Environmental RTDI Programme 2000–2006

CLIMATE CHANGE

Scenarios & Impacts for Ireland

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Final Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

International Context

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) is the most authoritative assessment of global climate change to date. Produced by several hundred leading scientists in various areas of climate studies, its principal conclusions include the following:

- Global average temperature has increased by 0.6 ± 0.2°C since 1860 with accelerated warming apparent in the latter decades of the 20th century. A further increase of 1.5–6.0°C from 1990 to 2100 is projected, depending on how emissions of greenhouse gases increase over the period.

- The 20th century was the warmest of the last millennium in the Northern Hemisphere, with the 1990s being the warmest decade and 1998 the warmest year. Warming has been more pronounced at night than during the day.

- Reductions in the extent of snow cover of 10% have occurred in the past 40 years, with a widespread retreat also of mountain glaciers outside the polar regions. Sea-ice thickness in the Arctic has declined by about 40% during late summer/early autumn, though no comparable reduction has taken place in winter. In the Antarctic, no similar trends have been observed. One of the most serious impacts on global sea level could result from a catastrophic failure of grounded ice in West Antarctica. This is, however, considered unlikely over the coming century.

- Global sea level has risen by 0.1–0.2 m over the past century, an order of magnitude larger than the average rate over the past three millennia. A rise of approximately 0.5 m is considered likely during the period 1990–2100.

- Precipitation has increased over the land masses of the temperate regions by 0.5–1.0% per decade. Frequencies of more intense rainfall events appear to be increasing also in the Northern Hemisphere. In contrast, decreases in rainfall over the tropics have been observed, though this trend has weakened in recent years. More frequent warm-phase El Niño events are occurring in the Pacific Basin. Precipitation increases are projected, particularly for winter, for middle and high latitudes in the Northern Hemisphere and for Antarctica.

- No significant trends in the tropical cyclone climatology have been detected.

These global trends have implications for the future course of Ireland’s climate which it is judicious to anticipate. This report presents an assessment of the magnitude and likely impacts of climate change in Ireland over the course of the current century. It approaches this by establishing scenarios for future Irish climate based on global climate model projections for the middle and last quarter of the present century. These projections are then used to assess probable impacts in key sectors such as agriculture, forestry, water resources, the coastal and marine environments and on biodiversity.

The purpose of the report is to firstly identify where vulnerability to climate change exists in Ireland and what adjustments are likely in the operation of environmental systems in response to such changes. In some sectors, e.g. agriculture, some new opportunities may arise. In other instances, e.g. water resource management, long-term planning strategies will be necessary to mitigate adverse impacts. Long lead times for adjustment characterise many sectors, e.g. forestry, and it is important to provide as much advance warning of likely changes as possible to enable adaptation to commence early. By anticipating change it may be possible to minimise adverse impacts and to maximise positive aspects of global climate change.

Regional Context: Downscaling from Global Climate Models

Global Climate Models (GCM), forced by projected increases in greenhouse gases, are used to simulate future projections of climate change as a consequence of enhanced greenhouse warming. However, direct output from these GCMs is inadequate for regional-scale impact analysis due to their coarse spatial resolution. Therefore, a technique is required to downscale these coarse-scale climate simulations to a finer spatial resolution, which can then be utilised for impact analysis. High spatial resolution scenarios were generated using a statistical downscaling technique applied to GCM output from the Hadley Climate model to project likely changes in Irish climate from the 1961–1990 averages. The results of this analysis suggest that:

- Current mean January temperatures in Ireland are predicted to increase by 1.5°C by mid-century with a further increase of 0.5–1.0°C by 2075.

- By 2055, the extreme south and south-west coasts will have a mean January temperature of 7.5–8.0°C. By then, winter conditions in Northern Ireland and in the north Midlands will be similar to those currently experienced along the south coast.

- Since temperature is a primary meteorological parameter, secondary parameters such as frost frequency and growing season length and thermal efficiency can be expected to undergo considerable changes over this time interval.

- July mean temperatures will increase by 2.5°C by 2055 and a further increase of 1.0°C by 2075 can be expected. Mean maximum July temperatures in the order of 22.5°C will prevail generally with areas in the central Midlands experiencing mean maxima up to 24.5°C.

- Overall increases of 11% in precipitation are predicted for the winter months of December–February. The greatest increases are suggested for the north-west, where increases of approximately 20% are suggested by mid-century. Little change is indicated for the east coast and in the eastern part of the Central Plain.

- Marked decreases in rainfall during the summer and early autumn months across eastern and central Ireland are predicted. Nationally, these are of the order of 25% with decreases of over 40% in some parts of the east.

Impact Assessments

Agriculture

The scenarios produced were used as inputs to crop simulation models for a range of present and potential future crops. The simulation results show that the expected climate changes will have a major impact on Irish agriculture which, though significant, cannot be regarded as catastrophic.

- For livestock production, the expectation of more frequent summer droughts will require supplementation of grazed grass.

- Maize silage is increasingly likely to replace grass silage, potentially increasing grazing land areas. At the same time, increased production of grain maize is expected.

- Barley is another potentially important source of energy for supplemental feeding of livestock. The expected increases in cereal grain production may be expected to reduce the cost of feed barley. However, extra irrigation costs may bring the economic viability of the crop into question.

Although warmer temperatures would be expected to result in shorter winter housing times for livestock, a trend towards wetter winters may result in problems of poaching and soil damage which may negate this. The balance of grazing season length against winter rainfall will dictate the stored feed requirement, and the actual climate will dictate the choice of forage crop grown. Opportunities to spread slurry or dirty water in winter will be further reduced and increased slurry storage requirements are likely to be needed.

In the summer months drought stress is likely to become increasingly important. Irrigation will become important for all crops in the eastern half of the country. This will have a major economic impact. Irrigation in dairying in the drought-prone south-east is currently justified economically only if water is available without charge. With the projected scenarios, a much greater area of agricultural land will be affected by drought, and the quantities of water required for irrigation will be larger. There may also be competition from other users, and the consequent economic effects may make certain crop production uneconomical.

- For potato, drought stress will be the most important limiting factor determining its viability and it is likely that potatoes may cease to be a commercially viable crop over much of Ireland.

- Spring barley yield increases of approximately 25% are likely by 2055 with harvesting time earlier than today.

- Maize grain yields are expected to increase dramatically, in western areas by more than 150% on today's national average value.

- Soybean will remain a marginal crop. Although temperature conditions become more favourable, precipitation changes mean that any gains could be negated by drier summers.

Irish agricultural land use distributions will alter in response to climate change. A sharpening of east–west contrasts is likely to occur with livestock production dominating more to the west, and arable production dominating east of the Shannon. Planning for irrigation requirements may be needed, particularly in the east.

Water Resources

Using the climate scenarios as inputs to a hydrological model a number of likely impacts were suggested:

- A widespread reduction in annual runoff is suggested; this will be most marked in the east of the country.

- Winter runoff is predicted to increase.

- All areas will experience a major decrease in summer runoff, particularly in the east of the country. These reductions are likely to average approximately 30% over large parts of eastern Ireland by mid-century.

- The magnitude and frequency of individual flood events will probably increase in the western half of the country.

- Seasonal flooding may occur over a larger area and persist for longer periods of time. Areas such as the Shannon basin will be vulnerable to these changes

- Turloughs in western Ireland will also be particularly vulnerable to these changes.

- During the summer months, long-term deficits in soil moisture, aquifers, lakes and reservoirs are likely to develop. It is likely that the frequency and duration of low flows will also increase substantially in many areas.

Since evaporative losses are also likely to increase during summer months, the water resource changes projected will have a significant effect on reservoir yields. Water supply infrastructure is expected to come under growing pressure particularly in the Greater Dublin Area and the strategic implications of this are profound for a number of areas, particularly spatial settlement strategy.

The projected changes in water availability pose potential problems for the dilution of water-borne effluent. With a greater frequency of low flow conditions, additional precautions will be required to ensure that concentrations of water pollutants do not give rise to acute effects. It is recommended that minimum flow constraints are determined more conservatively, particularly where new urban or agricultural discharges are envisioned. Greater incorporation of groundwater protection considerations is also recommended as aquifers assume increasing importance as sources of water supply as competition for reduced surface resources intensifies.

Forestry

Forests cover 9% of the land area of Ireland, a figure which it is planned to double by 2030. In planning for the future, foresters must select species that will perform optimally over a full rotation of 40–50 years. The time span that this report addresses is, therefore, highly relevant in influencing decisions being taken today in the forestry area.

Increased CO_2 concentrations and warmer temperatures are expected to benefit Irish forest growth. Decreased summer rainfall, however, would negate this, as would any increase in storm frequency. Secondary effects of climate change on forest productivity are also expected to be considerable. Increased nutrient mineralisation in warmer temperatures is likely, though so also are changes in pest and disease incidence. Among the more significant of the latter are:

- Green spruce aphid (winter warmth may encourage large population increases)
- Pine weevil (favoured by warmer temperatures)
- Great spruce bark beetle (currently a major problem in continental Europe)
- European pine saw fly (outbreaks occur given a series of three consecutive dry summers)
- Fomes (optimum temperature for the growth of this fungus is 22.5°C)
- Phytophthera disease of alder (recently identified in Ireland, may thrive in warmer, drier summers)
- Honey fungus (grows optimally at temperatures of 20–25°C; drought conditions render trees more liable to infection).

Increased fire damage and increased deer and squirrel populations may also constitute negative indirect impacts of climate change on forestry.

The interaction of different effects on forest growth is difficult to model, and different species will respond differently to changed climatic conditions. However, there is no reason to believe that Sitka spruce will not continue to be viable as the mainstay of commercial forestry in Ireland. Despite this, there is a need to assess different provenances and species in long-term research trials. Particular attention should be given to alternative provenances for Douglas fir and western red cedar. It is also recommended that the national tree-breeding programme should be re-assessed in the light of current knowledge on potential climate change with a view to the selection of traits that will accommodate and capitalise on these changes. The potential for the production and transplanting of containerised nursery stock should also be reassessed. Finally, it is urged that climate change scenarios should be included in the Forest Inventory and Planning System currently operated by the Forest Service in the Department of Marine and Natural Resources.

Natural Ecosystems and Biodiversity

Changes in climate zonation were identified as having a range of impacts for natural ecosystems and biodiversity in Ireland, with considerable gaps in knowledge and data requiring further research to enable definitive conclusions in key areas. The projected increases in temperature, combined with a longer growing season, were found to have the potential to cause distributional and behavioural changes in Irish species (Table 1).

Climate changes are also likely to result in significant alterations to habitat conditions, though movement of habitats in Ireland will be restricted by non-climatic considerations. Salt marshes and sand dune habitats are vulnerable to sea-level and climate changes and may experience significant changes in species composition. Montane heaths are suggested to be particularly sensitive to climate change as many montane species are at the lower altitude/southern latitude edge of their distribution, with limited migration potential, and an increase in temperature combined with summer drying may prove detrimental for this habitat in Ireland. Similarly, peatlands are expected to suffer considerably from summer drying. An increase in decomposition, a reduction in peat formation, more erosion, changes in species composition, loss of stored carbon and an increase in acid runoff may occur in this already fragile resource.

Marine Ecosystems

The existence of many marine species in the seas around Ireland is temperature controlled. However, it is difficult to extrapolate predictions for land temperature increase to determine likely changes in sea temperatures, particularly for sub-surface temperature changes which may be controlled by larger oceanographic circulation patterns. Thus, although species that are sensitive to climate change may be identified quite easily, the extent to which actual changes will happen is difficult to predict (Table 2). Many of the impacts are likely to be indirect, where the reduction of one species allows for an increase in another through reduced competition. A notable impact exists with respect to salmon farming, however, where an increase in sea temperature may have serious consequences. Salmon are near the southern range of their distribution and any increases in temperature could

Table 1. Potentail effects of climate change on natural ecosystems and biodiversity in Ireland.

Distributional changes

- Decline (in some cases extinction) of Arctic and Boreal relicts, cold-hardy species, water-dependent species, wetland and oceanic species.
- Extension of Boreo–temperate species and other species that favour increased temperatures, e.g. deep-rooted calcareous forbs, butterflies, insect predators and pests.
- Increases in migrant species – mainly insects and vagrant birds.
- Changes in distribution of introduced or invasive species.

Behavioural changes

- Changes in the phenological processes of plants (bud burst, germination and leaf emergence).
- Changes in plant decomposition and productivity.
- Alterations in competitive interactions between plants.
- Increased numbers of generations of many insects which may lead to population growth.
- Greater winter survival rates of invertebrates.
- Changes in phenological processes of insects, e.g. earlier appearance of butterflies.
- Earlier breeding of amphibians.
- Possible changes in the competitive relationships between frogs and newts.
- Changes in timing of migration, hatching, development and spawning of freshwater fish with negative and positive implications for specific species.
- Increased competition for niche space, e.g. *Salvelinus alpinus* (Arctic char) and other species.
- Changes in bird migrational patterns.
- Earlier breeding of birds and larger and more numerous clutch sizes.
- Greater numbers of overwintering birds; reduced mortality but greater competition between species.
- Changes in the life cycle of bats.
- Greater winter survival rates of bats.
- Reduction in birth weight of *Cervus elaphus* (red deer).

harm the commercial viability of farms and render them subject to increased algal bloom, pest and disease problems.

Sea-level rise and the Irish coast

The coast is a dynamic environment which is constantly responding to processes that are operative on a range of time scales. The single most important control on these processes is sea level, which has varied considerably over the past 20,000 years. Global sea level is projected to rise by approximately 0.5 m by the end of the century, predominantly due to warming and expansion of the ocean water body. In Ireland, this figure will be modified by local land-level changes, though a higher platform for wave attack will inevitably mean greater erosion of 'soft' coastlines, formed of glacial drift or unconsolidated materials. As a general approximation, land retreat of about 1 m can be anticipated on sandy coastlines in Ireland for every centimetre rise in sea level.

Inundation risk must also take into account storm surge events and high tide frequencies. A value of 2.6 m for extreme water level presently occurs with a return frequency of 12 years on the west coast and 100 years on the east coast. These return periods of extreme water level are likely to reduce considerably as sea levels rise. Combining these extreme water levels with a sea-level rise of 0.49 m places approximately 300 km^2 of land in Ireland at risk of inundation.

In situations where land loss cannot be economically defended, it should not be contemplated. Where infrastructure is at risk of inundation, cost-beneficial solutions may exist. This is particularly the case in the cities of Dublin, Cork, Limerick and Galway, and for assets such as railway lines, airports, power stations. 'Hard' engineering solutions should be viewed as a last resort outside of these categories, however, as this type of engineering can have dramatic effects further along the

Table 2. Level of certainty of potential impacts of climate change on marine ecosystems.

Factors	Level of certainty
Increase in temperature	
Biogeography	
Range shift for species on limit of distribution	Likely
Restriction of Northern species range	Likely
Extension of Southern species range	Likely
Loss and gain of species at local level due to alteration in habitat suitability	Likely
Increase in the survival of exotic species	Very likely
Fisheries	
Reduction in spawning capabilities for some species	Possible
Loss or reduction of 'colder water' species	Likely
Gain or increase in 'warmer water' species	Likely
Aquaculture	
Shift in habitat suitability leading to changes in viability of cold/hot water species	Possible
Increase in harmful infections	Likely
Increase in exotic species	Very likely
Increase in algal blooms	Likely
Loss of production in salmon due to reduction in maturation time	Likely
Reduction in availability of local smolt	Likely
Increase culture possibilities for other species	Very likely
Increased precipitation	
Biogeography	
Range shift for species on limit of distribution	Less likely
Restriction of Northern species	Less likely
Extension of Southern species	Less likely
Loss and gain of species at local level due to alteration in habitat suitability	Likely
Fisheries	
Reduction in spawning capabilities in coastal areas	Less likely
Aquaculture	
Development of husbandry techniques and technologies	Likely
Sea-level rise	
Biogeography	
Extension of habitats inshore	Likely
Loss of intertidal habitats in low-lying areas (coastal lagoons and estuaries)	Likely
Fisheries	
Reduction in suitable spawning grounds	Less likely
Aquaculture	
Reduction in available intertidal sites	Less likely
Increased storm events	
Biogeography	
Local change in intertidal species from wave-sheltered species to wave-exposed species	Less likely
Fisheries	
Loss of fishing days	Likely
Aquaculture	
Reduction of suitable intertidal and coastal sites	Likely
Requirement to develop offshore sites	Likely

coastline. Recommendations for coastal management policies to cope with sea-level rise would include the following:

- no building or development within at least 100 m of ‘soft’ coastline
- no further reclamation of estuary land
- no removal of sand dunes, beach sand or gravel. Measures to protect and rehabilitate dune systems should be implemented.
- all coastal defence measures to be assessed for environmental impact
- where possible, the landward migration of coastal features such as dunes and marshes should be facilitated.

Conclusions

Over the next half-century significant climate change can be anticipated in Ireland. A statistical downscaling technique has been used to provide this analysis of the regional dimension of such climate change. Considerable uncertainty remains with respect to future climate conditions, and much more work is required in several key areas. However, forward planning is needed now for adaptation to climate change in Ireland. In key areas such as agriculture, water resources, coasts, marine and the natural environment, impacts are likely to be significant. This report provides a perspective as to how changing climate may necessitate changes in current practices.

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1 Introduction

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1.1 Climate Change: the International Background

Scientific concern with respect to the potential impacts of human activities on the climate of the Earth resulted in the first World Climate Conference being held in February 1979. This led to the establishment of the World Climate Programme (WCP) by the World Meteorological Organisation (WMO) in collaboration with the United Nations Environment Programme (UNEP) and the International Council of Scientific Unions (ICSU). The WCP recognised the need to understand the potential serious global problem of human-induced impacts on the climate system. It also recognised that the proper use of climate information is necessary for national socio–economic development.

Subsequent research under the WCP and by other organisations indicated that some aspects of global climate could be predicted and that human activity was capable of changing the global climate system. The potential implications of a changing climate indicated a number of causes for concern, particularly for countries and regions already experiencing climatic stresses. Governments responded to these findings by establishing, in 1988 through UNEP and WMO, the Intergovernmental Panel on Climate Change (IPCC). The IPCC had the objective of conducting a formal assessment of the state of understanding of climate change, the socio–economic implications of any change and the possible response options available to governments. The Second World Climate Conference was held in 1990. The ministers and other representatives noted the potential impact of human activities on the global climate system and committed themselves to take active and constructive steps in a global response. One of their main recommendations was the need to establish a Global Climate Observing System (GCOS).

The Intergovernmental Panel on Climate Change (IPCC) independently assesses the scientific literature and provides vital scientific information to the climate change process. The current structure of the IPCC consists of three Working Groups: Working Group I addresses the science of climate change, Working Group II deals with impacts, vulnerability and adaptation, and Working Group III deals with mitigation of the impacts of climate change. The First Assessment Report was produced in 1990. In reaction to the IPCC report on climate change and the Second World Climate Conference, world governments meeting at the United Nations Conference on Environment and Development (UNCED) (The Earth Summit) in Rio de Janeiro in June of 1992 established the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC committed developed countries to reduce emissions of greenhouse gases (GHGs) to 1990 levels by the end of 2000. The ultimate objective of this process was to achieve the stabilisation of greenhouse gas concentrations "*at a level that would prevent dangerous anthropogenic interference with the climate system*". It was also considered desirable that such a level "*should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change.*"

The Second Assessment Report (SAR) was published in 1995, and its statement that "*the balance of evidence suggests … a discernible human influence on global climate*", stimulated international negotiations on what became the Kyoto Protocol, which was finalised in Kyoto during December 1997. The Kyoto Protocol aimed to achieve a 5.2% reduction in emissions of six key GHGs (CO_2, CH_4, N_2O, SF_6, hydrofluorocarbons and perfluorocarbons) by 2012. The European Union (EU) policy is that the commitments made at Kyoto be honoured and that an emission reduction target of 8% be achieved by the target date. As part of a burden-sharing arrangement with EU member states, Ireland has been set a target of restricting the growth of emissions to less than 13% over the reference year of 1990 during the commitment period of 2008–2012. The National Climate Change Strategy, published in 2000, provides a strategic framework to tackle the emission reduction of 13.1 Mt CO_2 equivalent required to comply with the national target (Department of the Environment and Local Government, 2000).

The Third Assessment Report (TAR) of the IPCC was published in 2001 (IPCC, 2001). Many of the conclusions and trends suggested in the previous reports are reiterated and given more confident expression, though several aspects of the global climate system remain imperfectly understood.

Among the principal conclusions of the TAR are the following:

- Global average temperature has increased by 0.6±0.2°C since 1860 with accelerated warming apparent in the latter decades of the 20th century. A further increase of 1.5–6.0°C from 1990 to 2100 is projected, depending on how emissions of greenhouse gases increase over the period.

- The last century was the warmest of the last millennium in the Northern Hemisphere, with the 1990s being the warmest decade and 1998 being the warmest year. Warming has been greater at night than during the day.

- Reductions in the extent of snow cover of 10% have occurred in the past 40 years with a widespread retreat also of mountain glaciers outside the polar regions. Sea-ice thickness in the Arctic has declined by about 40% during late summer/early autumn, though no comparable reduction has taken place in winter. These trends are considered likely to continue. In the Antarctic, no similar trends have been observed. One of the most serious impacts on global sea level could occur from a catastrophic failure of grounded ice in West Antarctica. This is, however, considered improbable over the coming century.

- Sea level has risen 0.1–0.2 m over the past century, an order of magnitude larger than the average rate over the past three millennia. A rise of approximately 0.5 m is considered likely during the period 1990–2100.

- Precipitation has increased over the landmasses of the temperate regions by 0.5–1.0% per decade. Frequencies of more intense rainfall events appear to be increasing also in the Northern Hemisphere. In contrast, decreases in rainfall over the tropics have been observed, though this trend has weakened in recent years. More frequent warm phase El Niño events are occurring in the Pacific Basin. Precipitation increases are projected, particularly for winter, for northern middle and high latitudes and for Antarctica.

