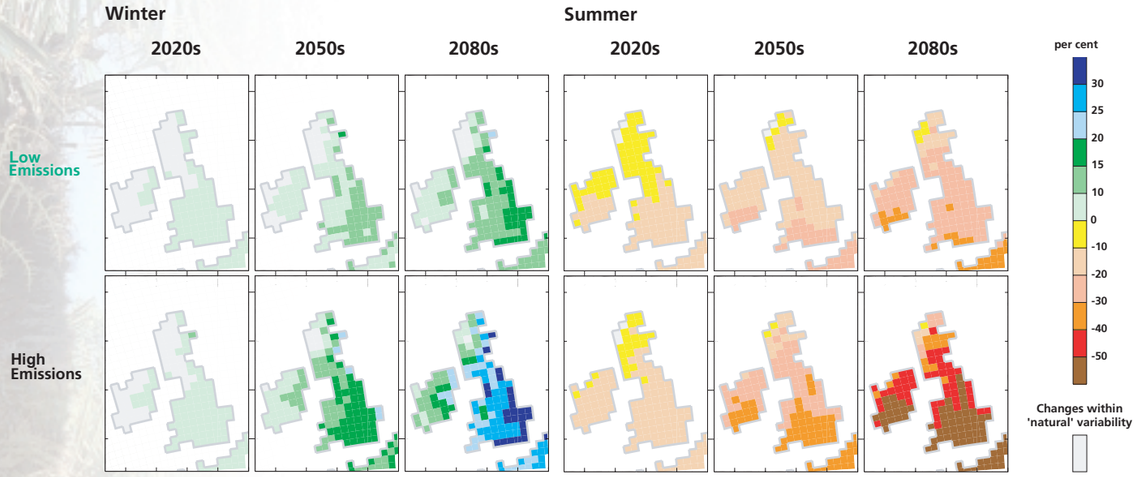
By the 2050s sea levels are expected to rise by 14-18 cm, and by the 2080s by 23-36 cm. The effects will be greatest in the south east, where the land mass is naturally subsiding. Coastal flooding could damage some domestic and major heritage gardens.

These climate changes will have major effects on plant growth and on the ways in which we design, plant and maintain gardens.

Change in average winter and summer **temperature** for the low and high emissions scenarios.



Percentage change in average winter and summer **precipitation** for the 2020s, 2050s and 2080s for the low and high emissions scenarios



Source: UKCIP02 Climate Change Scenarios

Plants in a warmer world: how climate affects plant growth and development

Plants are influenced by extreme weather events and by gradual climate changes, the effects of which are more insidious but potentially dramatic. A small change in average annual temperature of, say, 0.1°C has a cumulative effect through the growing season, with a large net impact. An analogy would be a small change in bank interest rate, which might have little immediate effect on the daily economy but would have a profound impact on annual accounts.

Effects of individual elements of climate change have been tested in controlled environments for some plant species of agricultural importance and there is already evidence that rises in temperature and atmospheric carbon dioxide levels have increased growth of forest trees. Further research is required for the majority of garden plants.

Higher carbon dioxide levels

Atmospheric carbon dioxide, the primary agent of climate change, is used by plants in photosynthesis to produce chemical energy, sugars and other organic molecules essential for plant growth and development. Increases in carbon dioxide levels, which are expected to rise from the current 350 parts per million (ppm) to between 525 and 810 ppm by the 2080s under the low and high emissions scenarios respectively, will increase the rate of photosynthesis and so enhance plant growth. Experiments show that doubling carbon dioxide levels can increase plant growth by as much as 50 per cent, although this varies depending on plant species, temperature, water supply and mineral nutrient availability.

"... doubling carbon dioxide levels can increase plant growth by as much as 50 per cent .."

Bisgrove and Hadley (2002)

The way in which plants use the additional products of photosynthesis varies between species and is affected by other environmental factors. Under conditions of water stress, some plants divert resources into root production, improving water uptake. Plants use water more efficiently as carbon dioxide levels rise, because a reduction in the numbers and opening of stomatal pores on leaf surfaces slows water loss. Nitrogen is also used more efficiently, so although plants will grow more rapidly, fertiliser requirements do not necessarily increase. Increases in carbon dioxide levels can hasten bud burst, flowering and fruiting and lead to earlier cessation of growth, depending on species investigated. In roses, higher carbon dioxide levels increase the number of flower buds, which bloom earlier and accelerate flowering.

Higher carbon dioxide levels can hasten bud burst
(Stephen Robson, NTPL)

Higher temperatures

Higher temperatures increase growth rates, provided that no other factors are limiting. It is unlikely that the higher temperatures expected by the 2080s will physically damage plants in the open ground, except for brief, exceptional periods, but damage may occur in glasshouses unless these are well shaded and ventilated.