- No significant trends in the tropical cyclone climatology have been detected.

These changes are principally linked to the atmospheric build-up of greenhouse gases and particularly carbon dioxide (CO_2) produced by burning fossil fuels. The current atmospheric CO_2 concentration is 33% higher than pre-industrial levels. This concentration is not likely to have been exceeded during the past 20 million years. Methane (CH_4) levels have also more than doubled since the late 18th century.

Nitrous oxide (N_2O) concentrations have increased by 16% since 1750 while the concentrations of halon gases that contribute both to ozone depletion and to the enhanced greenhouse effect have been stabilised or reduced as a result of the Montreal Protocol and its successors. However, the depletion of stratospheric ozone since 1980 is considered to have negated some of the warming which would otherwise have occurred as a result of these gases. Similarly, vulcanicity, especially in the period 1960–1991 is also believed to have negated some of the warming trend over recent decades.

These trends in GHGs, and improved modelling capability, have led the IPCC to assert that the evidence for a human influence on global climate is now stronger than claimed in earlier reports. The contention is made that "*increasing concentrations of anthropogenic greenhouse gases have contributed substantially to the observed warming over the last 50 years.*" However, major gaps in our understanding of the uncertainties of the climate system remain. Little progress has been made in quantifying the indirect effects of aerosol loadings on climate. The roles played by the oceans, the feedbacks associated with clouds and sea ice, the operation of biogeochemical systems remain problematical and further work in these areas is required. However, there is a high degree of scientific consensus that the build-up of greenhouse gases is trapping thermal energy in the Earth's atmosphere and that the consequent 'warming' is causing climate change.

1.2 Climate Change as the Climate Norm

Variability over a great range of time and distance scales is an inherent characteristic of Irish climate. When averaged over many years a unique climatic fingerprint emerges, composed of means, extremes and frequencies of various meteorological parameters. Conventionally 30 years of observations have been used in Ireland, as elsewhere, to establish the so-called climatic norms. On this basis statistical estimates of the probability of specific departures from the norm, i.e. estimates of the once in a century wind gust or the once in 50 years daily rainfall total for a place, can be derived. Insurance companies could make policy loadings for ground subsidence based on the probable incidence of summer drought or for burst pipes based on probable incidences of winter frost damage.

It is now clear that this approach to climatic appraisal is limited, as long-term climate trends alter the climate norm. It is now clear that in Ireland, as elsewhere, baselines established on data for recent decades cannot be extended either far into the past or into the future and need to take account of climate trends and in particular those being projected to result from the anthropogenic impacts on climate. The Third Assessment Report is currently the most authoritative assessment of these impacts and how they may change global social and economic activities.

1.3 Approaches to Assessing Climate Change Impacts in Ireland

The Third Assessment Report (TAR) makes it clear that the reductions in GHG emissions under Kyoto are insufficient to prevent some climate change from happening and that current levels of GHGs are such that anthropogenically induced climate changes will become more evident in the coming decades. It is, therefore, necessary that governments, including the Irish government, should plan for future climate scenarios. These plans can only be based on climate model projections, which currently provide relatively coarse spatial data for areas such as Ireland, that are coupled to current understanding and management of factors governed by climate and climate extremes.

This report presents an assessment of the magnitude and likely impacts of climate change in Ireland over the course of this century, a first step in the process by which national planning for future climatic conditions can be undertaken.

Firstly, possible change scenarios for Irish climate around the middle and last quarter of the present century are established. The approach used here is described in Chapter 2 in which climate models are discussed. Methods by which the coarse information currently available from climate models can be downscaled for use in Ireland are also outlined. These projections are then used to assess probable impacts on key sectors such as agriculture, forestry, water resources, coastal and marine environments and on biodiversity. These topics are considered in subsequent chapters.

This report aims to identify where vulnerability to climate change exists in Ireland, and what adjustments are likely in the operation of environmental systems in response to such changes. In many cases, such as in agriculture, some new opportunities may arise under changed climatic conditions. In other instances, e.g. water resource management, long-term planning strategies will be necessary to avoid adverse impacts. Long lead-in times for adjustment characterise many sectors, e.g. forestry, and it is important to provide as much advance warning of likely changes as possible to enable adaptation to commence early. By anticipating change, it is possible for a country such as Ireland to position itself to minimise the adverse impacts and maximise the positive aspects which global climate changes may present.

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2 Establishing Reference Climate Scenarios

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2.1 Global Climate Models

Global Climate Models (GCMs) have in recent years become increasingly sophisticated vehicles for predicting future climate. The Third Assessment Report of the IPCC assessed 34 coupled Atmosphere–Ocean GCMs (IPCC, 2001) and noted that several were able to simulate successfully 20th-century temperature trends when driven by appropriate radiative forcing scenarios. This improvement in model performance has come about as a better understanding of climatic processes has been incorporated into the models and as major advances in computing have enabled less simplification and more realism in input parameters to be achieved. Of particular importance has been the rapid growth in computer speed (Fig. 2.1). This is crucial in global climate modelling since each iteration of the calculations for a variable at an individual grid point location may require the retrieval, calculation and storage of up to 10^5 numbers. When the number of variables, levels and grid squares is taken into account, the limitations of computer power for providing high-resolution spatial and temporal output become apparent.

A relatively coarse grid size is currently used by GCMs. This is typically of the order of 2.5° × 3.75° and the European domain of the UK Met Office Hadley Centre GCM, known as the HadCM3 model, is shown in Fig. 2.2. Ireland is represented by one grid square. When output from the GCM is obtained from such model runs, only a first approximation to climate change conditions is available for Ireland. The simplification of the Irish coastline and topography also results in predictions for which a better representation of the geography of Ireland would permit greatly enhanced detail. In addition, the grid cell implicitly assumes a homogenous land cover for the entire square. Ireland has a mosaic of land types, ranging from bare rock to peat, which give distinctively different energy budgets and, thus, yield microclimatic characteristics which may manifest themselves as regional-scale climatic modifications. Such aspects cannot be represented readily in a large GCM grid square although they may be significant influences on climate in aggregate.

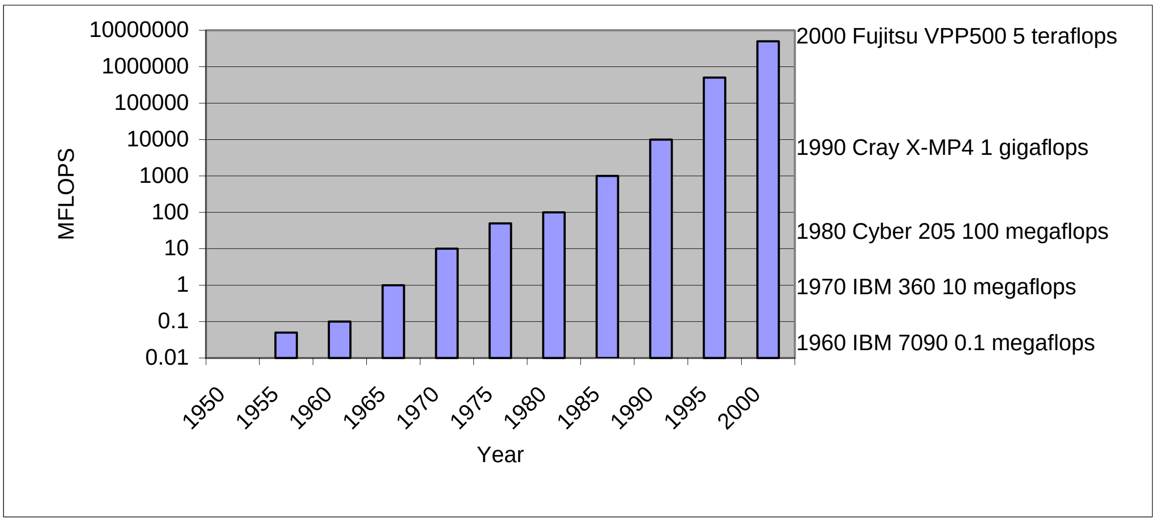


Figure 2.1. Growth of computing power 1950–2000 (MFLOPS refers to millions of floating points operations per second).

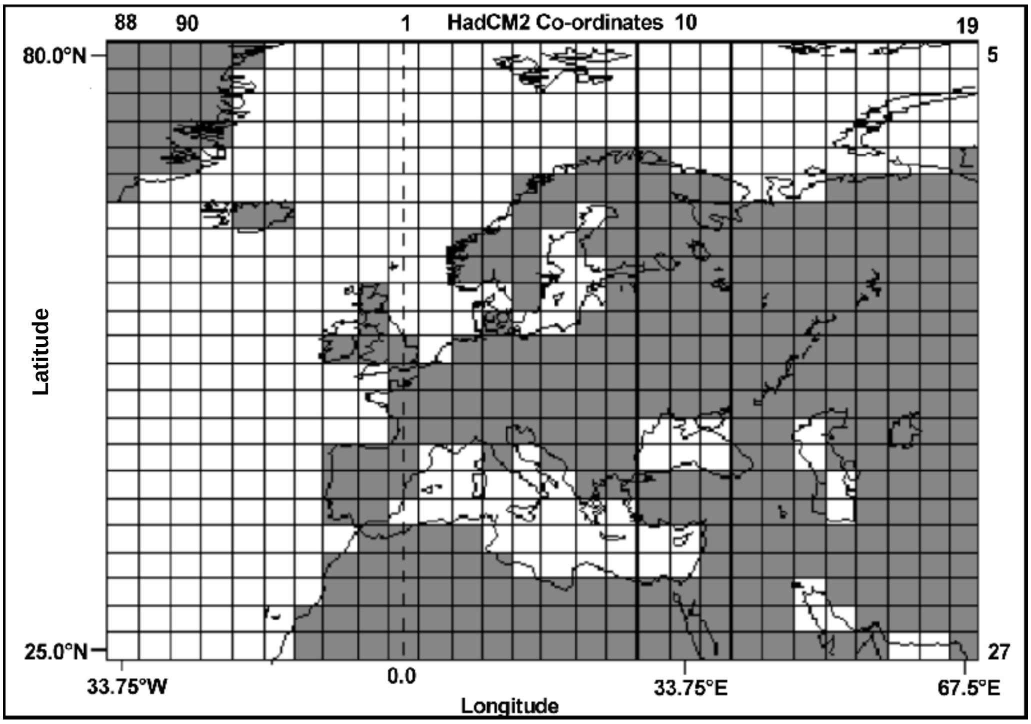


Figure 2.2. Grid Representation of Europe employed in both the HadCM2 and HadCM3 Global Climate Models. The 2.5° × 3.75° grid resolution equates to about 240 × 278 km in the vicinity of Ireland.

2.2 Downscaling of Global Climate Models

The relatively coarse resolution of GCM output represents a major drawback in their utility for assessing the impacts of climate change. This is because many of the impacts require analysis at sub-grid scale and it is at sub-grid scale that any policy measures to mitigate change must be applied (Lamb, 1987). For example, assessing changes in the likely discharge of the River Liffey or changes in the viability of growing maize in Co. Louth would need much more regionally detailed climatic projections than those available from the Irish grid box. It is for this reason that climate scenarios at a smaller scale must be sought. Obtaining such regional scenarios involves developing a technique to translate the GCM output to finer spatial scales, a technique known as downscaling.

A number of approaches currently exist whereby increased spatial detail may be inferred from coarse grid GCM output. The first of these, regional climate modelling, is a dynamic approach involving further computer modelling which makes particular use of grid cells in the vicinity of the area of interest. In essence, the boundary conditions for the region of interest are provided by the grid output for the area from a coupled ocean–atmosphere GCM. This output in turn drives a nested regional-scale climate model with grid sizes typically of the order of 50 km. Such Regional Climate Models (RCM) have recently been run for Scotland and the south-west of England by the Hadley Centre at scales of 50 km (Hulme *et al.*, 2001). These are likely to be available for extensive parts of Britain and Ireland over the next few years at grid scales of 25 km. While RCMs offer a considerable elaboration of regional detail by comparison to their parent GCM (Fig. 2.3), difficulties continue to persist with this approach (Giorgi and Francisco, 2000). These centre on the inescapable fact that the level of accuracy of the parent GCM largely determines the level of accuracy of the RCM. This is a problem common to all approaches to downscaling. Continuing difficulties persist also in the interfacing of the GCM output to provide the boundary conditions for the nested RCM (Hewitson and Crane, 1996). Thus, while an RCM approach offers considerable promise for providing future climate scenarios, they are presently very demanding on computing resources and are still

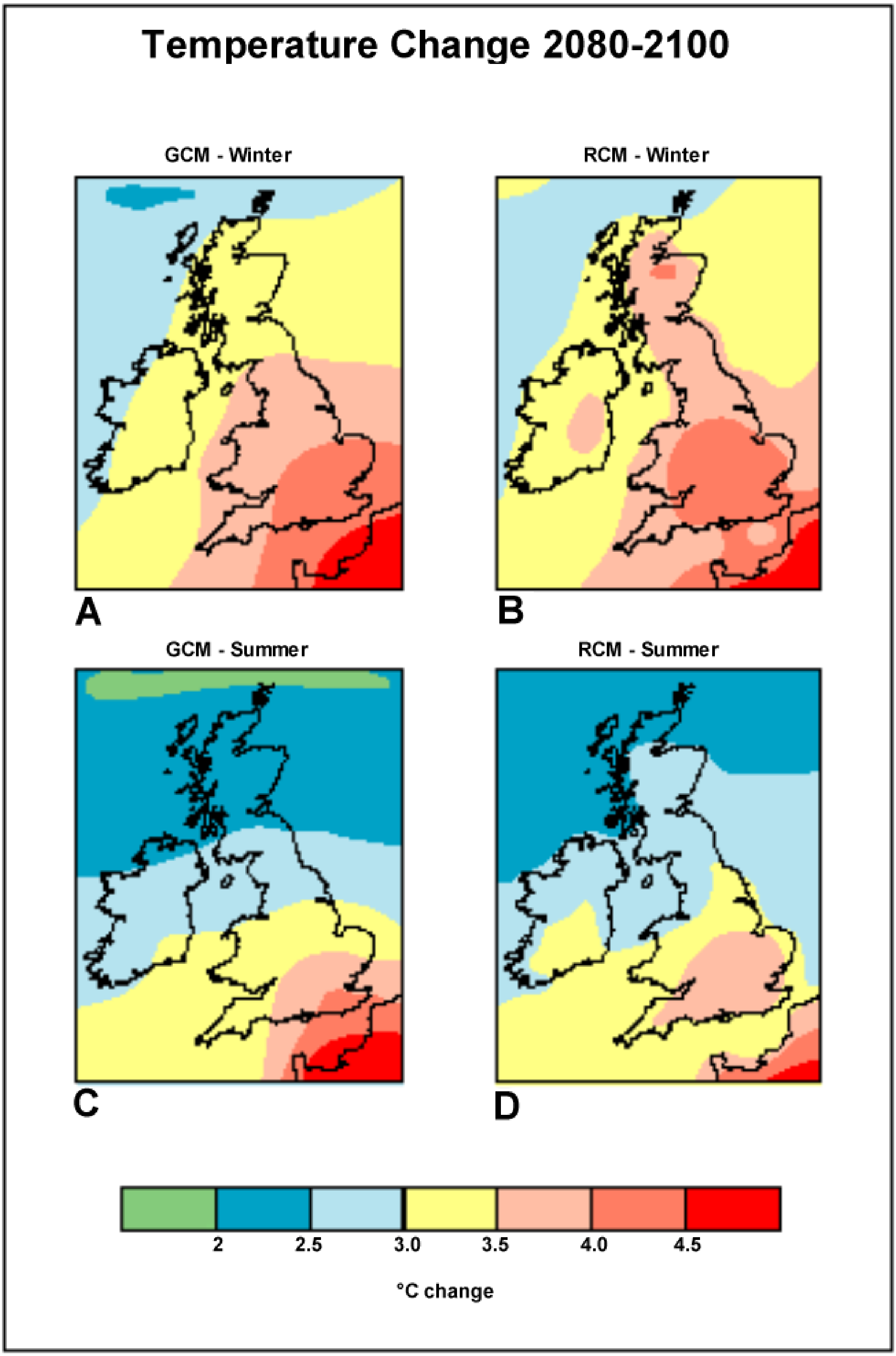


Figure 2.3. Comparisons between GCM and RCM outputs.

output at resolutions that are too high for many practical impact assessment purposes.

A second approach is known as pattern scaling because the existing spatial pattern is largely replicated in the future scenario. This is the simplest form of downscaling which entails applying an output figure for an entire GCM grid square to an existing baseline climatology within that grid cell. For example, if a mean annual temperature increase of 2.7°C for 2050 is predicted for the Irish grid cell by a GCM, this value would then be added to each annual average from the observational network within Ireland and the data interpolated to provide a regional scenario for Ireland.

Although quite simplistic, this technique does provide a preliminary product that can be subsequently used for impact modelling. Such an approach was first described by Santer *et al.* (1990) and was employed for the projections for 2030 in the IPCC First Assessment Report (Mitchell *et al.*, 1990) and in the UKCIP98 Report (Hulme and Jenkins, 1998).

The use of pattern scaling for producing Irish climate scenarios has one additional problem. Essentially, it assumes that the climate changes are the same irrespective of the altitude or location within the grid. For example, the change in mean temperature at the top of Carrantuohill would be assumed to be the same magnitude as on the shores of Lough Neagh. This is clearly inappropriate. Because of this, great caution must be exercised in the use of a pattern-scaling approach for generating climatic scenarios, especially for a country with a large topographical variation, such as Ireland.

A third approach is to apply statistical downscaling techniques to GCM data. A number of statistical downscaling techniques have evolved in parallel to regional climate modelling and pattern scaling. Among the earliest approach was circulation typing, which entailed the matching of present climate characteristics to a synoptic circulation scheme, such as the Lamb Weather Type (Sweeney, 1985). This method has been applied to generate analogue scenarios derived from past climate data. This technique suggested winter precipitation increases of 10–25% and summer decreases of up to 15% for Ireland for mid-century (Sweeney, 1997). A second approach has been to use a stochastic weather generator perturbed by GCM output to yield daily weather for the new time period concerned. Inherent in this is the assumption that the probability of extremes does not change between the present and future (generated) climate.

One of the most widespread approaches to downscaling raw GCM output has been the incorporation of mesoscale predictor variables in an empirical statistical technique that establishes linkages between the GCM output and surface observations. The technique is based on the assumption that GCMs simulate mesoscale aspects of climate better than surface variables such as temperature and pressure (Palutikof *et al.*, 1997). The approach involves establishing relationships between conservatively changing upper air variables, such as geopotential temperatures and heights and local surface observations. Over a training period, the relationship between these sets of variables is established and assumed to be robust in a changing climate situation. Since the mesoscale variables also are output by the GCM, the local surface variables in a changed climate situation may then be generated. Downscaling is performed on individual point locations, both for the baseline and future runs of the model, and the differences are applied to the observational data to provide a climate change scenario (Wilby and Wigley, 1997). This technique was utilised for this study.

2.3 Derivation of the Baseline Climatology

A Digital Elevation Model (DEM) of Ireland was derived from the 30Arc Second Global Elevation dataset of the U.S. Geological Service (GTOPO). The resolution of the DEM was approximately 1 km^2 at the latitude of Ireland. The DEM, comprising 83,880 grid cells, was then projected to the Irish National Grid. This formed the baseline on which climate data were mapped. The accuracy of the height dataset was estimated to be such that 90% of the cells were ±30 m from the true altitudes. For climatological purposes in Ireland, this is adequate, particularly for areas such as the Central Plain where topographical change is gradual. For extensive upland areas, such as the Antrim Plateau and Wicklow Mountains, it is also adequate at a 1 km^2 resolution. The

DEM probably provides a slight underestimate of height where a free-standing mountain exists which may be bifurcated into two or more cells with average heights 'weighted' by the lowland component in the cell. Similarly, where narrow ridge-like upland areas exist, such as in the peninsulas of Cork/Kerry or the Ox Mountains of Sligo, some underestimation of absolute height may occur. Against this, a 1 km^2 resolution enables relatively good discrimination of relief features over most of Ireland.

Monthly climate data for both the Republic of Ireland and Northern Ireland for the period 1961–1990 were obtained from Met Éireann and from the British Atmospheric Data Centre of the UK Meteorological Office. This amounted to 560 stations for precipitation (Fig. 2.4) and 70 stations for maximum/minimum temperature.

Data for incident radiation, sunshine hours and potential evapotranspiration were also acquired for as many locations as possible. A criterium of 70% data capture was applied to each station. Where this was not achieved, the station data were discarded. It was also considered important to acquire data across as large an altitudinal range as possible. For precipitation, the altitudinal range extended up to 808 m Ordnance Datum (O.D.) while temperature data included stations up to 710 m O.D.

In order to derive climatological values for the areas between the station locations, a regression model was employed similar to that of Goodale *et al.* (1998). Initially a first-order regression equation was developed and tested. Higher order regression equations were used and the best fit was determined by examining the R^2 statistic. A second-order polynomial regression equation was identified as most applicable for the available data. Intuitively a quadratic trend surface represents many of the key spatial trends in Irish climate with a coast–interior–coast contrast superimposed on a south-west–north-east latitudinal gradient (Fig. 2.5). For example, winter temperatures in Ireland do show a coast–interior–coast contrast as the dominant spatial feature, while summer temperatures have a more overt latitudinal control apparent.

Each of the climatic variables was predicted according to the following equation:

$$\textit{Climatic Variable} = a + bx + cy + dx^2 + ey^2 + fxy + gz$$

where a is a constant, b–g are co-efficients derived from the regression, x is the row number of the grid cell (km), y is the column number (km), and z is the elevation above sea level (m).

The baseline values used in the climate equations for the key variables are shown in Table 2.1 (a–d). Some measures of the explanation of the variance provided by the various equations are also presented, as are the standard errors.