Higher temperatures produce faster seed germination, bud burst, leaf expansion and flowering. Advances in flowering date can be predicted for species whose temperature response characteristics are known. Plants like Mexican orange *(Choisya ternata)* and *Rhododendron* 'Praecox' are likely to flower earlier, but others such as honesty *(Lunaria annua)* and bleeding heart (*Dicentra formosa)* will be largely unaffected.

"Grape cultivation could extend as far north as Scotland during the second half of the 21st century."

Bisgrove and Hadley (2002)

Grapes could be grown in Scotland in future *(RHS)*

Temperature increase is likely to extend the northern limit for growing some vegetables and fruit. Grape bud burst and maturity dates may advance by up to 50 days and yield may increase by up to 25 per cent by the 2050s.

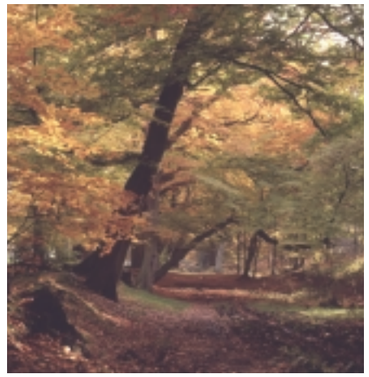
Temperature levels play a key role in regulating the annual growth cycle of perennial plants. Normal bud burst often depends on accumulated experience of winter chilling, which breaks dormancy and prepares buds to open as soon as favourable spring weather arrives. At the end of the growing season, falling temperatures halt growth and trigger leaf fall. The intervening period constitutes the growing season, which will extend as climate changes. Currently spring is arriving 2 - 6 days earlier per decade and autumn two days later each decade. Precocious spring flowering, delayed leaf fall, extended lawn growth and unseasonal winter flowering are already commonplace and will increase in extent and frequency as climate changes.

Earlier springs lengthen the growing season and allow earlier planting dates. Bud burst of most plants will be advanced, but the likelihood of frost damage to precocious growth will be no greater than at present, because frosts will become less frequent. Frost damage in autumn may become more serious, as higher average temperatures delay dormancy and clearer skies increase the possibility of frost.

Failure of plants to shut down metabolic activity in winter might increase frost damage, but higher sugar levels generated in tissues of evergreen species by winter growth might have the reverse effect. Species-specific effects are likely, and further research is needed.

Interactions between higher carbon dioxide levels and higher temperatures

As temperatures rise, plants respond more vigorously to higher carbon dioxide levels. Doubling atmospheric carbon dioxide levels and raising temperature by 3°C can increase growth by over 50 per cent, although this may not be reflected in higher yields. The benefits are greater in vegetables harvested early in development, such as carrots, than in those that are cropped closer to maturity, such as onion and cauliflower. Warmer temperatures shorten the growing period of vegetables like onions, lowering ultimate yields. In potato, higher carbon dioxide levels increase rates of photosynthesis and so slightly increase overall yields, but higher temperatures hasten foliage death.



Autumn is arriving later and later
(Michael Caldwell, NTPL)

Soils: winter waterlogging, summer drought

The UKCIP02 scenarios point to major changes in soil water content and hence nutrient availability. Managing these changes represents one of the biggest challenges for gardeners in the 21st century.

The compost heap: addition of organic matter will become increasingly important *(Stephen Robson, NTPL)*

"Evidence suggests that nitrate losses from soils may double. Maintaining soil fertility, by replacing organic matter, will be essential."

Bisgrove and Hadley (2002)

"Managing rainwater run-off .. will be of crucial importance."

Bisgrove and Hadley (2002)

Seasonal temperature increases will enhance biological activity of soil micro-organisms, leading to more rapid breakdown of soil organic matter and faster nutrient release. Increased availability of soluble soil nutrients will bring about faster and more vigorous plant growth, but will also increase the loss of soil nutrients through leaching. Heavier, intense rain, especially in winter when there is no vegetation cover, may wash away soil minerals, leading to pollution of streams, ponds and lakes.

Strategies for conserving soil fertility and moisture will depend largely on soil conditions and local effects of climate change. Peak garden demand for water will be greatest in the densely populated south east where it is least available. Free draining sandy soils will lose organic matter faster, further reducing water-holding capacity during summer droughts, and will be more prone to water erosion in winter. Addition of organic matter and mulching will be required. Heavy soils should retain sufficient water for plant growth in summer but winter waterlogging may kill plants unless grit is incorporated or raised beds are constructed.