For maximum temperature, it is apparent that the polynomial regressions account for 78–95% of the spatial variation across Ireland. Levels in excess of 90% generally applied during the winter half of the year with standard errors at this time down to ±0.22°C. For minimum temperatures, somewhat lower levels of explanation apply, 57–69%, with again slightly higher levels in winter. In fact, the stepwise regression discarded the x (longitudinal) component in this regression. The predictive equations provided high levels of explanation of the variance in the case of radiation. This ranged from 71 to 96%. However, lower levels of success were apparent with precipitation. The percentage of the variance explained averaged 73%. This was not unexpected given the localised nature of some precipitation events and the potential effect of sub-grid scale features in influencing receipt.

Baseline climatologies for the period 1961–1990, derived using the predictive equations, are shown in Figs 2.6–2.11. These display a high degree of regional detail as a result of the high-resolution approach employed. In the case of precipitation, the resolution of 1 km^2 appears capable of depicting smaller scale variations in receipt than are apparent from the normal maps based on interpolation alone. For example, the Barrow, Slaney and Suir river valleys are prominent features of reduced rainfall on the July map.

The production of baseline maps of radiation and potential evapotranspiration required an alternative approach due to the paucity of observational data. Only 15 stations measure incident solar radiation in Ireland. A much larger network of stations measuring sunshine

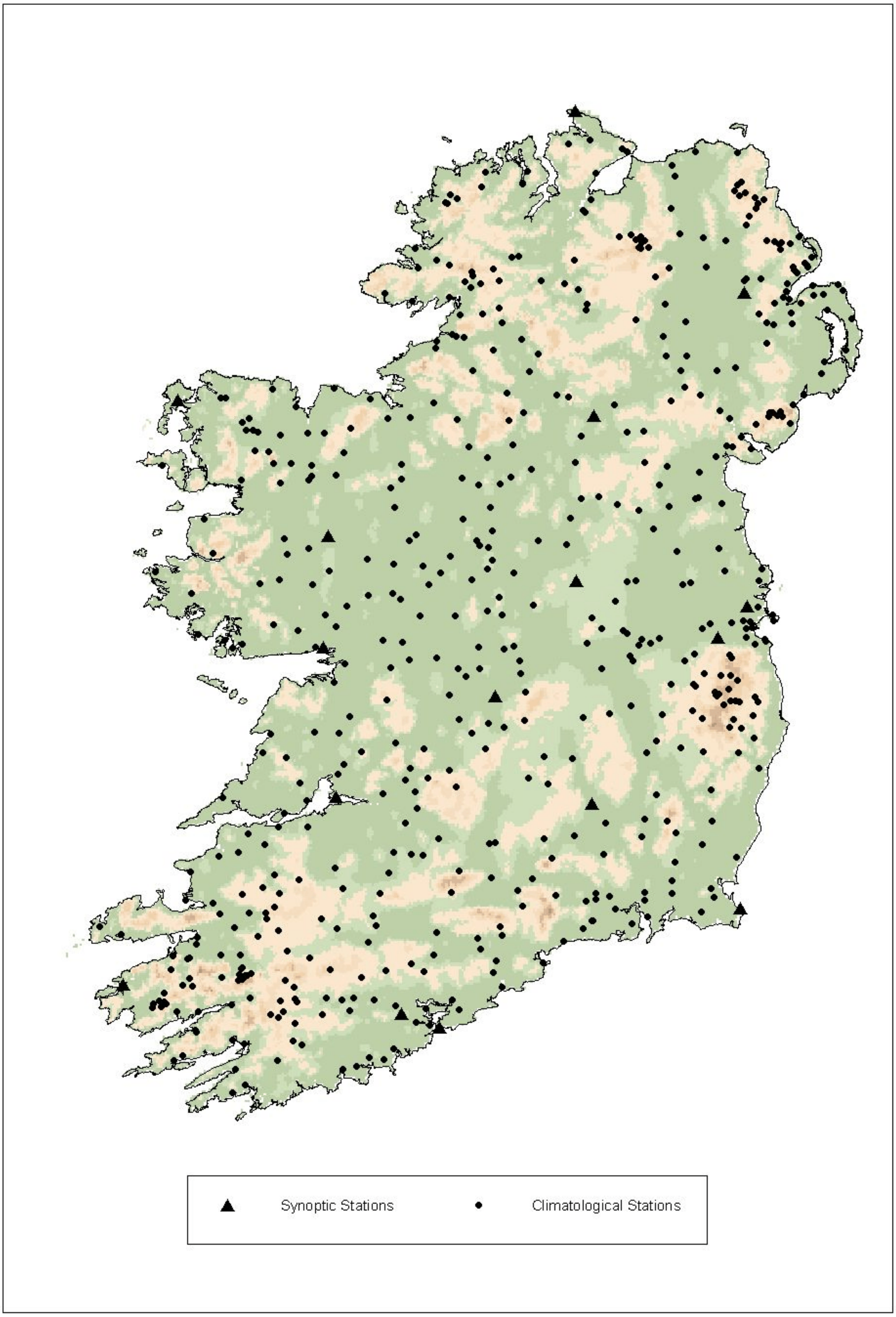


Figure 2.4. Locations of the 560 precipitation stations employed in the analysis.

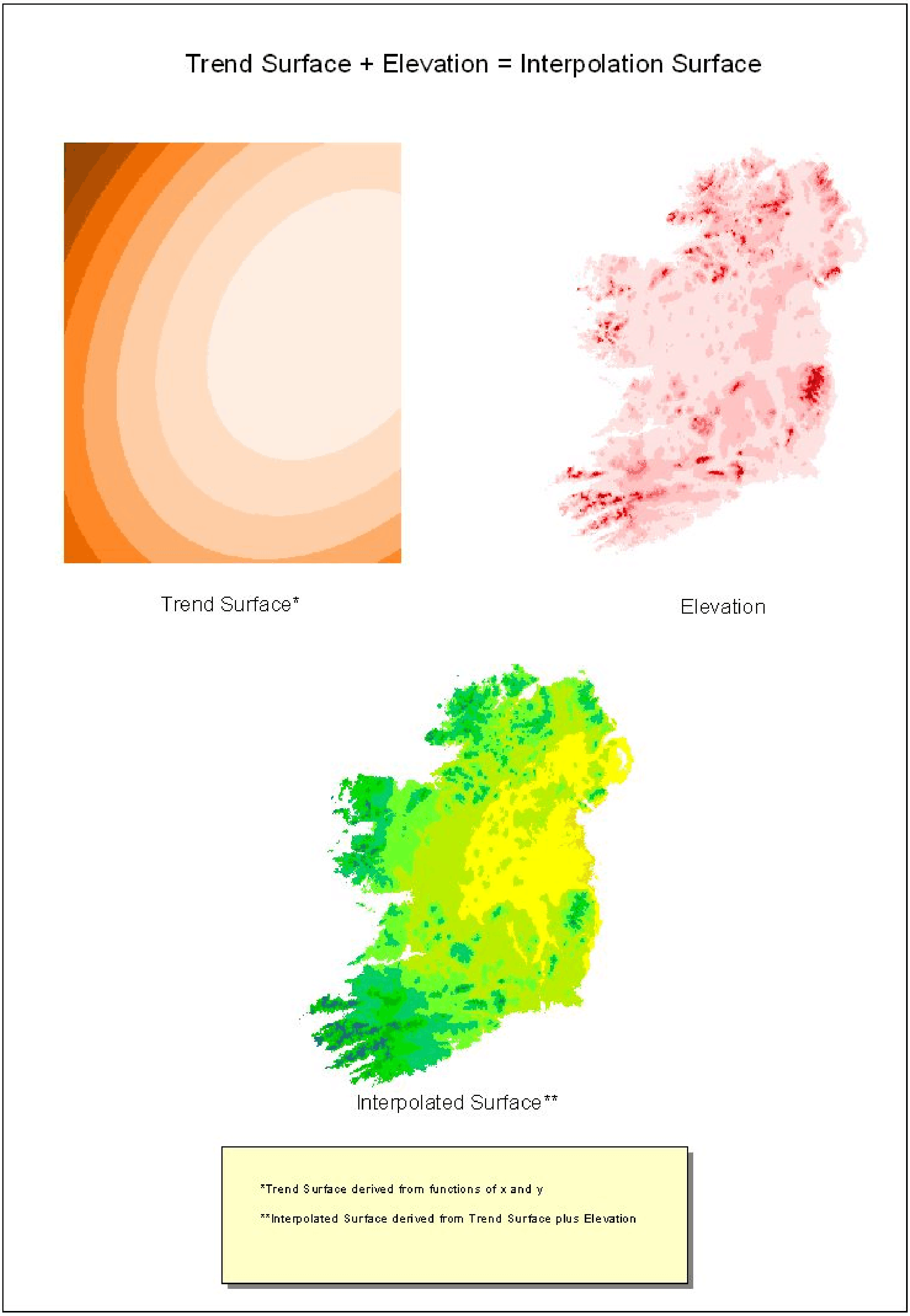


Figure 2.5. Trend surface and elevation – a schematic view of the procedure employed in deriving the baseline climate and also in interpolating downscaled point data for future climate scenarios.

Table 2.1(a). Polynomial regression statistics for maximum temperature, 1961–1990.

Month	Const.	Height	x (km)	y (km)	x^2	y^2	xy	Adj. R^2	SE
Jan	10.76	–0.008264	–0.012420	–0.007142	0.000026	0.000006	0.000000	0.91	0.25
Feb	9.95	–0.008922	–0.006325	–0.003455	0.000008	0.000000	0.000000	0.95	0.19
Mar	10.24	–0.007919	0	0.003958	–0.000003	–0.000015	0.000000	0.90	0.25
Apr	11.47	–0.006294	0.007239	0.008226	–0.000033	–0.000031	0.000021	0.80	0.34
May	13.97	–0.005732	0	0.011260	0.000000	–0.000027	0.000000	0.70	0.41
Jun	14.92	–0.005850	0.020010	0.011950	–0.000061	–0.000045	0.000032	0.78	0.40
Jul	16.67	–0.006283	0.021110	0.009679	–0.000063	–0.000047	0.000040	0.85	0.38
Aug	17.02	–0.006306	0.016830	0.007753	–0.000049	–0.000036	0.000028	0.83	0.34
Sep	16.24	–0.007522	0.006493	0.004334	–0.000021	–0.000025	0.000020	0.86	0.28
Oct	14.31	–0.007815	0	0	0.000000	–0.000007	0.000004	0.92	0.18
Nov	11.72	–0.008750	0	–0.007777	0.000000	0.000008	0.000000	0.91	0.23
Dec	11.51	–0.008067	–0.012420	–0.007548	0.000026	0.000007	0.000000	0.91	0.24

Table 2.1(b). Polynomial regression statistics for minimum temperature, 1961–1990.

Month	Const.	Height	x (km)	y (km)	x^2	y^2	xy	Adj. R^2	SE
Jan	4.93	–0.008927		–0.019330		0.000031		0.63	0.58
Feb	4.86	–0.008977		–0.018650		0.000028		0.69	0.53
Mar	5.35	–0.009179		–0.015350		0.000023		0.69	0.50
Apr	6.67	–0.008211		–0.017170		0.000027		0.63	0.53
May	8.74	–0.008943		–0.015200		0.000024		0.62	0.54
Jun	11.13	–0.008560		–0.011180		0.000016		0.66	0.46
Jul	12.77	–0.008057		–0.009252		0.000013		0.67	0.43
Aug	12.91	–0.008466		–0.012680		0.000019		0.57	0.54
Sep	11.90	–0.008852		–0.018350		0.000030		0.62	0.54
Oct	9.69	–0.007552		–0.017910		0.000030		0.57	0.52
Nov	7.52	–0.008131		–0.026990		0.000045		0.66	0.58
Dec	5.93	–0.007562		–0.021540		0.000035		0.61	0.58

Table 2.1(c). Polynomial regression statistics for radiation, 1961–1990.

Month	Constant	Height	x km	y (km)	x^2	y^2	xy	Adj. R^2	SE
Jan	2929160	–578.21		–1666.99	4.73		–4.18	0.96	59009
Feb	5146168	–797.39		–2265.99	2.25			0.86	100567
Mar	8489621	–982.82			14.02		–15.41	0.83	180165
Apr	15286638		–7013.36	–11010.50	40.70	28.51	–30.52	0.75	260798
May	19451989	–2945.96	–10612.93	–14415.74	62.95	40.54	–45.88	0.71	433044
Jun	18519338	–2815.61		–14922.77	46.23	39.06	–43.00	0.71	465819
Jul	17300190	–2448.87		–15413.95	46.01	29.67	–35.33	0.87	367435
Aug	15680788		–8997.56	–11914.09	59.49	29.09	–39.29	0.80	356851
Sep	10036326				23.78		–23.89	0.85	246864
Oct	5905547				14.43		–14.36	0.85	145261
Nov	3555111			–1866.58	7.34		–5.75	0.95	74114
Dec	2404503	–368.19	960.12	–2695.00				0.96	56746

Table 2.1(d). Polynomial regression statistics for precipitation, 1961–1990.

Month	Const.	Height	x (km)	y (km)	x^2	y^2	xy	Adj. R^2	SE
Jan	280.74	0.246	–0.984	–0.585	0.002218	0.001686	–0.001051	0.74	26.63
Feb	204.31	0.166	–0.602	–0.530	0.001332	0.001250	–0.000549	0.75	18.60
Mar	192.19	0.176	–0.707	–0.343	0.001574	0.001168	–0.000791	0.71	20.07
Apr	108.21	0.126	–0.309	–0.150	0.000757	0.000489	–0.000405	0.71	11.67
May	111.62	0.132	–0.335		0.000505			0.69	12.81
Jun	102.95	0.114	–0.321	–0.059	0.000542	0.000305	–0.000148	0.71	10.97
Jul	104.52	0.129	–0.290	–0.135	0.000500	0.000535	–0.000291	0.73	12.04
Aug	144.45	0.148	–0.455	–0.119	0.000869	0.000573	–0.000419	0.69	15.66
Sep	176.60	0.180	–0.665	–0.184	0.001542	0.000983	–0.000945	0.74	17.69
Oct	241.98	0.209	–0.903	–0.383	0.002018	0.001472	–0.001138	0.77	21.70
Nov	233.91	0.206	–0.944	–0.294	0.002200	0.001357	–0.001314	0.76	21.48
Dec	261.41	0.242	–0.984	–0.406	0.002309	0.001408	–0.001263	0.75	25.10

hours is maintained, however, and this can provide surrogate radiation data. Based on a well-established empirical formula which relates solar radiation to sunshine hours (Angstrom, 1924; Brock, 1981), solar radiation can be calculated from sunshine hours as follows:

$$Q / Qa = \mathrm{a} + \mathrm{b}\,(n / N)$$

where Q is the solar radiation received on the Earth's surface (MJ m^{-2}), Q_a is the potential solar radiation at the top of the atmosphere (MJ m^{-2}), n is the sunshine hours and N is the total day length (h). Values for the constants a and b were established for Ireland in previous research (McEntee, 1980) as 0.21 and 0.67, respectively. This enabled radiation baseline maps to be generated. January and July maps are shown in Figs 2.12 and 2.13.

Similar problems existed for the generation of Potential Evapotranspiration (PE) maps due to the sparse network of both wind monitors and stations measuring PE. Both wind and radiation are required inputs for the calculation of evapotranspiration according to the Penman method. As an alternative, regressions were run using temperature and radiation variables. These variables were regressed on actual Penman PE values calculated at each of the synoptic stations over the 30-year period. A separate equation was run for each month treating the 30 Januarys, Februarys and other months as separate datasets. Mean monthly temperature and mean monthly radiation receipt were found to provide good predictors of PE in the summer months May–August with R^2 values in the range 75–87% (Table 2.2). Prediction levels in winter were relatively low as wind assumed comparatively greater importance. However, for hydrological and agricultural purposes, the very small levels of PE at this time of year are not of major significance. Typically, monthly PE is less than 2 mm at inland locations in Ireland in December and does not form as important a component in water-balance considerations as in summer when July values in excess of 80 mm are typical.

Validation of the predicted PE values was then examined on a separate dataset for the synoptic stations 1991–2000. This gave good agreement between actual and predicted values (Table 2.3). Using the technique described above for temperature to interpolate between the data points, monthly maps of PE were derived. January and July values are shown in Figs 2.14 and 2.15.

2.4 Generating Downscaled Scenarios

Global Climate Models must be run with certain assumptions regarding trends in the emission of greenhouse gases over time. Population growth, economic growth and technological change will determine how these emissions will change over time. In addition, the effects of any policy measures taken to mitigate climate change should be incorporated into these projections. Normally, a range of emission scenarios is used in the model runs, based on assumptions for these variables. In the Second Assessment Report, the IPCC

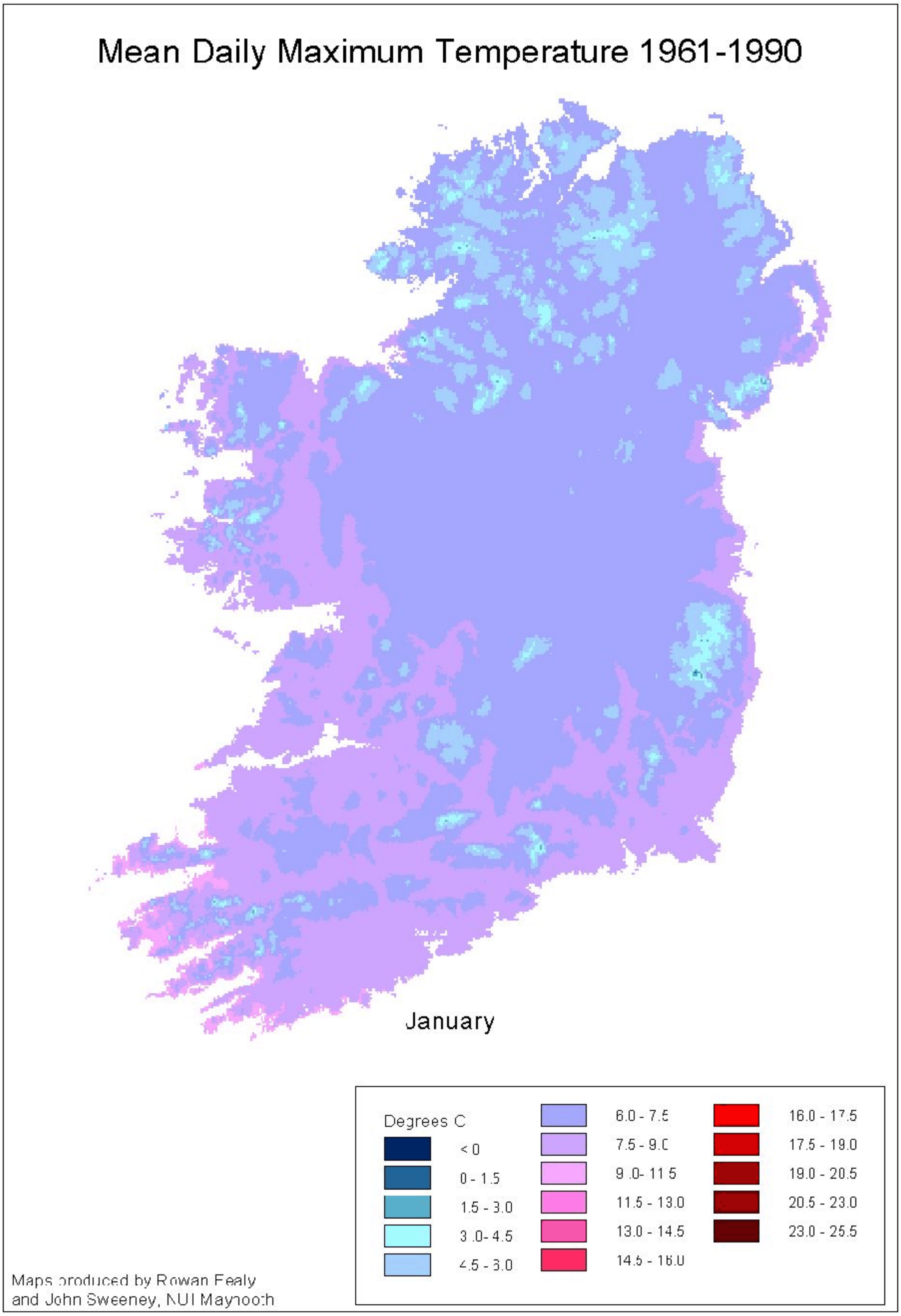


Figure 2.6. Baseline climatology: mean daily maximum temperature January at 1 km^2 resolution for the period 1961–1990.