Higher summer temperatures will increase water evaporation from leaves and the soil, lowering soil moisture content. A 3°C increase in soil temperature, of the kind that might be experienced by the 2080s under the high scenario, can increase such water loss by 30 per cent and decrease soil moisture by 25 per cent. When this effect is combined with substantially lower summer rainfall, plants will suffer from severe drought stress more frequently.

Sudden heavy downpours, coupled with soil compaction, poor drainage and landscaping with impervious materials, will lead to rapid surface run-off and localised flooding. Prolonged waterlogging weakens and kills tree roots and will increase the risk of damage to property from large moribund trees growing close to houses. Cedars at the National Trust garden at Osterley Park in Middlesex and hedges at Westbury Court in Gloucestershire have already been affected by flooding. This can be avoided by improving drainage, using gullies, soakaways and ditches in large gardens but is much more difficult to control in closely spaced, small suburban gardens.

Hedges at Westbury Court, Gloucestershire, have been affected by flooding *(John Millar, NTPL)*

Pandora's greenhouse: more pests, more diseases, more weeds

Garden pests, diseases and weeds tend to have short, rapid life cycles and reproduce in large numbers – ideal credentials for organisms that can benefit from the predicted changes in climate. Increased temperatures shorten pest life cycles so that populations increase faster, while longer growing seasons allow additional reproductive cycles at a time of the year when pest levels are already high.

Pests

Pests that undergo many breeding cycles in a growing season, such as thrips, aphids and spider mites, will complete their life cycles faster. Milder winters will benefit many insect pests that already overwinter as adults, while others that currently overwinter as eggs may also adopt this strategy. Earlier springs will allow them to disperse onto garden plants sooner, provided that these plant hosts also begin growth earlier. The cabbage aphid *(Brevicoryne brassicae)* already benefits from mild winters and for every 1°C increase in temperature, aphid attacks begin two weeks earlier. An increase in spring temperature of 2°C will allow cabbage root fly *(Delia radicum)* to become active a month earlier than at present. Faster plant growth reduces leaf nutritive value and can increase pest feeding activity by 20-40 per cent.

Beneficial or benign insects will be equally affected by temperature change, so increased natural predation of pests is likely. The nematode currently used as a biological control for vine weevil could become more widely used in future, as warmer conditions will enable it to be effective for a longer season. There is already evidence that butterflies are emerging earlier and that their ranges are extending, but increased activity of bees in mild winters reduces their chances of survival.

Many insect pests transmit virus diseases, which will become more prevalent as pest infestations intensify and occur earlier in the year, when plants are more severely vulnerable. Insects that are currently glasshouse pests, such as western flower thrips, may move into the open garden, carrying virus diseases such as tomato spotted wilt virus and Impatiens necrotic spot viruses, which can infect a range of vegetables. There is good reason to suppose that other pest species currently confined to the sheltered environment of glasshouses will move into the open garden. This has already happened with red spider mite.

Warmer temperatures in the UK are also likely to favour a northwards advance of native pest species and an influx of pests from continental Europe, either by natural migration or accidental introduction. Termites and a distinct strain of the Asian gypsy moth *(Lymantria dispar* ssp.*)* have already been recorded in southern Britain.

Warmer conditions will allow greater use of biological control of the vine weevil *(Chris Prior, RHS)*

***Carmeraria ohridella* is now affecting horse chesnuts in England** *(J. Metzer, LWF)*

Horse chestnut leaf miner *(Cameraria ohridella)* has devastated trees in Spain, become established in Northern Italy and recently appeared in Wimbledon. An influx of exotic pests into British gardens is a likely consequence of climate change.

Larger pests, like roe deer and grey squirrels, will be favoured by warmer winters, which will increase their survival rates. Grey squirrels have a predilection for beech *(Fagus sylvatica)*, which is also very sensitive to drought, and the combined effects of climate and squirrels on this species could be particularly severe.

Diseases

Plant diseases often have complex life cycles and a range of hosts, so predicting consequences of climate change for disease infestations is difficult. Wetter, warmer winters will favour the spread of water-transmitted diseases such as *Phytophthora*, or species with higher temperature requirements like red-thread *(Laetisaria fuciformis)* disease of lawns. Drier, warmer summers will increase the incidence of aerially dispersed spores of diseases like powdery mildew.

Continued plant growth during mild winters will enhance winter survival of diseases and lead to their rapid re-establishment in earlier springs. Rates of disease will depend on their tolerance of drier, warmer summers but in general higher temperatures would be expected to increase the severity of disease attacks. Drought also tends to increase plants' susceptibility to diseases, as in the case of sooty bark disease *(Cryptostroma corticale)* of sycamore. Warmer winters will favour bark and wood invading fungi such as honey fungus *(Armillaria* spp.*)* and apple canker *(Nectria galligena)*.

As with insect pests, climate change can be expected to bring an influx of new diseases from overseas, posing major threats to garden plants. Soil borne *Athelia (Corticium) rolfsii*, which would be a serious threat to garden plants, has already been introduced into Britain and could become established here if warmer winters enable it to survive. Olive scab *(Spilocaea oleagina)* has also been introduced and is an example of how gardeners may inadvertently introduce new diseases as they exploit climate changes to grow new plants.

Quarantine regulations, currently designed to protect plants of major economic importance, may need to be revised and extended to garden plants. Camellia petal blight *(Ciborinia camelliae)*, originated in Japan and has spread around the world, unimpeded by plant health authorities that did not consider it necessary to impose import restrictions. The disease has become established in Devon and Cornwall, at the northern limit of its climatic tolerance, but warmer conditions in future will favour its spread.

Oak wilt *(Ceratocystis fagacearum)*, a major disease in North America, is transmitted by an insect that cannot survive under current UK climate conditions. When these change, accidental introduction of this insect could be a serious threat to oaks in Britain.

Warmer conditions will favour honey fungus
(Chris Prior, RHS)

Camellia petal blight will spread from Devon and Cornwall *(Chris Prior, RHS)*

There is great potential for severe fungal damage to plants that form key structural elements in the formal planting of heritage gardens, including yew, box and holly. Box blight *(Cylindrocladium buxicola)* is spread by water splash and will be favoured by warmer, wetter conditions. Yew root rot *(Phytophthora cinnamomi)* will become a greater problem in wetter, warmer winters and will spread northwards and eastwards. Holly leaf blight *(Phytophthora ilicis)* arrived from the USA in the 1980s and its recent spread may be due to warmer, wetter winters. It has already caused damage in the garden at Nymans in Sussex. Other species at increasing risk from *Phytophthora* species include Lawson cypress and alders.

Holly leaf blight is already causing damage in the UK
(Béatrice Henricot)

Weeds

More favourable conditions for germination and growth will increase the need for weeding, while slow growth in dry summers may reduce the effectiveness of glyphosate and hormone-based herbicides, which work best on plants that are growing rapidly. Herbicide spraying will need to be conducted earlier in the year.

There is evidence that bracken *(Pteridium aquilinum)*, which is a serious weed on large estates, will benefit significantly from climate change, colonising at higher altitudes and penetrating further into lightly shaded woodlands.

Fears have been expressed about the possibility of the uncontrolled spread of alien plant introductions. Himalayan balsam *(Impatiens glandulifera)*, *Rhododendron ponticum* and Japanese knotweed *(Fallopia japonica)* have all escaped from gardens and pose threats to natural ecosystems. As the UK climate continues to warm it will be necessary to monitor carefully the potential and observed threats from invading exotic plants, but the threat that they represent should not be overstated.

Garden management in a warmer world

The character of our gardens and the plant collections found in them are influenced by the physical constraints of what may be grown, plant hardiness, temperature and water requirements, and what is desirable from the perspective of historical precedent, culture or fashion.

"Tresco has spread to Tunbridge Wells and is on its way to Teesside."

Bisgrove and Hadley (2002)

Climate change is likely to extend the range of species that can be cultivated *(Derek Croucher, NPTL)*

The craft and science of horticulture allows us to grow species that are poorly adapted to the climate in the United Kingdom, such as alpine plants and mediterranean species, and also to manage the garden environment to allow cultivation of highly bred cultivars which could not thrive unassisted. Current horticultural skills will need to be refined to ensure the survival of existing garden plants and allow the cultivation of new species.

Hardiness

Some 85 per cent of garden plants originate from areas with warmer climates than our own. Higher average winter temperatures will reduce frost damage to marginally hardy species, such as *Abutilon vitifolium*, Bottlebrush *(Callistemon* spp.*)*, *Carpentaria californica* and Jerusalem sage *(Phlomis fruticosa)*, and will extend their cultivation northwards. In general, higher average winter temperatures should enhance the winter survival prospects for the majority of species grown in our gardens.

Frost will remain a risk – albeit a diminishing one – throughout much of the UK, even in a warmer climate, at least until the end of the 21st century. By judicious soil preparation and recognition of local microclimates within large gardens, gardeners already extend the limits for cultivation of tender species. This skill will become even more important with climate change, to minimise the risk of frost damage to precocious buds in spring.