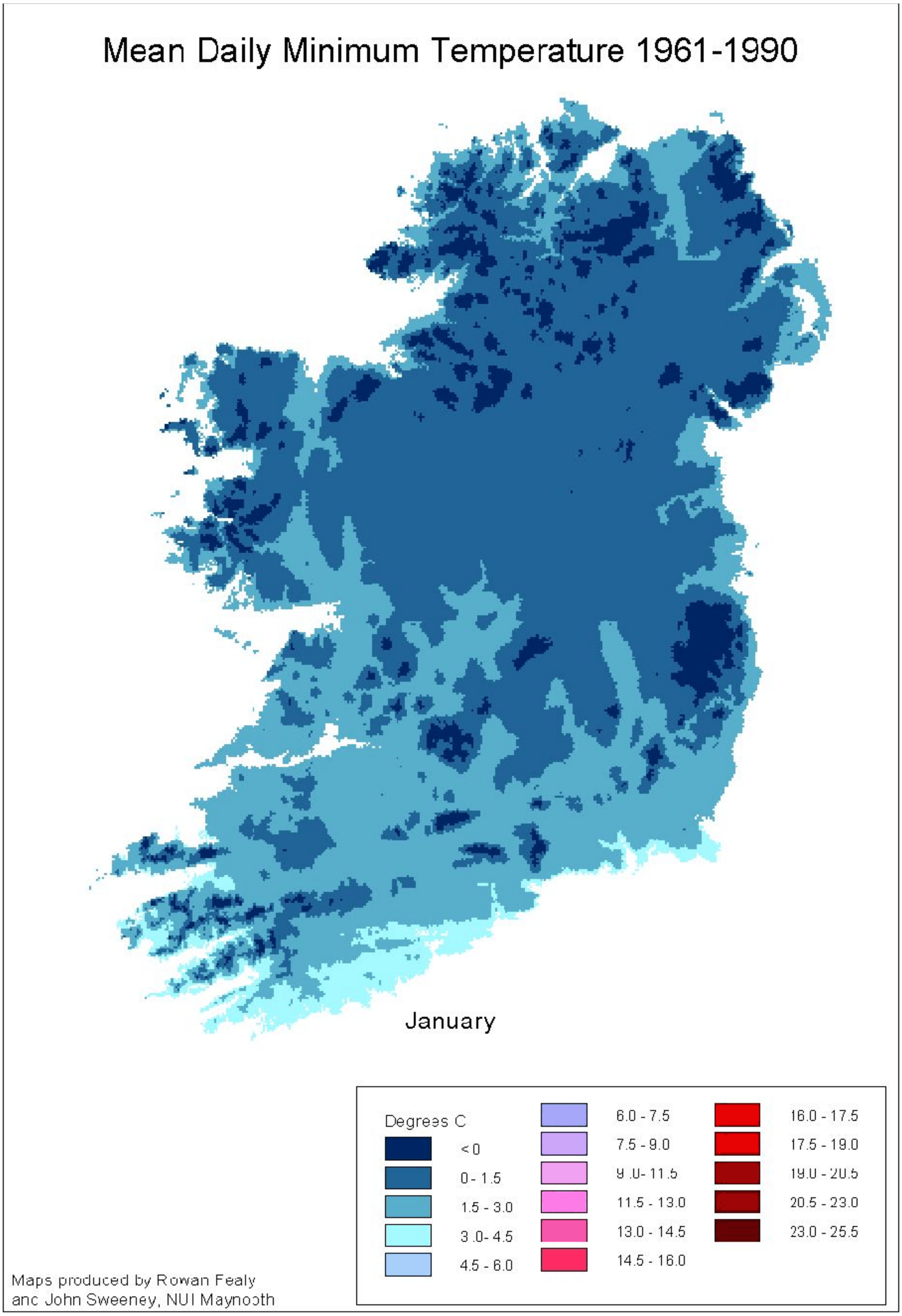


Figure 2.7. Baseline climatology: mean daily minimum temperature January at 1 km² resolution for the period 1961–1990.

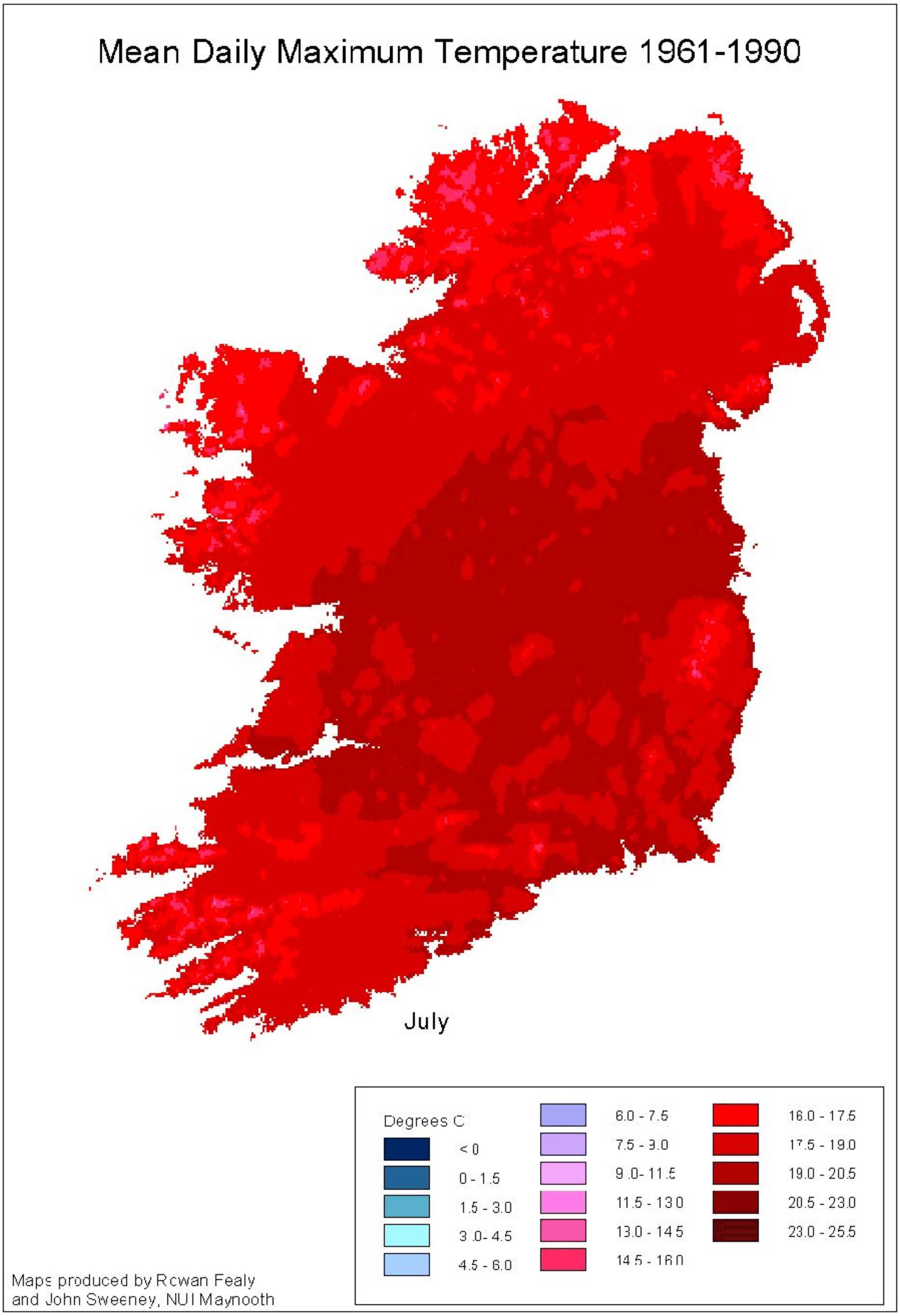


Figure 2.8. Baseline climatology: mean daily maximum temperature July at 1 km^2 resolution for the period 1961–1990.

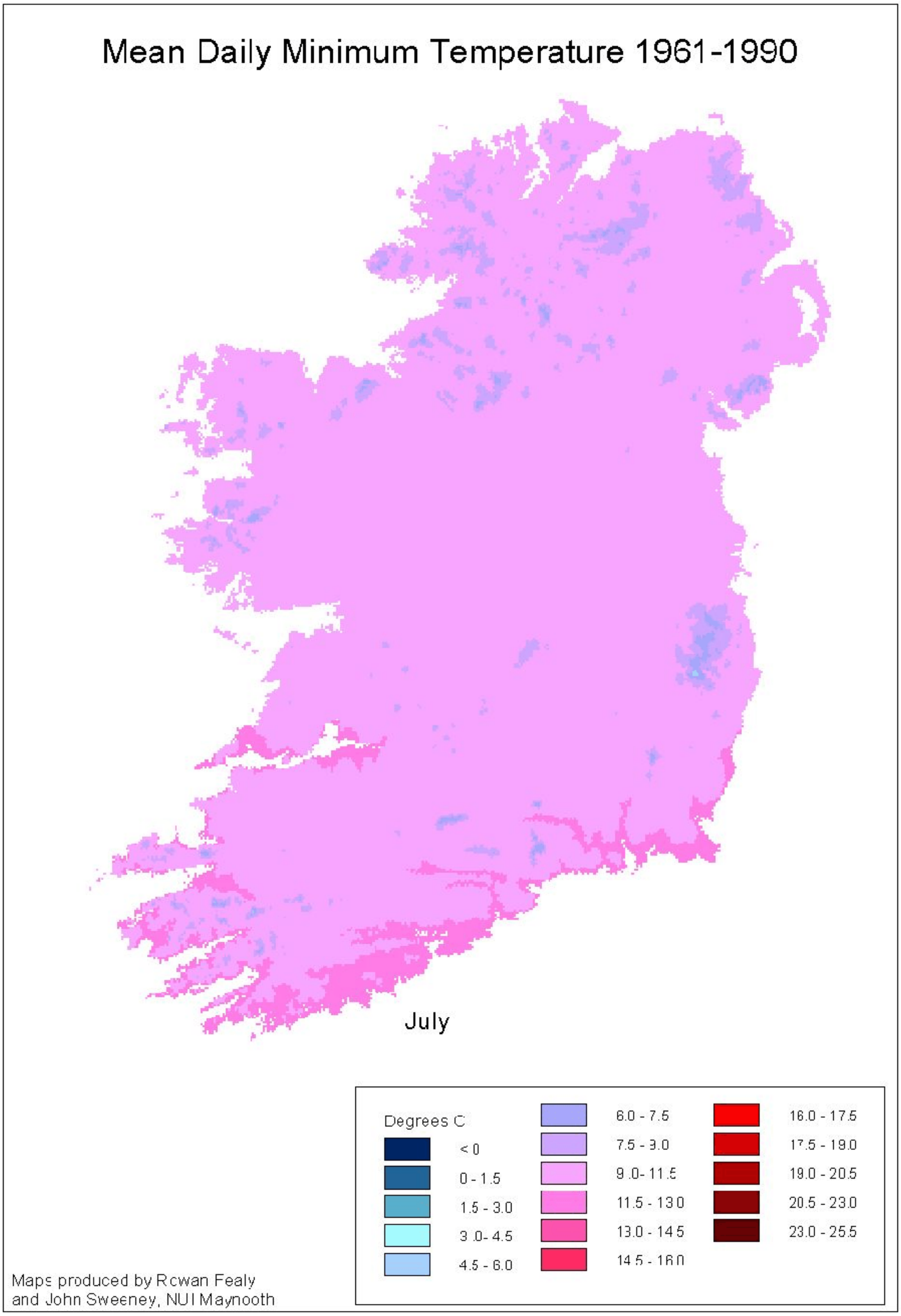


Figure 2.9. Baseline climatology: mean daily minimum temperature July at 1 km^2 resolution for the period 1961–1990.

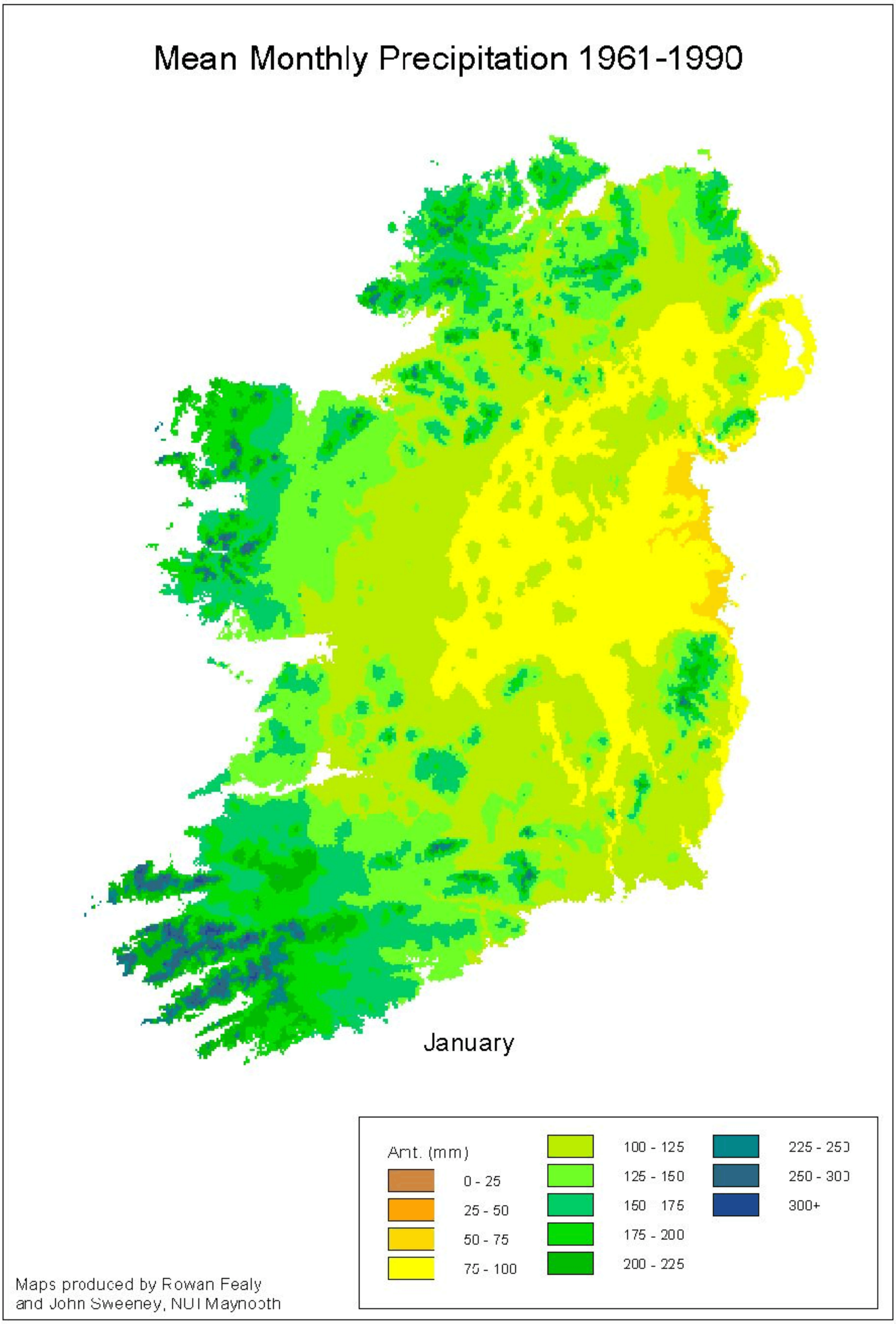


Figure 2.10. Baseline climatology: mean monthly precipitation January at 1 km^2 resolution for the period 1961–1990.

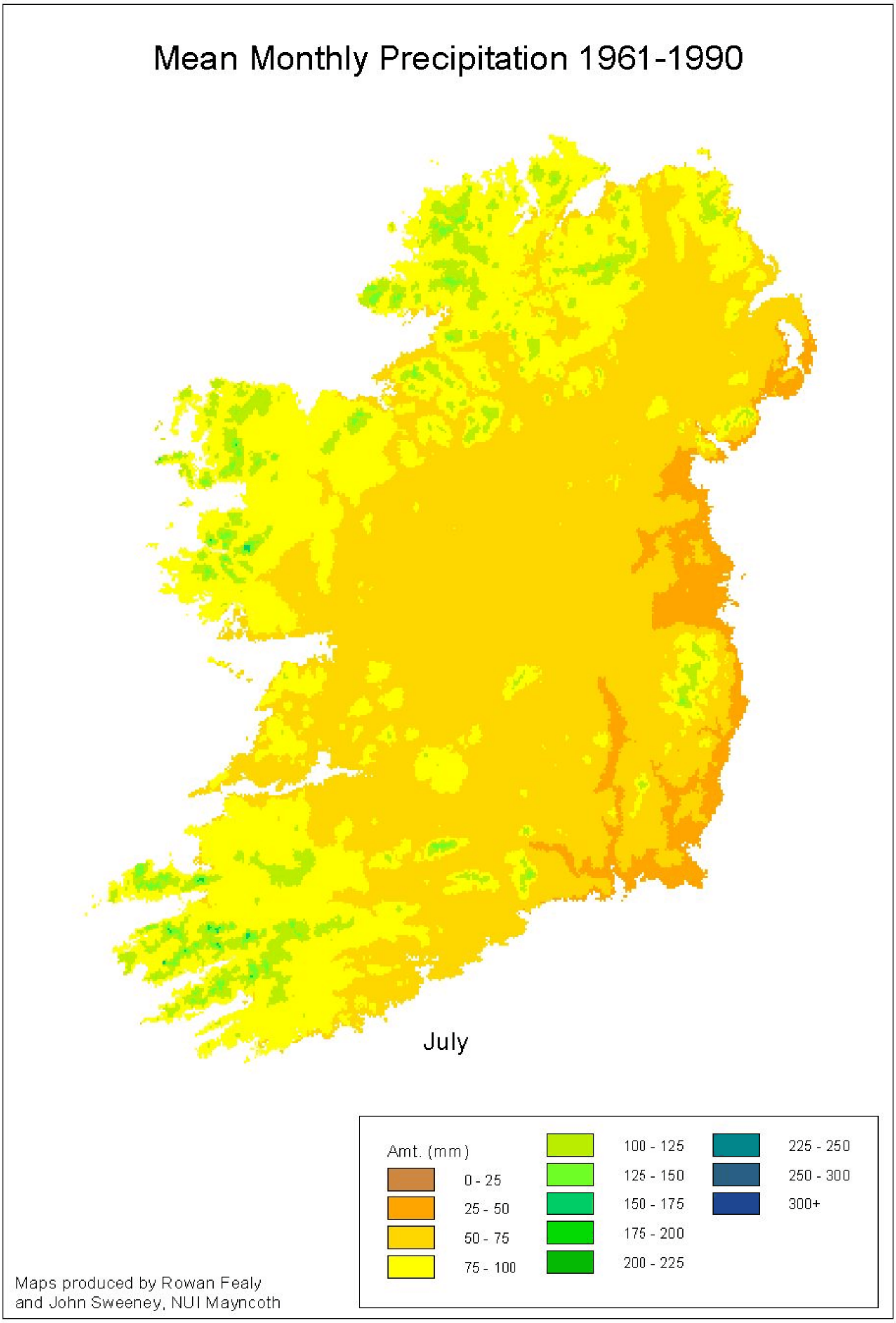


Figure 2.11. Baseline climatology: mean monthly precipitation July at 1 km^2 resolution for the period 1961–1990.

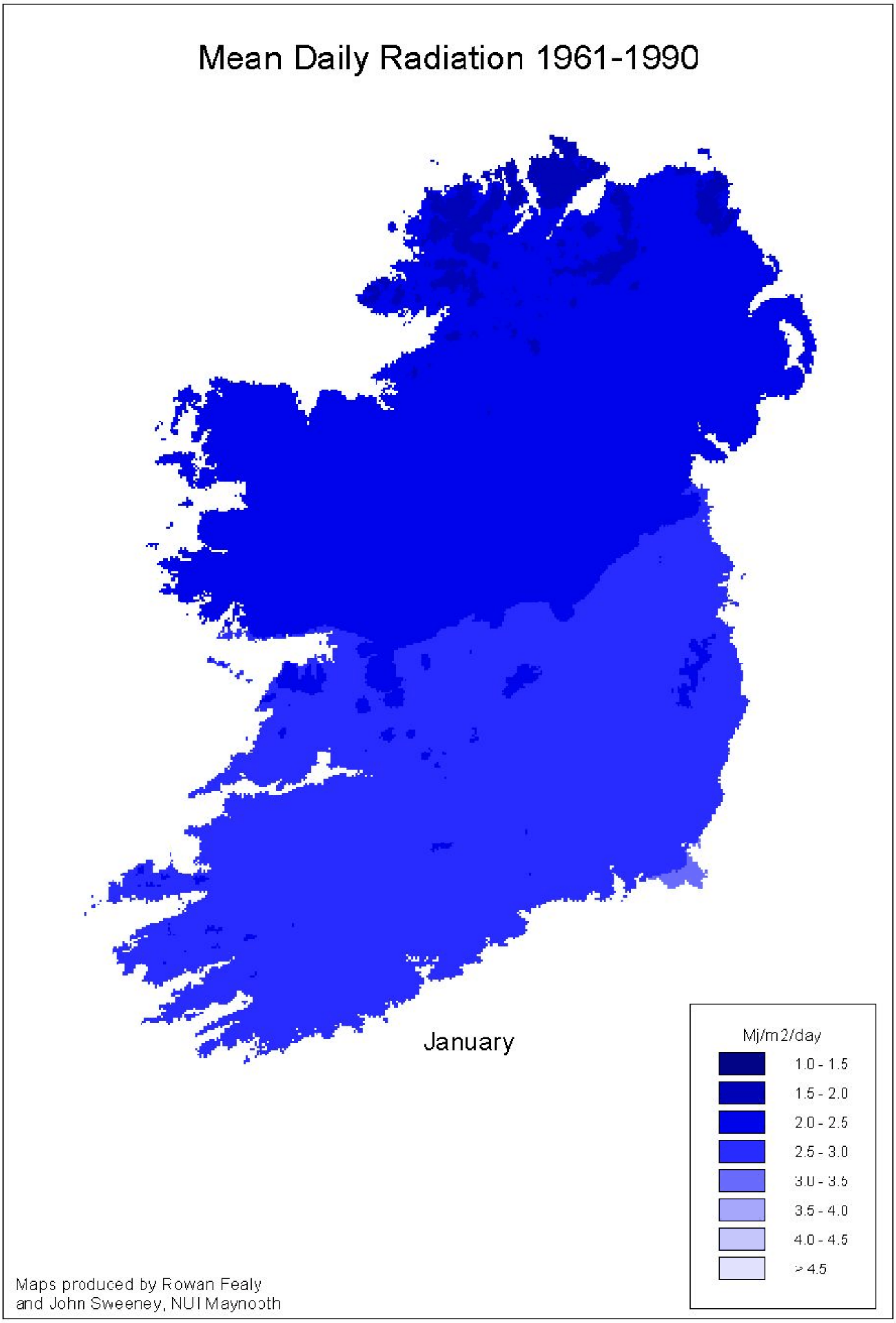


Figure 2.12. Baseline climatology: mean monthly radiation January at 1 km² resolution for the period 1961–1990.