Temperature and water

Maintaining plants is particularly difficult during periods of higher summer temperatures and drought conditions, especially in parts of southern England where water resources are already limited. Even short periods of extreme stress can kill many annuals and perennials, and may weaken perennials and trees, making them vulnerable to stress in subsequent years.

Gardeners in areas with summer water shortages can plant drought tolerant species, but these will require skilled cultivation. Such species do not tolerate saturated soil around their roots and will be vulnerable to disease in the warmer, wetter winters that can be expected in the 21st century.

Gardening in the Global Greenhouse: Summary Report
Garden management in a warmer world

".. in the contemporary garden, climate change offers exciting opportunities .."

Bisgrove and Hadley (2002)

Historic collection of plants, such as this fernery at Biddulph Grange, will become increasingly difficult to maintain *(Nick Meers, NTPL)*

The horticultural trade is already meeting consumer demand for exotic species *(Pardee Tree Nursery)*

Climate change and the character of gardens

The extent to which the overall style and character of gardens is affected by climate depends on how much we wish to preserve their character for cultural reasons.

Domestic garden design is subject to the whims of horticultural fashion, promoted by magazines and television programmes. Historically important gardens are maintained as cultural assets – to perpetuate significant layouts, period styles, plant collections and the accumulation of past owners' influences. In such gardens, maintaining their character and current combinations of species will require special attention and will become increasingly difficult and expensive, if not unsustainable.

Destruction of gardens because of climate change in the medium term is only likely in those few coastal gardens that could be directly affected by sea level rise, or perhaps in some that are subject to prolonged and persistent flooding inland. In such cases, documentary recording is probably the only option.

Domestic and contemporary gardens

Climate change could bring about rapid changes in garden style. Adventurous gardeners have always tried to explore the limits for cultivating unusual and demanding species, so climate change could provide new variations on familiar challenges. Their success will depend on careful soil preparation and plant maintenance during periods of drought or excessive rain. Currently, between 10,000-15,000 plant species and varieties are cultivated in British gardens; climate change is likely to extend the range of species that can be cultivated outdoors throughout the year, especially by gardeners in northern Britain.

The retail horticultural trade can respond to these changes in gardening fashion, and is already meeting consumer demand for such exotic species as phormiums, bamboos, cannas, palms, tree ferns and bananas which were, until recently, only grown in large, specialist gardens.

Heritage gardens

Most plants that are currently cultivated in heritage gardens are likely to be maintained over this century by the use of suitable soil moisture conservation techniques and irrigation in summer, but at increasing cost.

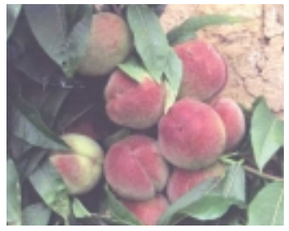
Difficult decisions over suitable replacement planting will arise when extreme weather events, such as storms, lead to loss of mature trees. When individual plants are unique or of particular historical, botanical or biological importance, then strenuous and expensive efforts will need to be made to maintain them in the face of climate change, as will be the case for archaeology contained within historic parks or gardens. Balancing consideration of future climatic conditions with issues of historical authenticity will become an increasingly important factor in the maintenance of heritage gardens. Garden conservation management plans offer a tool to plan ahead.

Difficult decisions will have to be made when mature trees in heritage gardens are lost through extreme weather *(George Wright, NTPL)*

Rewriting the garden manual: climate change and key garden components

All gardeners will need to plan for new planting opportunities, a longer growing season, improvements in garden drainage and watering facilities, continuous grass mowing and difficult growing conditions under glass.

Careful management will help avoid large scale storm damage in woodland *(NT)*



Peaches could replace apples
(Neil Campbell-Sharp, NTPL)

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

Some of the challenges gardeners will face, and some possible solutions, are set out below:

Trees

It should be possible to select tree provenances that will be better adapted to future climates than present cultivars by, for example, choosing disease-resistant species. Many existing long-lived trees will suffer stress from climate change and will require careful management programmes to deal with:

- summer drought, minimised by skilled soil management;
- waterlogging, avoided by planned drainage measures;
- damage and loss from high winds, requiring planned long term replacement programmes, planting in suitably sheltered site, and perhaps judicious crown reduction of vulnerable trees;
- large scale storm damage in woodland, minimised by avoiding uniform monocultures and planting a diversity of tree species in new woodlands;
- risk of damage to conifer hedges by fire in periods of extreme drought, reduced by limiting access and establishing fire prevention measures.

Fruit trees and bushes

Many existing cultivars have a minimum winter chilling requirement for bud break and flowering, which may not be met in future mild winters, so maintaining historically important cultivars will become more difficult.

Breeding new cultivars with a lower chilling requirement, or complete substitution of these crops may be needed. Pears, cherries and peaches, for example, could replace apples in some locations.

Shrubs

Most problems that afflict trees will also apply to shrubs, but to a lesser extent, and the same management procedures apply. Shade-adapted shrubs can be damaged by intense sunlight and weed competition after storm damage to the tree canopy, requiring temporary shading during a period of acclimatisation.

Sub-shrubs

Higher temperatures and fewer frosts will allow wider use of sub-shrubs such as *Fuchsia, Indigofera* and *Penstemon*, which are marginally hardy at present in many locations. In northern locations such species will still require careful management, to guard against late damage from frosts, which are unlikely to be totally eliminated during the next century.

The plants grown in traditional cottage gardens will require more care *(Neil Chrichton, NTPL)*

"Whilst the challenge for many gardeners may be the introduction of new and exciting species into their gardens, as the climate progressively changes a much greater challenge to gardeners.. will be to create the traditional English cottage garden."

Bisgrove and Hadley (2002)

Faster-growing foliage may obscure hyacinth flowers
(David Sellman, NTPL)

Herbaceous perennials

These are so diverse in their climate optima that it is difficult to generalise on their performance. Traditional herbaceous border species such as aster *(*e.g. *Aster novi-belgii)*, delphinium *(Delphinium x cultorum)*, lupin *(Lupinus x regalis* spp.*)* and phlox *(Phlox paniculata)*, requiring deeply cultivated, fertile, moisture retentive soil, will not adapt well to drier summers and will need more intensive care, as will old cultivars of iris, which tolerate dry summers but are killed by winter waterlogging. Selecting species and cultivars that are drought resistant and tolerant of waterlogged soils in winter will be a challenge for plant breeders and nurseries. More thorough staking of herbaceous plants will be required, to withstand periods of intensive rainfall in summer.

Bulbs

Species propagated from bulbs and underground storage organs typically require low winter temperatures to stimulate root development and, in some cases, high summer temperatures to initiate flower bud development. Requirements of different species vary widely, but if warmer winters lead to failure of root initiation, lifting and refrigeration of bulbs would be needed to ensure normal development. Higher soil and air temperatures in spring may alter the balance between flower and foliage development in species such as hyacinth (*Hyacinthus orientalis*).

Warmer summers will benefit summer and autumn flowering subjects and will permit cultivation of a wider range of species in the open border. Tulips and some crocus cultivars do not tolerate waterlogging, so will either require excellent soil drainage regimes, or will need to be lifted and stored over the winter.

Annuals

Higher temperatures in spring will accelerate germination, development and flowering of hardy annuals, and lead to their earlier death. This trend might be minimised by better soil preparation and irrigation. Higher temperatures will favour use of a much wider range of half-hardy bedding plants that will no longer be subject to frosts. Separate spring, summer and autumn bedding schemes will be desirable when the length of the growing season increases.

Lawns will need year-round maintenance
(Mike Sleigh, RHS)

Lawns

Fine lawns – the icon of British gardens – are high-maintenance features particularly suited to our current climate. Hot summers and wetter winters will increase browning during droughts, promote soil compaction during wet weather and increase risk of diseases. A longer growing season will demand year-round mowing and lawn care. More extensive moss growth in winter is likely, although summer drought will minimise its impact on the lawn. These changes will raise maintenance costs in large gardens, making conversion to more natural meadow areas an attractive proposition in less formal areas. The cost of lawn irrigation, if permitted at all in areas of water shortage, will be an important consideration.

The cost of lawn irrigation will be a consideration
(David Sellman, NTPL)

Warmer weather will give rise to more algae in ponds
(NT)

In gardens open to the public, managing visitor access to lawns to minimise soil compaction will be important. Unpredictable summer rain and prolonged grass growth through winter will force greater flexibility in mowing regimes to avoid lawn damage, raising costs when contracted labour is employed.

In the longer term, conversion to lawns constituted from coarser, more drought resistant grasses that tend to be less tolerant of close mowing may be needed, to reduce costs of irrigation and sward maintenance.

Garden paths and wooden structures

Paths act as conduits for storm water run-off, and so are prone to rapid erosion. Path design and choice of surfaces can minimise this hazard. In winter and early spring slippery algal growth on paths is likely to increase.

In addition to unpredictable storm damage, cycles of summer drying and intensive and prolonged rain will lead to more rapid deterioration of wooden structures. More robust construction and use of more durable timbers from sustainable sources will be required. Shading and better ventilation in greenhouses will be needed in summer, for the benefit of plants and gardeners who work under glass and, as winters become warmer and wetter, good ventilation will be essential to deter fungal diseases.