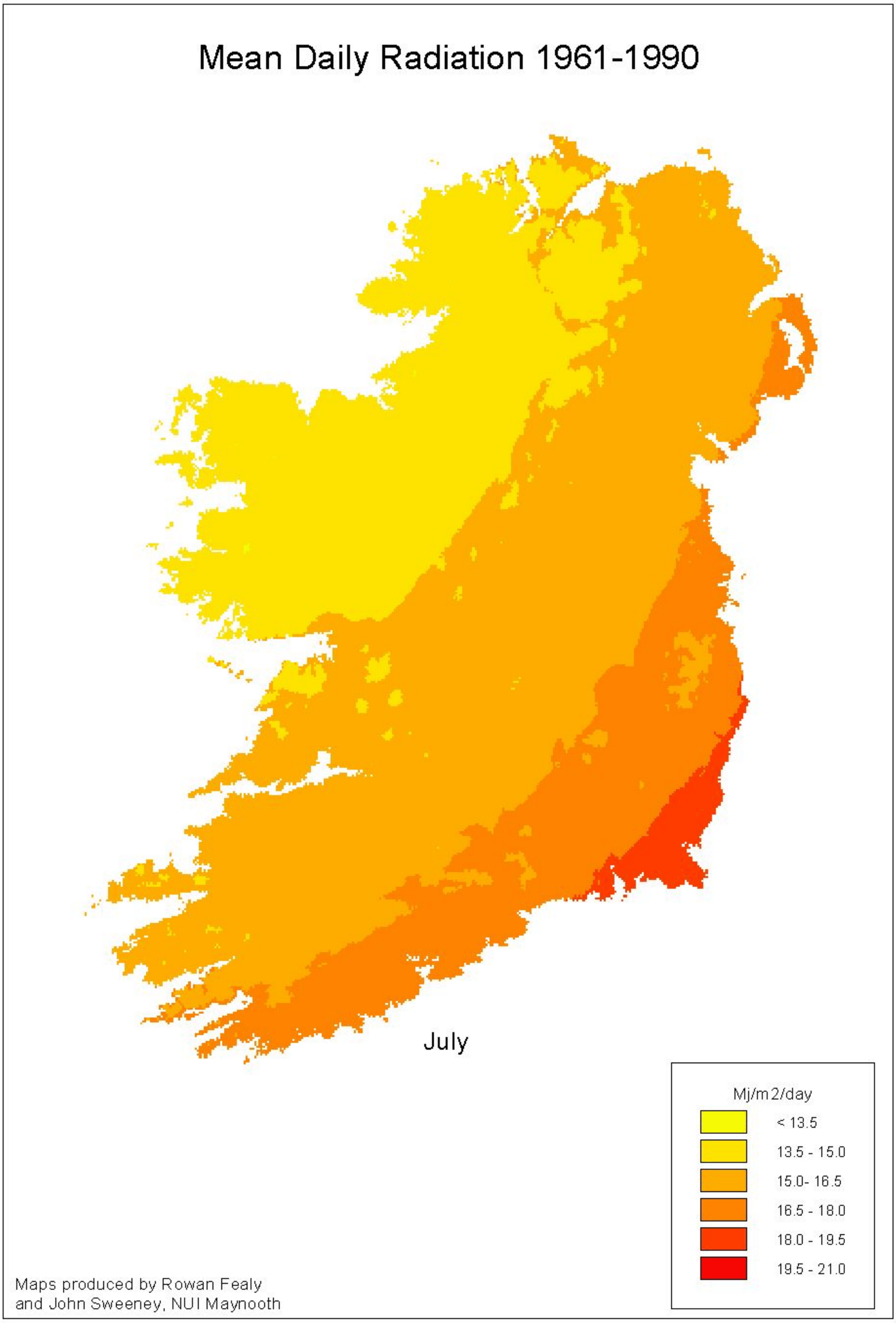


Figure 2.13. Baseline climatology: mean monthly radiation July at 1 km^2 resolution for the period 1961–1990.

Table 2.2. Regression Equations used to relate temperature and radiation to Penman PE.

Month	Constant	Temperature	Radiation	Adj. R^2	SE
Jan	–2.72	1.85		0.25	5.48
Feb	5.70	0.85	0.0000018	0.07	5.65
Mar	–8.59	2.32	0.0000034	0.38	5.13
Apr	–12.01	1.88	0.0000039	0.64	4.62
May	–24.25	2.85	0.0000042	0.77	5.14
Jun	–22.11	1.89	0.0000047	0.86	4.27
Jul	–34.47	2.83	0.0000045	0.87	4.94
Aug	–25.61	2.33	0.0000041	0.75	4.70
Sep	–27.39	3.11	0.0000031	0.50	5.12
Oct	–8.98	1.93	0.0000018	0.18	5.51
Nov	–3.82	2.22	–0.0000012	0.27	5.12
Dec	–0.98	2.22	–0.0000043	0.38	4.81

Table 2.3 Correlations between actual and predicted PE based on independent verification time period of 1991–2000.

Month	Modelled PE
Jan	0.521
Feb	0.418
Mar	0.454
Apr	0.674
May	0.866
Jun	0.934
Jul	0.870
Aug	0.916
Sep	0.732
Oct	0.467
Nov	0.264
Dec	0.633

outlined six scenarios which involved a range of CO_2 and sulphur dioxide (SO_2) emissions to the year 2100. More recently the IPCC Special Report on Emission Scenarios (Nakićenović, 2000) expanded these to 40, of which four have gone into common use in model runs (Table 2.4). Generally, the more recent set of emission scenarios projects less SO_2 loading on the atmosphere than its predecessors. This is the principal reason why the IPCC Third Assessment Report shows increased warming by comparison to the 1992 and 1995 estimates.

For the production of downscaled climate scenarios, given the known uncertainties in GCM predictions, it would have been desirable to utilise a variety of different

Table 2.4 Emission scenarios (Source: Hulme *et al.*, 2001).

	CO_2 emissions 2100 (GtC)	SO_2 emissions 2100 (TgS)
IS92a	20.4	146
IS92b	19.2	140
IS92c	4.8	54
IS92d	10.4	64
IS92e	35.9	231
IS92f	26.6	180
SRES A1-B	13.2	31
SRES A2	28.8	64
SRES B1	6.5	32
SRES B2	13.7	51

models in this exercise. In this way, by averaging the output, a composite pattern might be expected to produce a better estimate of future climate change, minimising a range of possible errors. However, although models differ considerably in their output predictions, some of these differences reflect systematic rather than random differences, and model averages may not always result in reduced error margins.

Practical considerations dictated that a climate scenario using one GCM only would be constructed in this study. The criteria for selection of the GCM were based primarily on its ability firstly to simulate present climate and secondly on it being state-of-the-art in terms of its sophistication. HadCM3 was selected as best meeting these criteria.

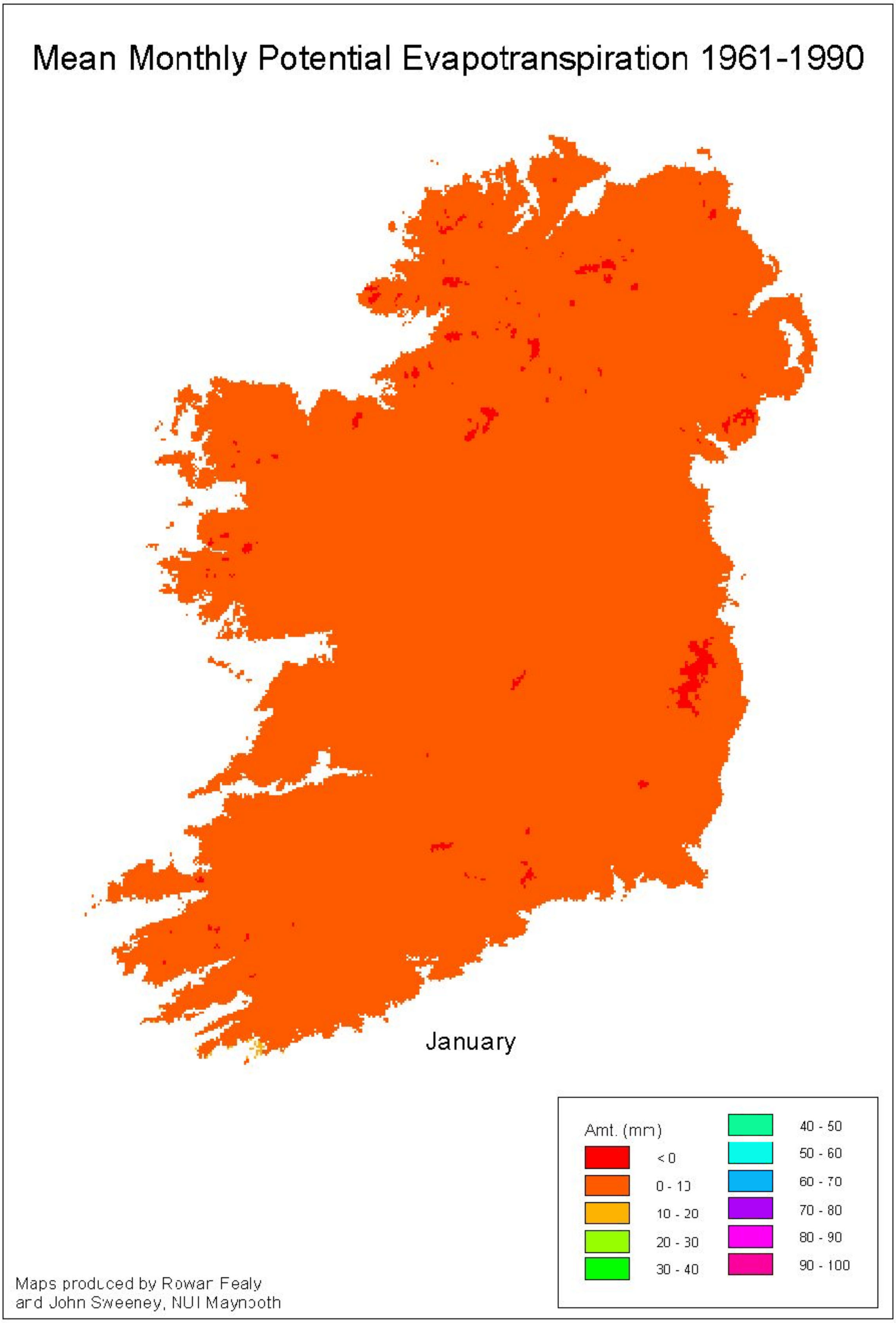


Figure 2.14. Baseline climatology: mean monthly potential evapotranspiration January at 1 km^2 resolution for the period 1961–1990.

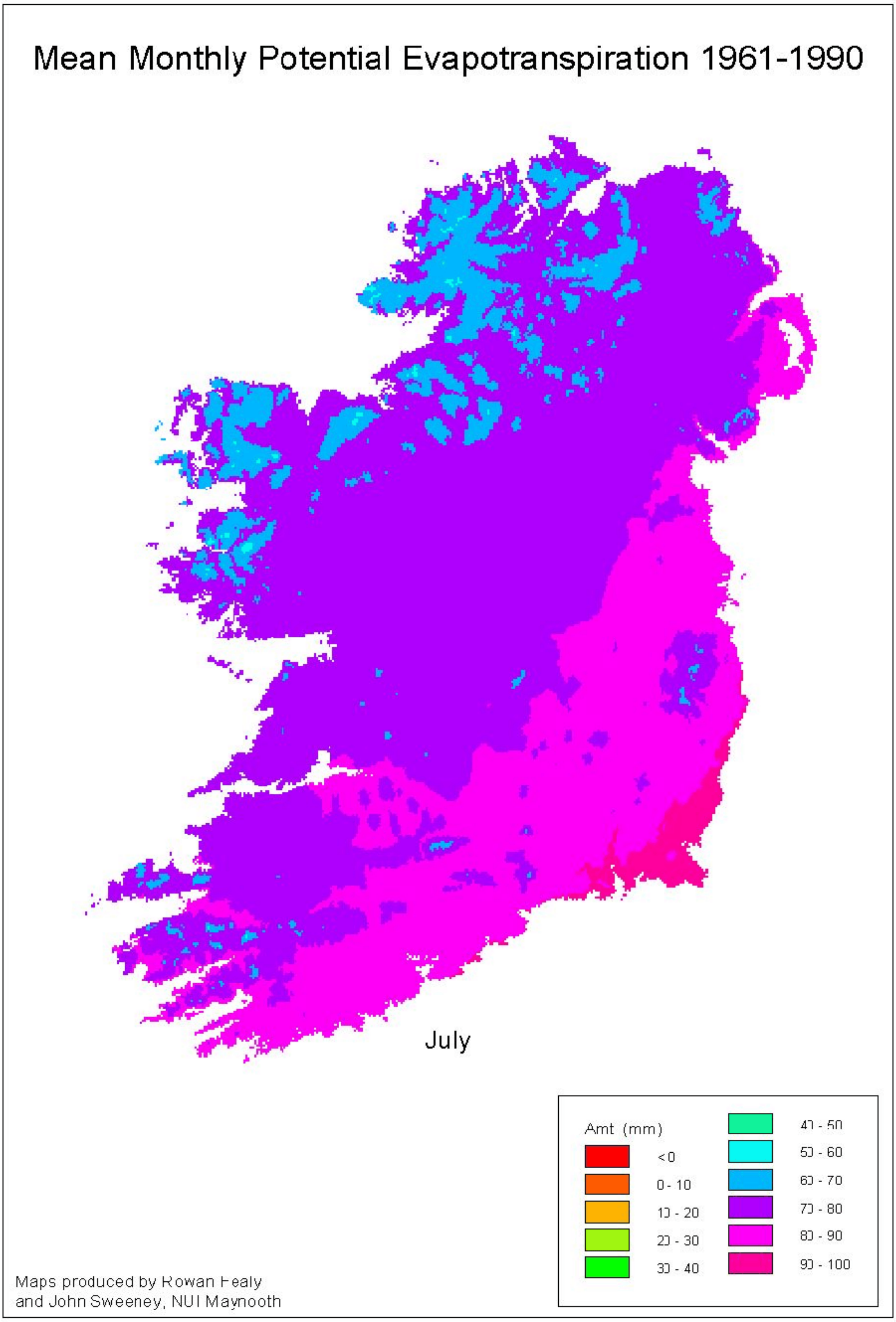


Figure 2.15. Baseline climatology: mean monthly potential evapotranspiration July at 1 km^2 resolution for the period 1961–1990.

HadCM3 is a coupled ocean–atmosphere GCM developed by the UK Meteorological Office as a version of their unified forecast and climate model. The model has a relatively fine grid size for a GCM (2.75 × 3.75°). This equates to a surface resolution of about 240 × 278 km in the vicinity of Ireland. Nineteen vertical levels in the atmosphere are employed in the atmospheric component, which also incorporates improvements in radiation and convection inputs and land-surface representation on previous generations. The time step of the model is 0.5 h.

Perhaps the most radically different aspect of HadCM3 by comparison to its predecessors is in its oceanic component. A 20-level oceanic model is employed in tandem with the atmospheric model. This operates at a resolution of 1.25° × 1.25° meaning each atmospheric grid cell has six oceanic grid cells associated with it. At this resolution, the oceanic component of the model can simulate currents in a much more realistic manner.

Results from the Coupled Model Inter-comparison Project suggested that HadCM3 was as effective in simulating mean monthly observed temperature and precipitation patterns as other leading models. Like other models, however, HadCM3 was less effective in simulating observed precipitation. This was particularly the case polewards of 55°N. This implies that less confidence can be attached to precipitation scenarios for these areas.

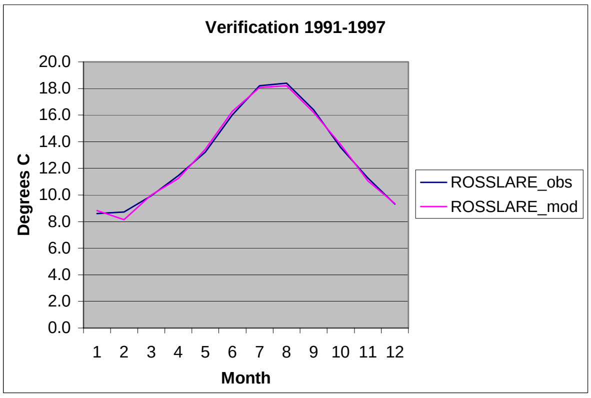
Daily output for nine grid cells in the vicinity of Ireland was extracted from a HadCM3 run. Once isolated, only the cell specific to Ireland was utilised further. The particular run concerned (HadCM3GGa1) was based on historical increases in individual greenhouse gases from 1860 to 1990 and then partly on the emission scenario IS95a. This involved a 1% per annum rise in radiative forcing but no consideration of tropospheric ozone. The end product was a ‘middle of the road’ scenario which produces global temperature increases of approximately 3.5°C by 2100. More recent runs of HadCM3 have employed the new SRES scenarios A2a and B2a. These have produced slightly more and slightly less warming, respectively, than GGa1, though the level of inter-annual ‘noise’ is such that the three scenarios produce almost indistinguishable trends until mid-century and SRESA2a and GGa1 are relatively indistinguishable until the 2090s.

The first step in downscaling is to match surface observational data to mesoscale data, which also exist as output from the GCM. The mesoscale variables employed consisted of upper air re-analysis data for the period 1961–1990 acquired from the National Center for Environmental Prediction/National Center for Atmospheric Research based in Boulder, Colorado. Re-analysis data essentially involve data assimilated from a number of point sources and then analysed to produce quality controlled gridded output (2.5 × 2.5°). A spatial domain comprising 16 cells in and around Ireland was selected and data from these cells were extracted. These data included the height of the 500 hPa surface, the 500–850 hPa thickness, mean sea level pressure, specific and relative humidity. These 16 cells were then regridded to conform to the output resolution of the GCM. All potential predictors were normalised using the corresponding means and standard deviations as advocated by Karl *et al.* (1990). The final predictors were then selected using a stepwise multiple linear regression analysis. The selected predictors were found to have a high correlation ($r > 0.9$) with observed data from Valentia. These mesoscale re-analysis data were then regressed on local surface variables for the same period from a large number of locations within Ireland to establish transfer functions unique to each point and for each month individually.

The second step entails extracting the same key variables from the HadCM3 output for time slices in the future. The transfer functions could then be used to predict the future surface conditions at the same points. Statistical downscaling was conducted for 250 stations for precipitation, and 60 for temperature. Polynomial regression, as used in deriving the baseline climatology, was then again employed to redistribute the downscaled values across the domain at a resolution of 10 km^2. Downscaling was undertaken for three periods: 1961–1990, 2041–2070 and 2061–2080. The modelled differences between the 1961–1990 and later runs were calculated. The differences were then added to the baseline climatology. Scenarios of change for approximately 2055 and 2075 by comparison to the 1961–1990 averages could thus be constructed.

Verification of the transfer functions was undertaken on an independent dataset for the period 1991–1997. For example, for temperatures at Rosslare and Valentia good agreement was apparent between actual and predicted values (Fig. 2.16).

Validation statistics for temperature, precipitation and radiation are shown in Table 2.5. Validation was performed using an independent dataset from 1991–1997. In general, temperature verification was good, particularly for summer maxima. Minimum temperature were predicted successfully for all seasons using the technique. As expected, downscaling of precipitation is less accurate at all times of the year. Radiation gave reasonable results overall, giving further confidence to the technique used for the calculation of evapotranspiration. Bearing in mind the limitations of the procedures involved, the production of scenarios for 2041–2070 and 2061–2090 was carried out at a resolution of 10 km^2.



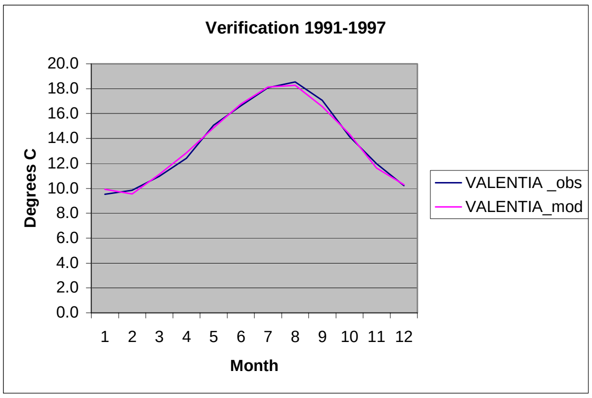


Figure 2.16. Validation of the temperature transfer functions for Valentia and Rosslare for the period 1991–1997.

2.5 Climate Scenarios for Ireland 2055 and 2075

Figures 2.17 and 2.18 show a mean January temperature in the range 6–7.5°C by mid-century over much of the southern half of Ireland, and 7.5–9°C along southern coasts. A general increase of approximately 1.5°C is apparent increasing to approximately 2.5°C by 2075. By mid-century, winters in Northern Ireland and in the north Midlands will be similar to those of Cork/Kerry during the 1961–1990 period. Since temperature is a primary meteorological parameter, secondary parameters such as frost frequency and growing season length and efficiency can be expected to undergo considerable changes over this time interval. Signs of earlier springs and lengthening of the growing season over the past three decades have been detected both in the instrumental record and in ecological events such as leaf unfolding and bird migration (Sweeney *et al.*, 2002). These lend credence to the suggested future projections.

Figures 2.17 and 2.18 show mean July temperatures of 16.5–18°C as far north as coastal Counties Antrim and Derry by mid-century. General increases of approximately 2°C are apparent with highest values to be found inland away from north and west facing coasts.

Table 2.5. Validation summary using an independent dataset for the period 1991–1997.

Downscaled variables	Range of monthly values of Pearson's 'r'	Mean average error	Root mean square error
Maximum temperature	0.23–0.94	0.04°C	0.87°C
Minimum temperature	0.54–0.92	0.03°C	0.83°C
Precipitation	0.36–0.85	0.29–30.02 mm	24.24–48.72 mm
Radiation	–0.13–0.63	0.35 MJ day^{-1}	1.12 MJ day^{-1}

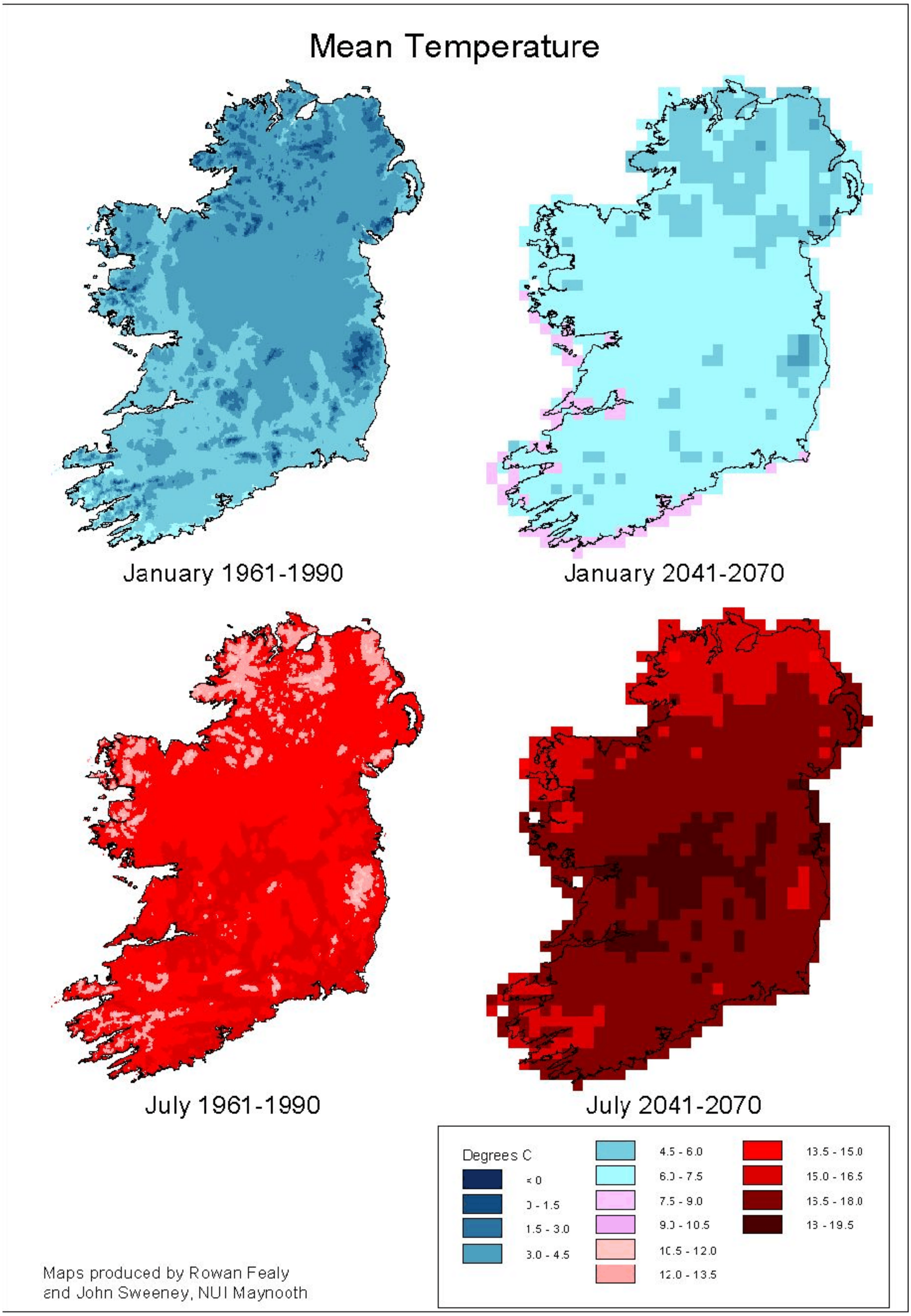


Figure 2.17. Downscaled mean temperature scenarios for Ireland for the period 2041–2070 at a resolution of 10 km^2. This approximates to the period around 2055.

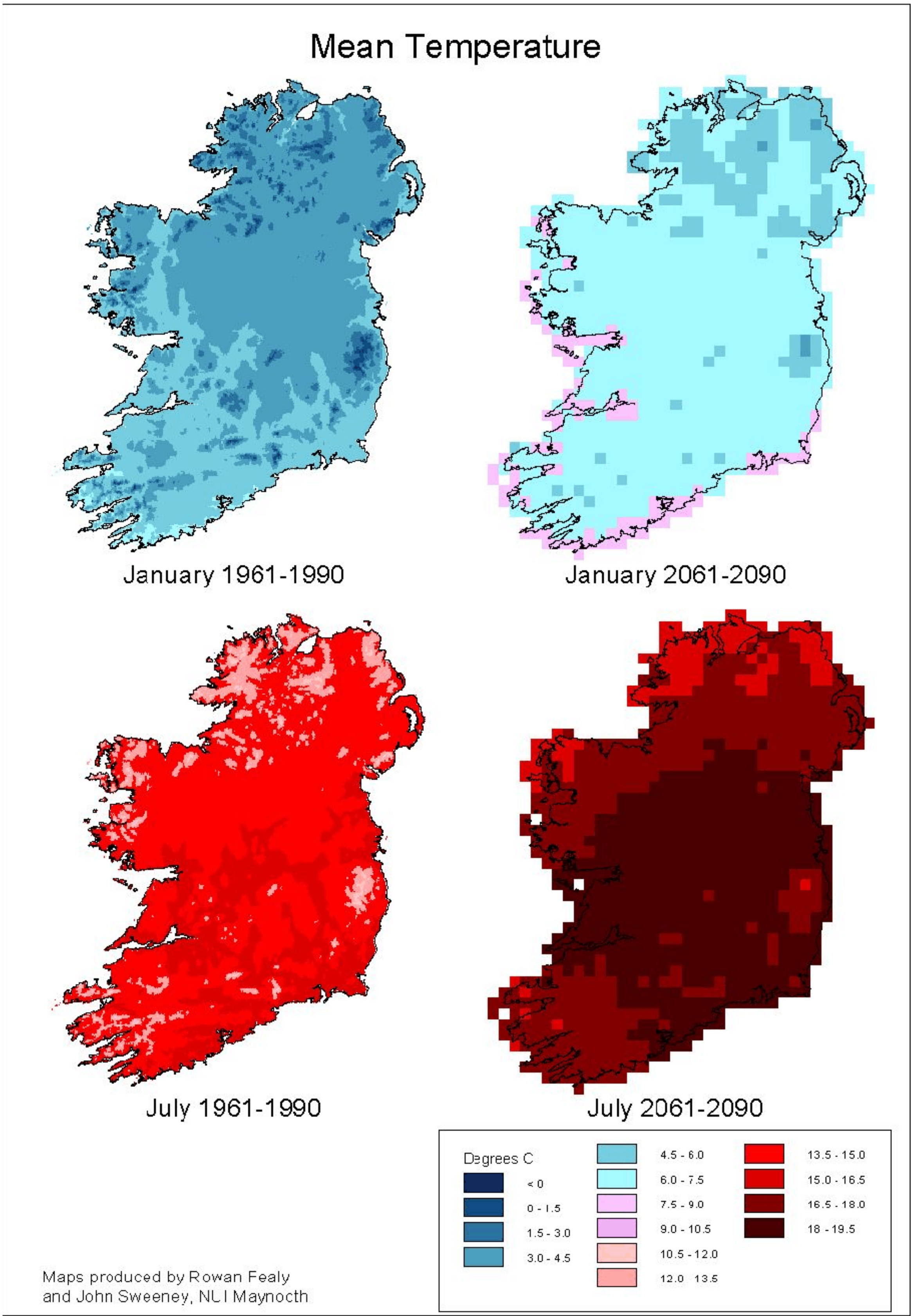


Figure 2.18. Downscaled mean temperature scenarios for Ireland for the period 2061–2090 at a resolution of 10 km^2. This approximates to the period around 2075.

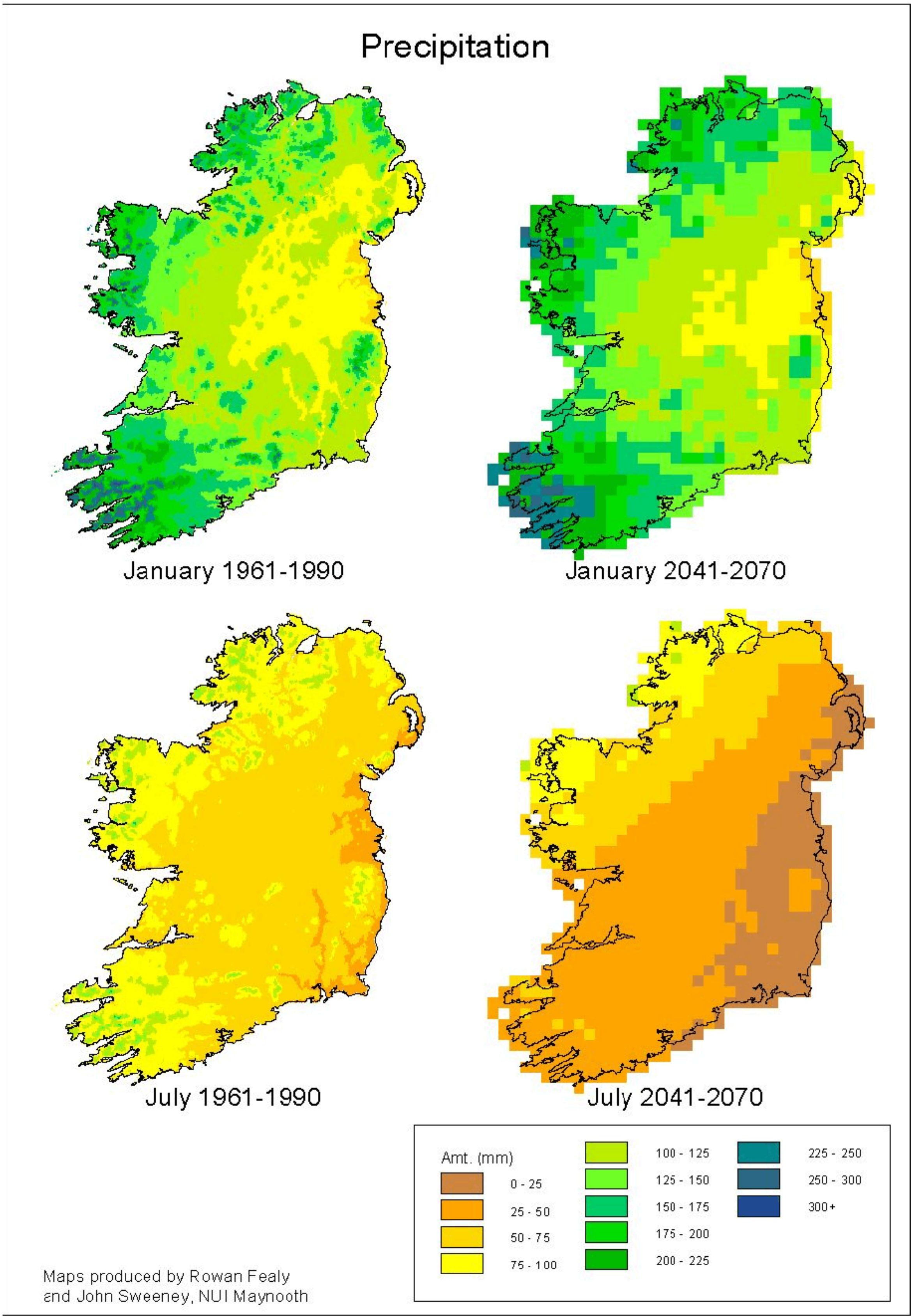


Figure 2.19. Downscaled precipitation scenarios for Ireland for the period 2041–2070 at a resolution of 10 km^2. This approximates to the period around 2055.

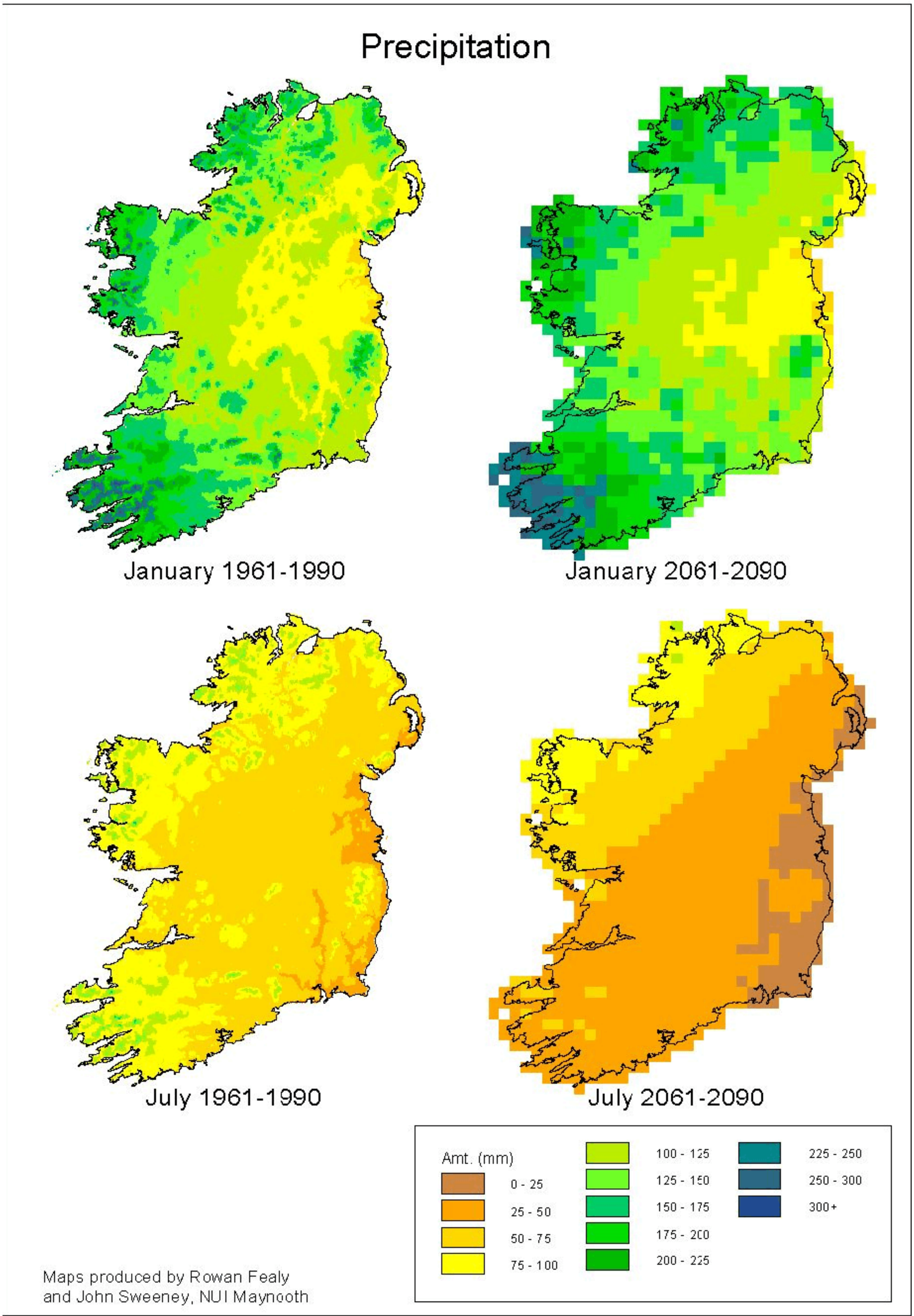


Figure 2.20. Downscaled precipitation scenarios for Ireland for the period 2061–2090 at a resolution of 10 km^2. This approximates to the period around 2075.

This 'continental' effect is further enhanced in the 2075 scenario. Combined with reduced summer precipitation amounts, the principal impact of this is likely to manifest itself in increased evapotranspiration and increased occurrence of soil moisture deficits and drought stress.

Precipitation scenarios are inherently less reliable than temperature given the uncertainties of GCMs in this area. This has been a feature of many downscaling studies (Burger, 1996; Wilby *et al.*, 1998). However, average monthly R^2 values of 0.51 were obtained for the training functions with baseline climate suggesting that some confidence could be suggested for the future scenarios. Figures 2.19 and 2.20 suggest that winter increases in precipitation will be observed over most of Ireland. On average these amount to 11%. The greatest increases are suggested for the north-west where increases of approximately 20% are suggested by mid-century. Little change is suggested as occurring on the east coast and in the eastern part of the Central Plain. Somewhat surprisingly, some small areas of decreased precipitation are indicated for the extreme east coast. This may relate to a disproportionately low frequency of predicted easterlies for the east coast from the HADCM3 model. This finding is in contrast to the Hadley Regional Model (HadRM2) and pattern-scaled downscaling by UKCIPS which suggested increases for everywhere in Ireland in winter. Further work is clearly required in this area to resolve the likely direction of the precipitation trend along the east coast of Ireland in winter.

For summer, a more explicit signal is apparent with marked reductions in rainfall across eastern and central Ireland. Nationally, these are of the order of 25% with decreases of over 40% in some parts of the south-east suggested. These are in line with earlier analogue-based approaches (Sweeney, 1985). Such decreases, if realised, would clearly have profound implications for agriculture and water resource management.

The 10 km^2 gridded output data for the scenarios for 2055 and 2075 provide, together with the baseline climatology, a valuable database for impact assessment models of various kinds.

2.6 Scenario Data for Impact Assessment

Caution must be exercised when using climate scenarios of any kind. Scenarios are not a forecast of future climate conditions. Rather, they represent one plausible outcome of a changing balance of forcing processes.

In this analysis, a particular caveat must be emphasised. This centres on the fact that output from only one Global Climate Model has been employed to derive the scenarios. In the time available, multiple model use was not considered feasible and while HadCM3 is a 'state-of-the-art model' in many respects, like any model it is subject to imperfections. Further work using a combination of GCMs would be desirable and it is hoped to carry out this work shortly.

Bearing in mind this caveat, a number of conclusions can be tentatively drawn regarding the future course of Irish climate.

Generally, Irish climate can be expected to exhibit changes over the coming century broadly similar to those proposed for global scales. Mean temperatures appear to be set to warm by 0.25°C per decade, with no marked spatial departure from the currently observed pattern. Mean winter temperatures outside the uplands will be everywhere above the threshold for grass growth. Precipitation estimates, though more tentative, suggest wetter winters by up to 15% in the uplands of the south-west and a less clear signal in eastern parts. Combined with increases in Potential Evapotranspiration this situation has implications for sectors such as agriculture, water resources, biodiversity, forestry and the coastal environment which are explored in the remainder of this report.

Acknowledgements

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3 The Impact of Climate Change on Irish Agriculture

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3.1 Introduction

The impact of climate change on agricultural production in Ireland is related to three specific factors: atmospheric carbon dioxide concentration, precipitation and temperature. Temperature will be related to the incident radiation, the influence of air masses and the cloud cover, while precipitation will be related to the stability and temperature of air masses. In Ireland, rainfall is currently sufficient to ensure that very little irrigation is required for crops. Increased temperatures and changing seasonality of precipitation may have significant impacts on the operations of farms, the crops that can be grown and the necessary infrastructure to ensure successful farm enterprises. In this report, the impact of climate change will be viewed in terms of changing crop yields estimated by simulation modelling using climate change scenarios for 2055 and 2075.

In a previous report on the impact of climate change in Ireland published by the Government of Ireland (1991), the section of the report assessing agricultural impacts was based on particular assumptions concerning likely changes in climate by 2030. These comprised a 2°C increase in temperature spread evenly over the year and country, a 10% increase in October–March precipitation and a 10% decrease in April–September precipitation. Predictions were then made using, firstly, crop growth simulation models for site-specific locations, the results of which were extrapolated to regions of the country using expert knowledge. Secondly, predictions were based on comparison with sites elsewhere in Europe believed to be currently analogous to the future climate of Ireland. Thirdly, predictions made use of expert opinion and knowledge about crop, animal, pest and disease responses to temperature and precipitation.

In the current work, a different approach to the spatial analysis of climate impact has been taken. By using scenarios generated by downscaling the Hadley Centre HadCM3 Global Climate Model in conjunction with a group of crop simulation models, a prediction resolution using 100 km^2 grid cells (10 × 10 km) covering the whole country was possible. For each grid cell, a baseline climate (1961–1990), and 2055 and 2075 estimates of climate parameters were derived. From these values, a weather simulator was used to create 30 years' worth of daily data that could be used with the crop simulation models. For each grid cell, barley, maize, potato, soybean and grass production were simulated. The mean production for the 30-year simulation was then assessed with respect to baseline production. This approach is in line with accepted methodologies (e.g. Parry, 1990).

A number of points are worth noting about the nature and content of this report. Firstly, the general ideas developed in previous reports are not likely to change much in light of the current finding, e.g. warmer at all seasons and wetter in winter is still the general thinking. Secondly, the discussion is not presented with a focus on absolute yield values because of issues with model calibration and testing (which were undertaken). Rather, the predicted yields are classified relative to the current national mean yield to provide an indication of relative regional impacts. It is also important to stress that the project has been based on accumulating a solid theoretical framework and the necessary tools for analysing the effects of climate change on the primary production component of agriculture. As such, the impacts of secondary components such as pollution and pest/disease are not considered in the simulation modelling. Essentially the project used mathematical simulation models to estimate the geographical distribution of crop production (primary production) under present climate conditions compared with a future scenario as modelled by a general circulation model (HadCM3). The climate change downscaling work was conducted at the Department of Geography, National University of Ireland, Maynooth (Sweeney and Fealy, 2002) and is presented in Chapter 2. It is assumed that the scenarios used represent the best available estimates (at the time of writing) of climate change likely to occur in Ireland. Finally, it should be noted that the soils defined are theoretical and represent typical regional perspectives. The naming of soils is done to provide a suggested link to existing soil survey data.