Brown lawns will become a more common sight
(English Heritage)

Ponds, lakes and water supplies

High summer temperatures will lead to increased frequency of algal blooms in ponds, promoting stagnant conditions. Water features in gardens will need more intensive maintenance, with frequent topping up of small ponds in summer. Seasonal fluctuation of water levels in large lakes and ponds will require the use of spillways and sluices in winter and improved marginal planting in summer, to minimise the visual impact of falling water levels.

Supply of water for irrigation during summer could be problematic across the UK. Rationing for all but essential uses is likely in critical areas. Water charges may also increase, encouraging installation of more efficient irrigation systems and the use of 'grey' water from domestic activities. Water conservation measures, either via soil mulching or collecting of rainwater in water butts, will become a summer priority and large gardens may need to construct reservoirs for irrigation purposes.

Hot work

Extreme summer temperatures represent a health hazard. Those working on energetic tasks will need to guard against dehydration and sunburn and will require better protective clothing when working with chemicals in hot conditions. Coping with effects of climate change will entail more work and stress, resulting from increased routine maintenance tasks and the need for greater flexibility in working practices in large gardens.

Working in extreme heat represents a health hazard
(RHS)

The bottom line: the commercial impact of climate change on gardens

Many major gardens depend on revenue from visitors. Garden managers will need to plan for the financial impacts of climate change. They will need to meet the cost of storm and flood repairs and rising insurance premiums, and to adapt to the effects of climate change by installing water storage facilities and flood protection. They will also need to prepare for a longer visitor season and greater visitor impact on the garden infrastructure. There is scope to develop environmentally sustainable gardening techniques further.

Enhanced autumn colour will extend the visitor season
(Mike Sleigh, RHS)

> "The gardening community has the potential to set an example of good practice which will further increase public appreciation and support for gardens.."
>
> *Bisgrove and Hadley (2002)*

Visits to heritage gardens

Climate, or more precisely prevailing weather, is just one of many factors that will influence future trends in garden visits. Many social, cultural and economic factors are involved, including population dynamics, disposable income, competing attractions and access to gardens by public transport.

Improved weather, especially early in the year, may attract more visitors to gardens, while prolonged autumns with 10-20 per cent less rainfall and enhanced autumn foliage colour are likely to extend the visitor season. Exceptionally high summer temperatures would be a deterrent, unless gardens incorporate design features such as shady woodland and lakeside walks to increase visitor comfort.

Gardens will benefit from investment in visitor facilities, such as glasshouses, shelters and information centres, if summer weather becomes even more unpredictable.

Garden managers need to be aware that climate change will favour increases in the number and variety of biting insects that breed in water, which may deter visitors.

The major impact of more garden visitors will be increased wear and tear, especially after heavy rain, which could be minimised by contingency planning for managing visitor movements. Gardens can draw on experience from the sports turf industry in coping with wear and compaction of lawns.

Gardeners need to be proactive in managing gardens in ways that make minimum demands on scarce water resources, and in demonstrating sound environmental practices to their visitors. This is important, both in terms of managing immediate problems caused by the current phase of climate change, and in modifying behaviour and attitudes to prevent further undesirable climate changes in the future. Gardens open to the public could help demonstrate sustainable horticulture techniques.

Garden industries

Nurseries and garden centres can benefit commercially from climate change, but will experience increased operational difficulties.

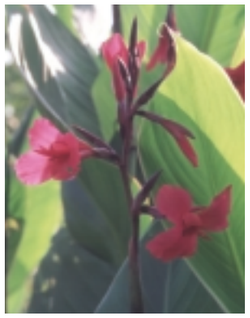
Most plants sold at horticultural retail outlets are grown in containers, with roots confined in small volumes of growing medium. Increased labour costs for watering will favour the installation of automatic watering systems. Contingency planning will be required to ensure reliable supplies during drought periods.

Increased incidence of stormy weather will require better staking and support of large container-grown plants, which are inherently unstable.

Working conditions under glass during hot summer weather will deteriorate, although a milder climate in general will make year-round outdoor working more amenable.

Extreme weather conditions are damaging to garden sales businesses *(Notcutts)*

It is difficult to plan for devastating extreme weather events, such as storms and hail, but businesses in areas with increasing risk of flooding may need to improve water run-off measures, face rising insurance premiums and consider relocation. For garden centres and nurseries, contingency planning for extreme weather damage will become increasingly important. Extreme weather conditions, such as drought and flooding, are also indirectly damaging to garden sales businesses, since public interest in gardening rapidly declines during such periods.