It is not the intention in this report to repeat the process of predicting what the range of impacts of climate change will be on agriculture in general. This has been done before (Farmer and Warrick, 1989; Parry *et al*., 1990; Government of Ireland, 1991; Brignall *et al*., 1994; Peng *et al*., 1995). Rather, it is to look more specifically at crop production. Reddy and Hodges (2000) provide a compilation of the influences of climate variables on specific aspects of crop biological production which can be used as a knowledge base for predicting how crops will respond to climate change in general. The relationships they describe are part of the mathematical simulation models used in this project. Parry and Carter (1988) presented a hierarchical schema of interactions between climate variation and other factors (Fig. 3.1) which defined three levels of interaction. This project attempts to quantify 1st-order interactions in terms of crop production and to make some assessments of 2nd-order interactions (e.g. farm management issues). It should be noted that there is no consideration of 3rd-order interactions on a(n) (economic) regional scale. The report will focus on the changes in primary production of five specific crops. These are: *grass* – because it represents the most important crop in Ireland at present, and underpins the entire livestock industry; *barley* – because it is a currently successful cereal crop; *maize* – because it is currently a marginal crop that may become a good source of high energy forage; *potato* – because it is a traditional root crop in Ireland that is sensitive to water stress in particular; and *soybean* – because it is not currently suitable for commercial production in Ireland and in conjunction with maize, may indicate the future route of Irish agriculture.

3.2 The Changing Agro–Climatology of Ireland

To place the impact of climate change on crop primary production in context, it is necessary to define a baseline agro–climatology of Ireland and then to examine how the areas defined will vary through time. The geographical distribution of the weather elements and predicted changes in their distribution have been presented in Chapter 2 (Figs 2.6–2.15, 2.17–2.20). The main features of the present geographical distribution of mean daily temperature, monthly precipitation and daily radiation are that temperature increases from south to north, precipitation from east to west and radiation from north-west to south-east. Although temperature, precipitation and radiation vary significantly between seasons, the broad features of the distribution of the element values are the same in all seasons. In the particular context of the assessment of climate impacts on agriculture, the seasons are defined appropriately as: Spring – March, April, May; Summer – June, July, August; Autumn – September, October, November; and Winter – December, January, February. The predicted climate changes in 2055 and

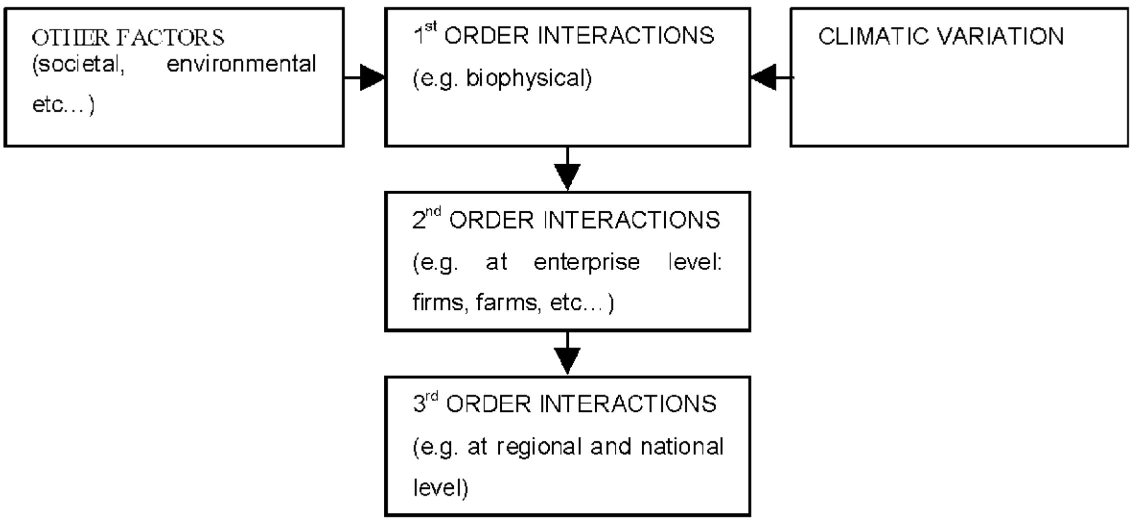
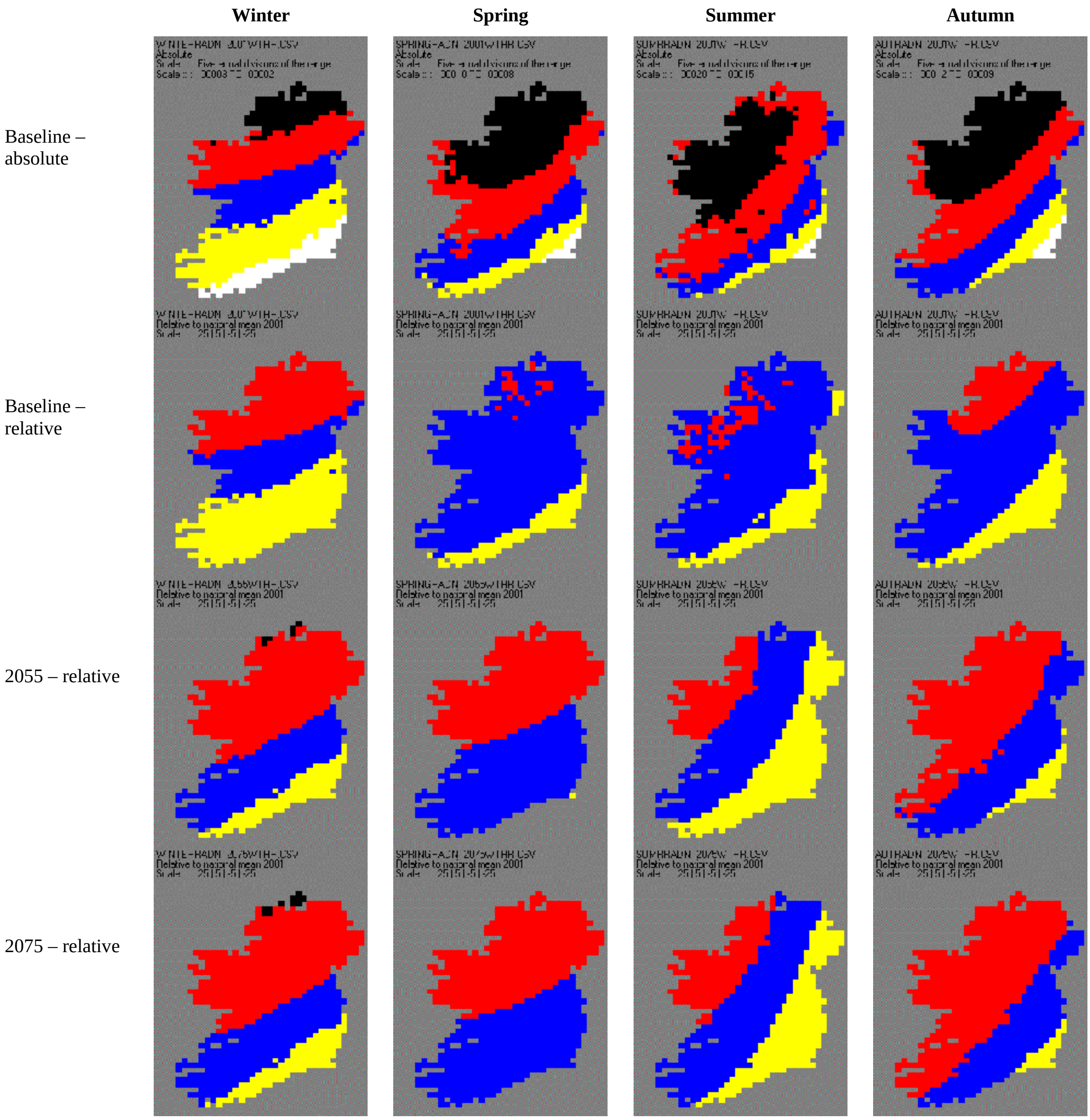


Figure 3.1. The levels of interaction for assessment of climate change in conjunction with other factors.

2075 are not expected to alter these distributions significantly. The general pattern of change in the elements is illustrated by comparing the geographical distribution of the element values expressed relative to the present national mean value of each.

The present geographical distribution of radiation (increasing from the north-west to the south-east) is similar in all seasons (Fig. 3.2). Climate change is not expected to alter the distribution. In spring, autumn and winter, radiation is expected to decrease generally. At



[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.2. Radiation distribution by season with values represented as classes based on absolute values, and relative to the national mean for baselines, 2055 and 2075. Details of absolute values can be found elsewhere in this report. White (high) >> yellow >> blue >> red >> black (low).

present, only a small area of the south-east has radiation values in spring that are between 5 and 25% greater than the present national mean and a smaller area in the north-west has radiation values between 5 and 25% less than the mean. By 2055, the former area will have disappeared and the latter will have increased to cover most of the northern half of the country. Similar changes are expected in autumn and winter and are expected to continue to 2075.

There is currently a clear north–south trend visible in the temperature data, where it is warmer in the south. However, the change in temperature suggests that the south and north of the country will warm less than the centre. The increase in temperature is not even throughout the year; a greater seasonal differentiation becomes apparent with greater increases in temperature in the summer months. The central eastern part of the country shows the greatest increase in summer temperature. The effect of climate change is to make all of the country warmer at all times of the year with less warming in the north-east and the south-west in winter.

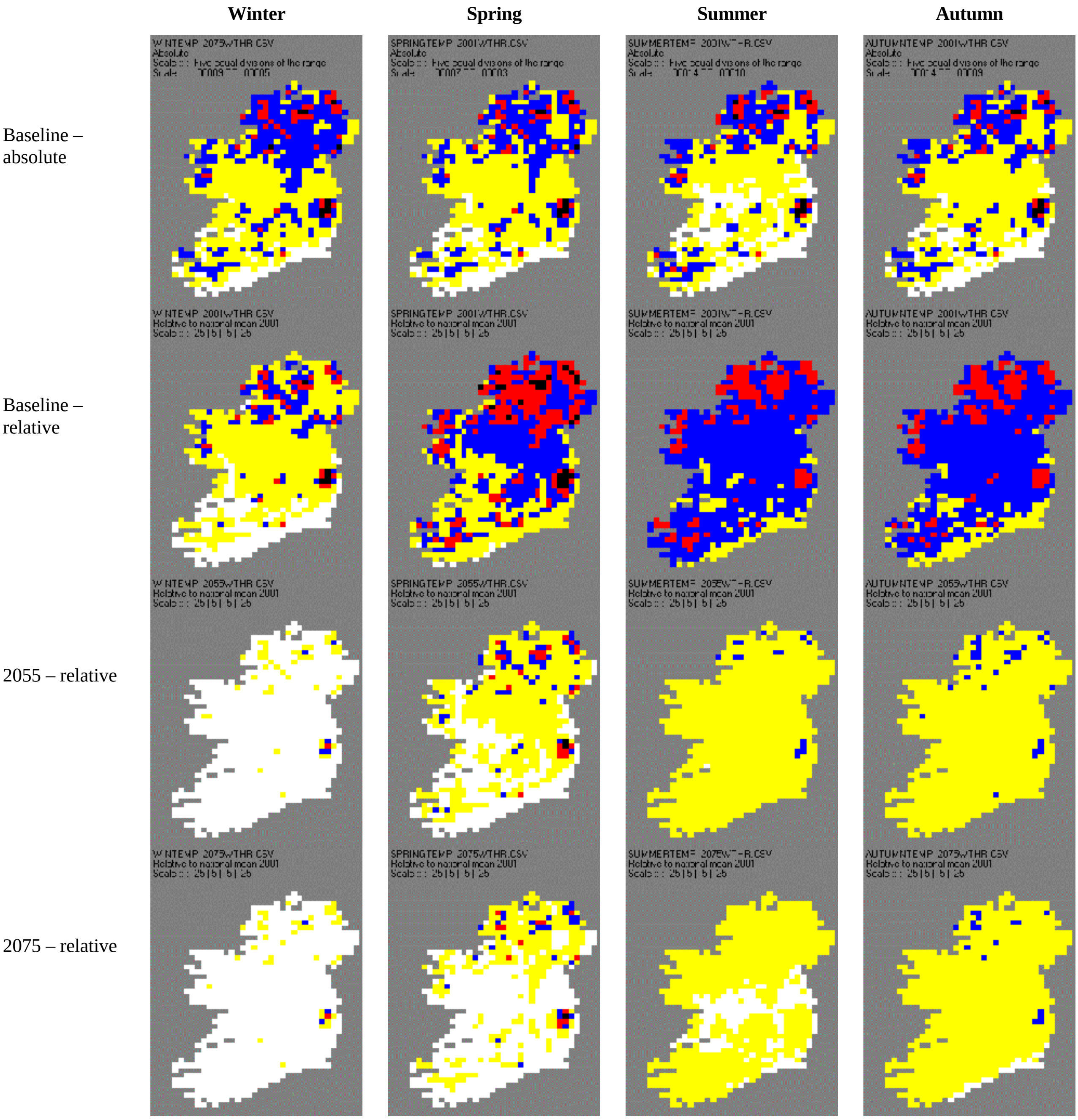
The predicted changes in temperature (Fig. 3.3) will be significant from an agricultural point of view. In spring at present, only a small area in the south (an extreme coastal strip) has temperatures greater then 6°C. In most of the southern half of the country, present temperatures are between 5.5 and 6.0°C. In the northern half, spring temperatures vary between 4 and 5°C. In the other seasons, the broad patterns are similar. Relative to the national mean, present spring temperatures are up to 1°C greater than the mean in most of the southern half of the country. In the northern half of the country, temperatures are a similar amount less than the national mean. In 2055 and 2075, the pattern is expected to change significantly. By 2055, in many parts of the southern half of the country, spring temperatures will be more than 1°C greater than the present national mean and in 2075 this area will extend to most parts of the country and in all parts temperatures will be greater then the present mean.

The responses in distribution of temperature are expected to be similar in autumn. In winter, temperatures in the most southern parts of the country will be more than 2.5°C greater than the present mean. In summer, the greatest increases in temperature are expected across the midlands.

The present geographical distribution of monthly precipitation in spring and winter and the distribution of relative values are similar (Fig. 3.4). The distribution in spring and winter is not affected by climate change in any major way. In summer and autumn, however, the area of the eastern coast where the present monthly rainfall in these seasons is more than 25% less than the mean is expected to increase in 2055 and extend to the Shannon. Apart from the extreme west (Donegal, west Mayo, west Galway and Kerry), rainfall in the area west of the Shannon will be between 5 and 25% less than the present mean.

A set of climatic classes defining land areas of similar climatic characteristics was developed based on the quartiles of the monthly temperature and monthly precipitation distributions for the 10 × 10 km grid cells covering the whole of Ireland. These classes integrate changing seasonal patterns. The deviation of each grid cell about the national mean (for a specified time period) was calculated. Those cells that fell in the first quartile were deemed cooler/drier, the second and third quartiles were deemed average and the fourth quartile was deemed warmer/wetter. Using these distributions, areas were allocated as falling into one of nine categories (Fig. 3.5), the properties of which are summarised in Table 3.1. In general, the south-west is warm and wet, the south-east is warm and dry, the north-west is cool and wet and the central eastern part of the country is relatively dry with average temperatures. It should be noted that class 1 (cool and dry) was only found for two cells in Ireland. The base data are presented in Figs 3.6 and 3.7. From these data and the data in Table 3.2 the change in climate was assessed as follows:

- little difference in precipitation between 2055 and 2075 (only a slight increase)
- low rainfall sites become more seasonally extreme, with winters similar to the present but with markedly drier summers (the effect is seen by 2055 but does not get more extreme by 2075)
- average rainfall sites get more seasonally extreme by a decrease in precipitation in summer and an increase in winter
- high rainfall sites get more seasonally extreme by a decrease in precipitation in spring and summer with little change in winter and a slightly wetter autumn

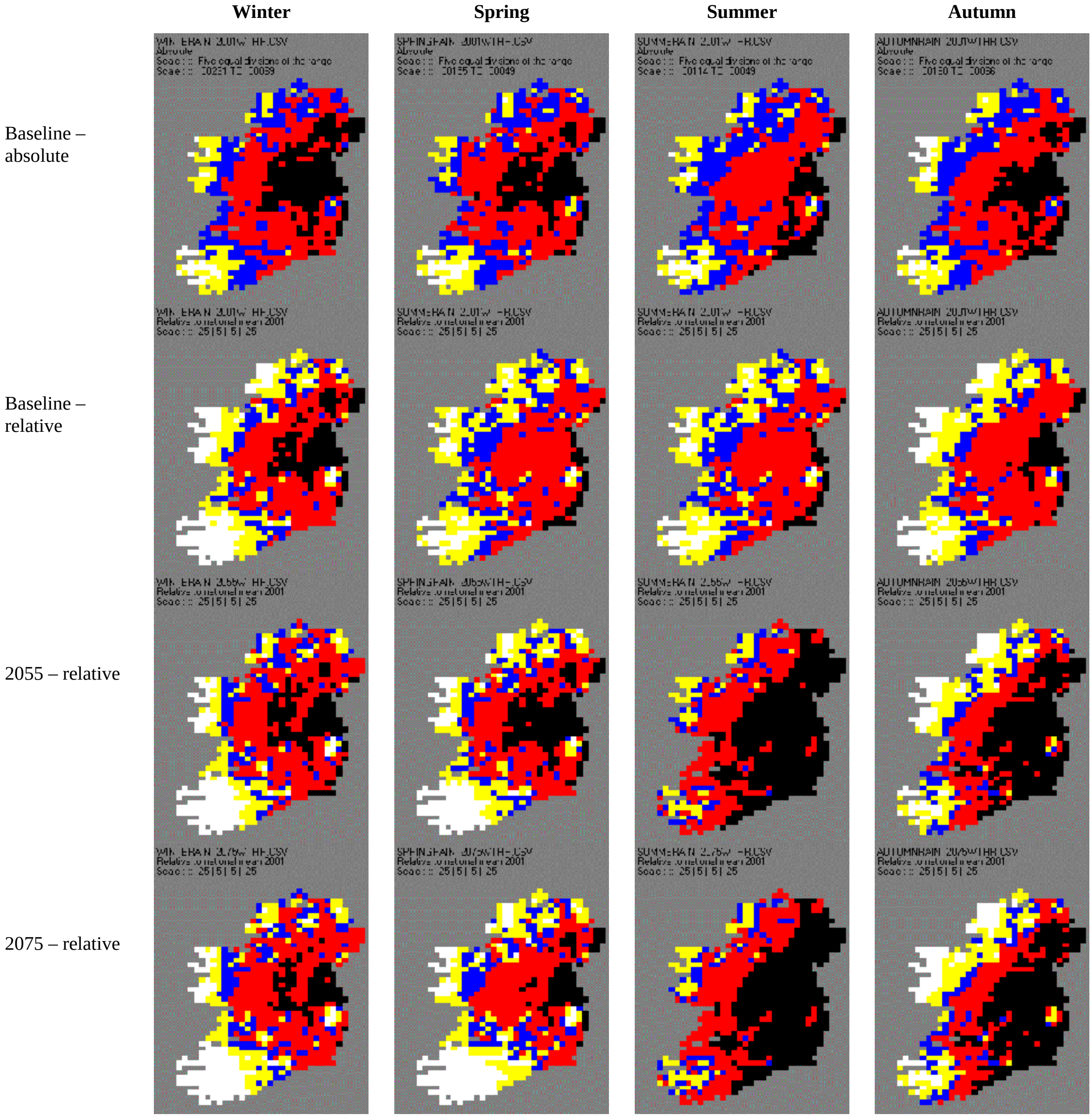


[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.3. Temperature distribution by season with values represented as classes based on absolute values, and relative to the national mean for baselines, 2055 and 2075. Details of absolute values can be found elsewhere in this report. White (high) >> yellow >> blue >> red >> black (low).

- little difference in temperature between 2055 and 2075 (only a slight increase)
- a relatively uniform increase in temperature of about 1.6°C over all agro–climatic classes.

The deviations from seasonal national mean values were assessed, and sites were classified as being either relatively consistent over all the seasons or those varying by season (e.g. always relatively warm in winter, spring, summer and harvest, or always relatively wet. Those that



[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.4. Precipitation distribution by season with values represented as classes based on absolute values, and relative to the national mean for baselines, 2055 and 2075. Details of absolute values can be found elsewhere in this report. White (high) >> yellow >> blue >> red >> black (low).

varied might be relatively warm in summer but relatively cool in winter).

Statistical analysis of the sites defined using the quartile distributions reveals that the nine classes were significantly different from each other for all months of the year, all seasons and annually. Using the defined classes based on baseline climate values, the change in climate for each class/spatial area was determined by analysis of the downscaled scenario data. The results were analysed to assess whether the current areas would remain significantly different with climate change. For all areas/classes, monthly, seasonal and annual temperature and precipitation values were significantly different regarding 2055 and 2075 data (Table 3.1).