Many plants, such as cannas, will perform better in a warmer climate
(Mark Bolton, NTPL)

Plants likely to perform better in a warmer climate
Source: Emmett (pers. comm.)

Genus	Species
Agavaceae	Agave Cordyline (Torbay palm) Yucca
Aizoaceae	Carpobrotus (Hottentot fig) Delosperma Drosanthemum
Aloaceae	Aloe
Araceae	Alocasia
Arecaceae	Chamaerops, Trachycarpus, Phoenix (Palms)
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

As undesirable effects of climate change become obvious to gardeners, there will be greater demand for solutions to gardening problems. There will be new marketing opportunities for environmentally benign solutions such as composting and organic techniques, water storage equipment and biological control methods for dealing with pests. Greater interest in irrigation systems is also likely.

Climate change will lengthen the growing season and extend peak sales periods for garden plants and sundries such as garden leisure equipment. Demand for replacement plants for those lost through drought or waterlogged soils in winter will increase.

There could be opportunities for marketing a wider range of perennial exotic species and plants that are currently half-hardy annuals, which will survive in the open garden in milder winters. Faster growth and flowering will encourage gardeners to replant bedding and containers more frequently.

Exploiting opportunities for marketing a wider range of plants requires advanced planning, since basic research is required to identify optimum cultivation techniques, especially for perennials, shrubs and trees which will need to tolerate summer drought and waterlogging in winter. Research will also be required in 'hardening off' procedures for species that are marginally hardy, although this will become less problematic by the 2080s.

Next steps: research and action

There are serious limitations in our knowledge of the likely impact of climate change on gardens.

This study has highlighted challenges and opportunities for the gardening industry to consider, as well as a number of areas for future research and recommendations for action (see below).

The partners will explore what research and practical action they can take together, as well as using this study to inform their own policy and decision-making.

Research:

The study has identified a need for research to:

- establish the degree of exposure of Britain's gardening heritage to climate change
- identify resources and level of investment required to maintain the integrity of those gardens of greatest historical significance
- establish the criteria for the management of significant plant collections on a national basis
- develop a greater understanding of how garden plants respond to climate change, specifically in relation to:
  - frost sensitivity and hardiness
  - winter dormancy
  - flowering and autumn colour
  - susceptibility to pests and diseases
  - interactions with symbiotic soil fungi and beneficial micro-organisms
- identification and monitoring of potentially invasive species
- minimise soil nutrient loss and reduce the impact of water logging and drought on plants
- develop methods for mowing grass that minimise compaction of wet soils
- improve methods for water management in the garden and heat management in glasshouses
- refine models for regional impacts, allowing more accurate prediction of future local climates
- investigate garden visitor response to climate change

Recommendations:

- encourage networking between major gardening organisations and institutions to exchange and coordinate observations, ideas and innovations, disseminate information and inform policy decisions
- initiate a *Hortus Europaeus*, to map the distribution of garden species in Europe, allowing large scale monitoring of effects of climate change on garden plant species
- produce a list of indicator plant species likely to be sensitive to climate change, allowing nationwide monitoring of its progress and impacts
- implement practical actions to enable gardens to adapt to climate change. Forward plan for flooding, drought, soil changes and structural impacts on buildings, features and facilities

The season for visiting gardens will lengthen
(Chris King, NTPL)

Key challenges and opportunities

Domestic gardens

Challenges include:

- managing drier soils in summer and wetter soils in winter
- maintaining soil fertility
- intensification of pest, disease and weed problems
- maintaining a smooth, green lawn
- meeting the needs of drought-adapted perennials and bulbous species that do not tolerate waterlogging in winter
- year-round plant growth, requiring continuous maintenance

Opportunities include:

- increased range of plants suitable for cultivation in the open garden
- northwards spread of optimum growing conditions for some plants
- warmer and drier summers and autumns for enjoying the garden

Heritage gardens and large gardens open to the public

Challenges include:

- maintaining historic gardens, their associated archaeology, wildlife interests, and their specimen plants as they adapt to a changing climate
- managing the impact of visitors during less predictable summer weather
- dealing with storms and flood
- increased maintenance costs, especially for fine grass swards

Opportunities include:

- potential for a longer visitor season
- developing an educational role, as centres of excellence in environmentally sustainable gardening techniques

Retail horticulture outlets

Challenges include:

- maintaining container-grown stock during summer drought
- minimising the impact of extreme weather on business activities
- marketing a wider range of plant species and varieties

Opportunities include:

- extension of peak periods of gardening activity
- marketing water conservation equipment