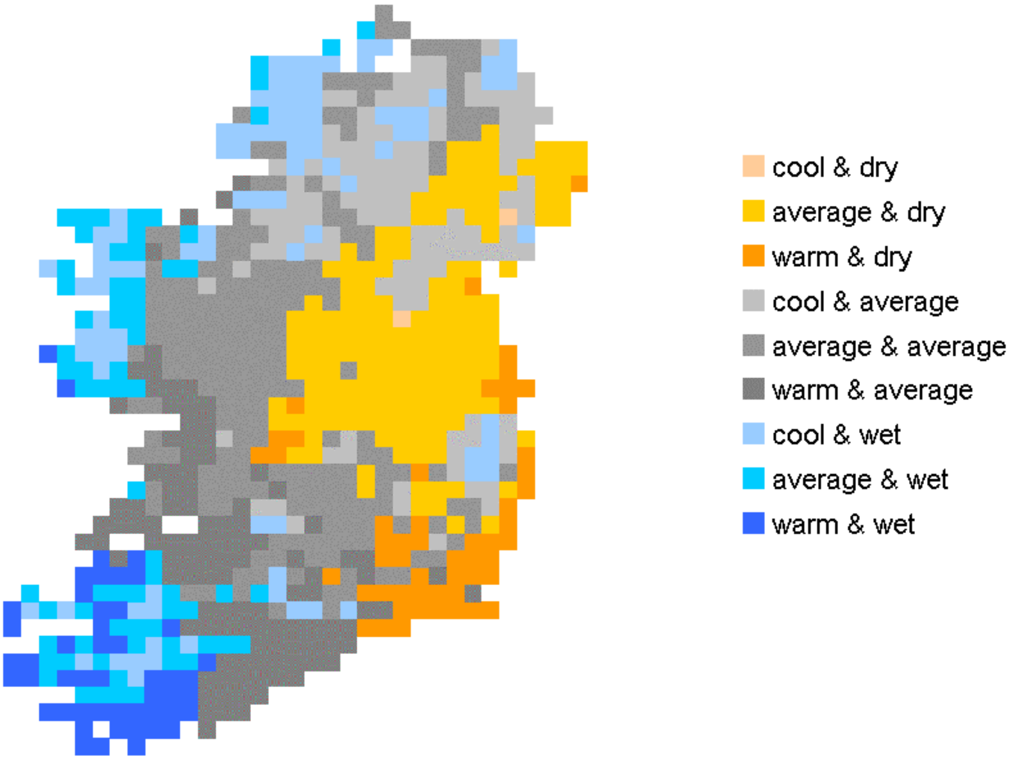


Figure 3.5. Agro–climatic classes based on quartiles of the temperature and precipitation distributions.

Table 3.1. Temperature and precipitation ranges for the quartile distributions used to develop the agro–climatic map in Fig. 3.5.

	Seasonal mean temperature (°C)			Seasonal mean monthly precipitation (mm)		
	Cool	**Average (t°)**	**Warm**	**Dry**	**Average**	**Wet**
Winter	<4.1	to	>5.0	<95	to	>136
Spring	<7.4	to	>8.1	<72	to	>93
Summer	<13.4	to	>14.3	<71	to	>90
Autumn	<10.7	to	>11.4	<94	to	>133

The change in the seasonality of precipitation is not even over the whole country (Fig. 3.8), but follows the same broad trend. Sites that were relatively dry (Classes 1–3) become more markedly seasonal with a drier summer extending from March into late September. Sites that were average (Classes 4–6) show a similar increased seasonality with a clear increase in precipitation by October that would have a significant influence on harvest operations. High rainfall sites (Classes 7–9) show the least impact of change in precipitation with notable decreases in later summer precipitation only, coupled with a modest increase in winter precipitation.

In the 1991 Climate Change report (Government of Ireland, 1991), the impacts on agriculture were assessed using a primary assumption that there would be a uniform 2°C increase in temperature over the whole country, all year, and a 10% increase in winter rain balanced by a 10% decrease in summer rain. Other scenarios were also assessed using similar assumptions of no spatial variability. To assess the validity of the assumptions of the 1991 report, the data used to create climate regions were analysed. It was found that climate change in terms of national mean temperature rise was predicted to be only about 1.6°C, and looking at the precipitation data, it can be seen that national mean rainfall rises in the winter

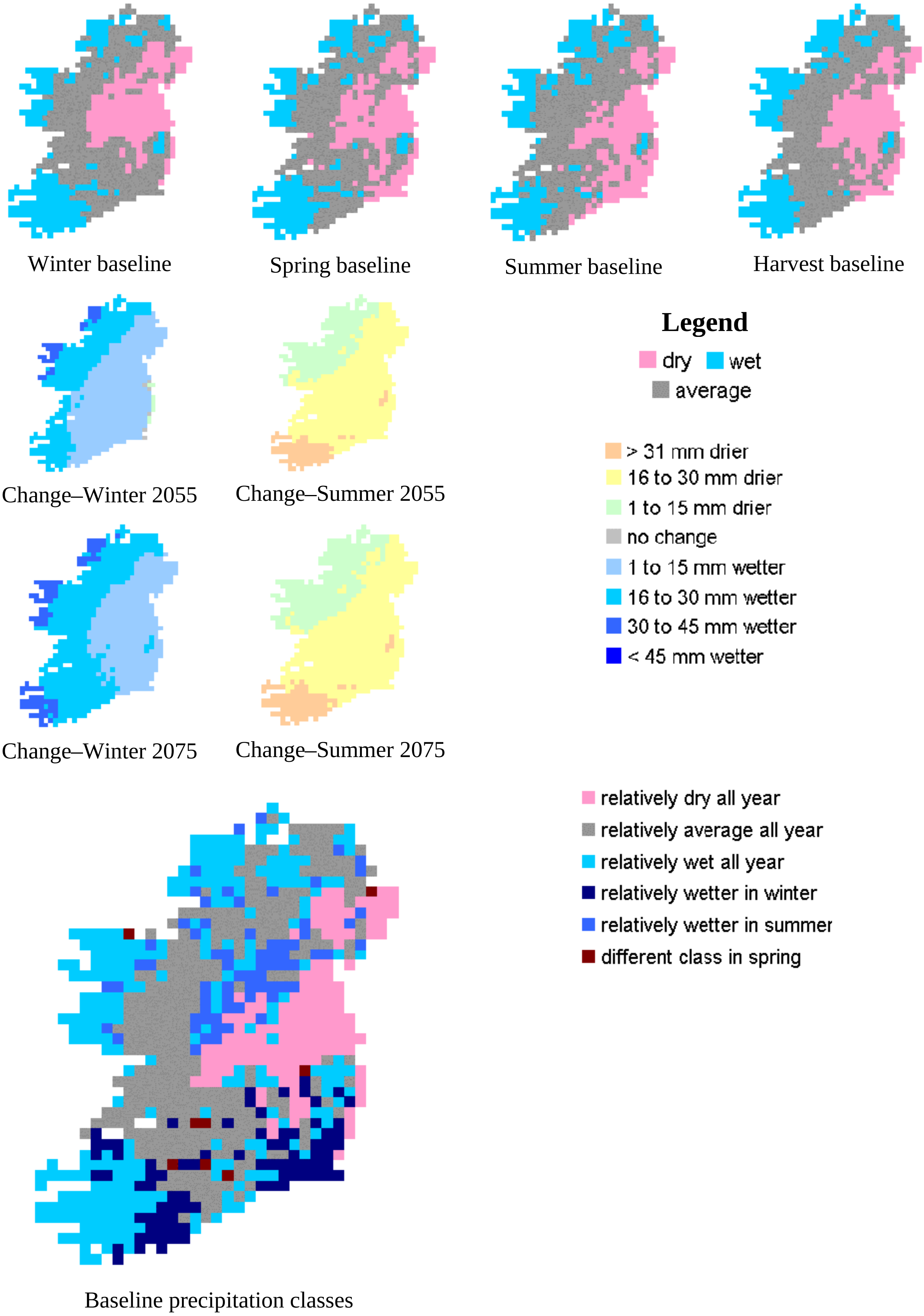


Figure 3.6. Baseline precipitation by season, change in precipitation in summer and winter and the baseline precipitation distribution for Ireland.

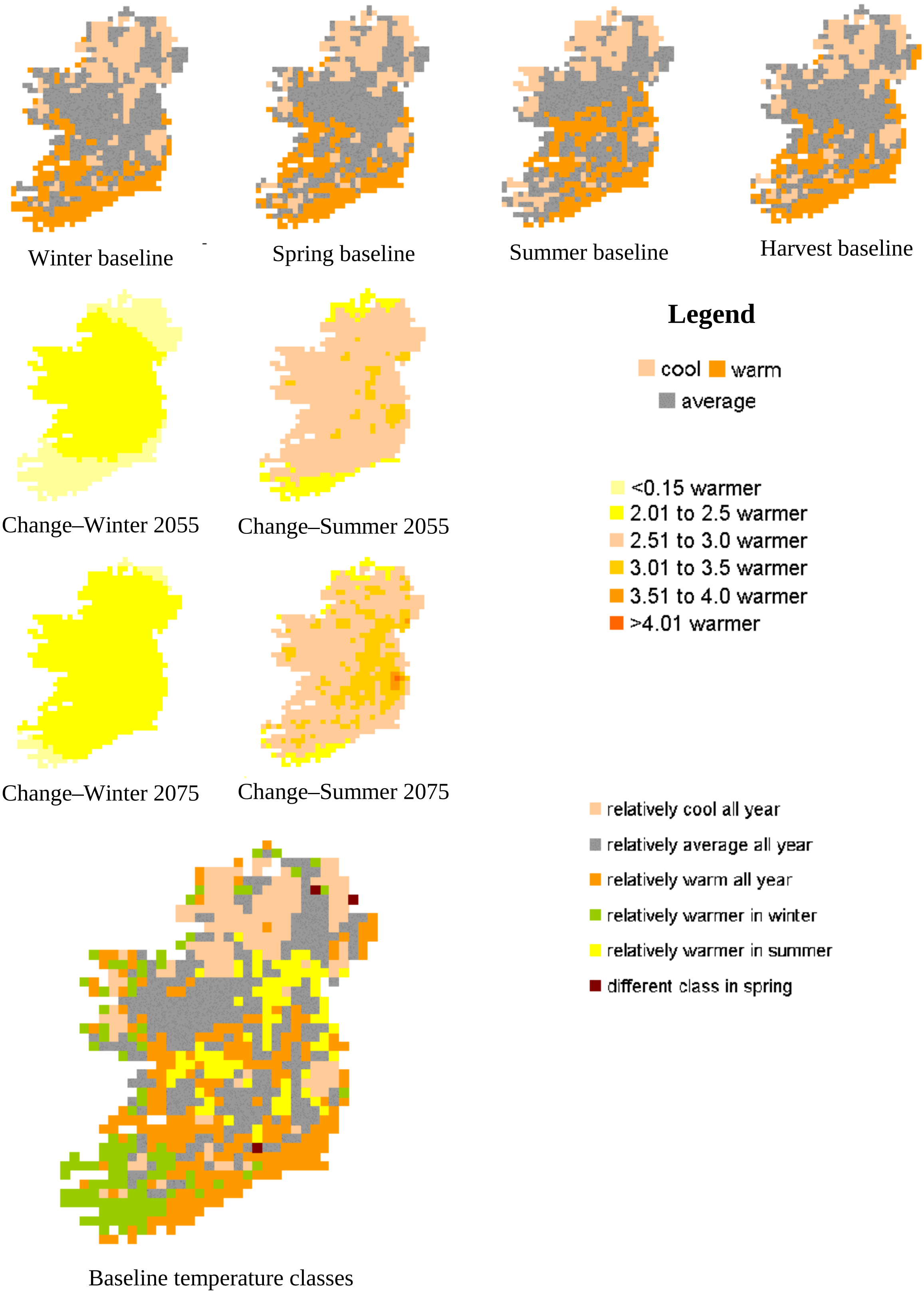


Figure 3.7. Baseline temperature by season, change in temperature in summer and winter and the baseline temperature classes for Ireland. Note the class <0.15°C change represents no significant change in temperature within the scope of the predictive models used in this work.

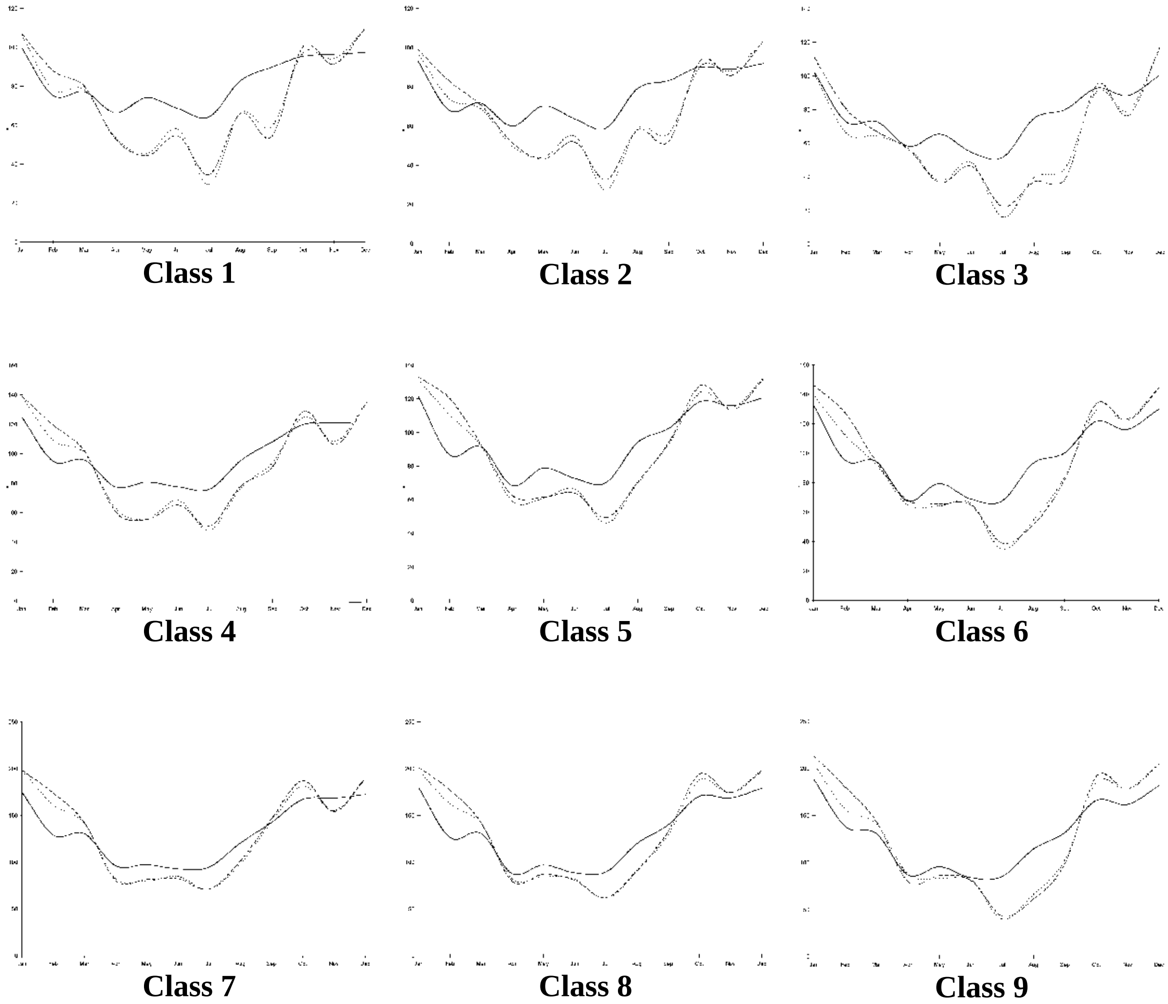


Figure 3.8. The changing seasonality of rainfall in Ireland (solid black line, baseline; short dash, 2055 and long dash, 2075).

(about 14%) and falls in the summer (about 21%). Furthermore, it is clear from Figs 3.6 and 3.7 that the assumption of a uniform change over the whole country was not valid.

Based on this analysis, the findings of the 1991 report on the impact of climate change on Irish agriculture should be viewed with care in terms of the absolute yield changes predicted both for sites and their spatial interpolation. However, the general interpretations relating to secondary impacts on farms should still remain valid.

To place the current research in context of second-order interaction (i.e. farm management issues rather than primary production issues, see Fig. 3.1), the impact of the change in agro–climatology on the management of farm enterprises can be assessed in general terms.

Forage and livestock production will be influenced by changing seasonal patterns. A summer drought stress (particularly in the east and south-east) may lead to less grass production in those regions and a change towards maize for forage, which should become a viable crop. This in turn will lead to a change in grazing patterns. In areas where grass production significantly increases, a smaller area will be required per head of stock. Thus alternative land uses may be desirable. The possible development towards earlier winter rainfall may lead to poaching and soil damage problems resulting in longer housing times for animals. In conjunction with this, an increase in winter rainfall will mean that the opportunity to spread slurry or dirty water in winter will be possibly

Table 3.2. The temperature and precipitation values for the nine defined agro–climate classes for baseline, 2055 and 2075 climates.

	Class 1		Class 2		Class 3		Class 4		Class 5		Class 6		Class 7		Class 8		Class 9	
	pptn	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**	**pptn**	**temp**
Baseline																		
Winter	91	4.0	84	4.5	92	5.3	114	3.7	110	4.5	120	5.4	159	3.5	162	4.7	170	5.8
Spring	73	7.3	67	7.8	65	8.4	85	7.0	80	7.8	80	8.4	108	6.6	105	7.6	104	8.3
Summer	72	13.7	67	14.1	60	14.6	83	13.3	79	13.9	76	14.5	103	12.7	99	13.4	94	14.1
Autumn	94	10.8	87	11.2	87	11.9	116	10.5	112	11.1	112	11.8	159	10.0	159	10.9	153	11.8
Mean	82	8.5	77	9.0	76	9.6	99	8.2	95	8.9	97	9.6	132	7.8	131	8.8	130	9.6
Temp	cool		average		warm		cool		average		warm		cool		average		warm	
pptn	Low rainfall						Average rainfall						High rainfall					
2055																		
Winter	156	5.5	140	6.1	134	6.8	128	5.3	112	6.1	120	6.9	140	5.0	169	6.2	174	7.1
Spring	59	8.6	54	9.1	53	9.6	73	8.3	71	9.0	74	9.6	101	7.9	103	8.9	104	9.5
Summer	51	16.2	47	16.5	35	16.8	64	15.6	61	16.2	52	16.6	85	15.0	78	15.6	62	16.0
Autumn	84	12.4	78	12.8	72	13.4	109	12.0	110	12.7	112	13.3	160	11.5	164	12.4	155	13.2
Mean	109	10.2	101	10.6	99	11.2	96	9.8	84	10.6	86	11.1	97	9.4	114	10.3	115	11.0
Temp	cool		average		warm		cool		average		warm		cool		average		warm	
pptn	Low rainfall						Average rainfall						High rainfall					
2075																		
Winter	158	5.8	142	6.3	136	7.1	130	5.5	116	6.4	126	7.2	148	5.2	180	6.4	186	7.3
Spring	59	8.9	55	9.3	53	9.8	73	8.5	72	9.3	76	9.8	101	8.1	103	9.1	103	9.7
Summer	52	16.8	48	17.1	35	17.4	65	16.3	61	16.8	52	17.1	85	15.7	78	16.2	62	16.6
Autumn	82	12.7	77	13.1	70	13.7	109	12.3	112	13.0	113	13.6	163	11.8	167	12.7	156	13.5
Mean	108	10.5	101	11.0	100	11.5	98	10.2	86	10.9	88	11.5	99	9.7	117	10.7	117	11.4
Temp	cool		average		warm		cool		average		warm		cool		average		warm	
pptn	Low rainfall						Average rainfall						High rainfall					

non-existent for the whole country. Thus slurry storage requirements may well increase. Previous studies (Government of Ireland, 1991) have suggested that shorter animal housing times would be required because of increased herbage production at the extremes of the seasons. However, based on the seasonality of precipitation (Fig. 3.8), this is not necessarily the case for all locations which means that changes in storage requirements and animal housing will be location dependent. The balance of grazing season length against winter rainfall will dictate the stored feed requirement and the actual climate may dictate the choice of forage crop grown. Lucerne as a forage crop may be most appropriate if maize suffers from drought as previously suggested (Government of Ireland, 1991).

Pest and disease management will change with a change in climate. Current pests and diseases are suited to a warm wet summer and a mild winter. Diseases reliant on surviving in wettish conditions in the summer will have problems with the increased drought tendencies (e.g. *Ostertagia*), and those that cannot survive a warmer winter (e.g. *Nematodirus*) will also be troubled. There will be a tendency for pests and diseases that are currently found further south in Europe to move northwards towards Ireland. Cold stress over extended periods will be less of an issue, but the climate change data available provide little indication of the nature of severe event occurrence. In cereal crops, brown rust may become more prevalent due to the warmer summers and more humid conditions as the seasons change. The wetter winters would favour take-all development, so a change to spring-sown crops would be desirable. As with animal disease, pests associated with root crops will move from the southern parts of Europe. For potato, drought stress will be the most important limiting factor given that farmers in the east of Ireland already have to flood-irrigate potato fields to ensure adequate yields. Given the increased seasonality of water supply, this may become problematic without the introduction of the necessary infrastructure. One of the significant impacts of the change in pest and disease prevalence will be a change in the spray requirements. It is quite likely that chemical intervention will increase with climate change. With respect to weeds, it is likely that weeds will adapt to climate change more rapidly than crops due to their genetic advantage (Bunce and Ziska, 2000). However, the balance of crop/weed interaction with respect to photosynthetic type will be of importance to the development of weed problems (C_3 species will tend to benefit from elevated CO_2 more than C_4 species). Another impact that may occur is the northward migration of European weeds that are not currently a problem in Ireland, but this will very much depend on the exact nature of climate change and its balance with crop protection strategies.

Wetter soil in winter will increase a susceptibility to runoff which in turn could mean that pollution problems will be more pronounced along with soil erosion problems. Poaching and tillage access timing will also become an issue. The changing seasonality of the precipitation distribution will mean that late harvesting will be difficult and a spring sowing will be desirable in some areas. The increase in winter precipitation may lead to a greater land area suffering from winter flooding which would have a major impact on the choice of land use with the anticipated changes in climate.

In terms of the impact of climate change on crop productivity, some fundamental impacts can be expected. Wheat productivity should increase with increased atmospheric CO_2. Lawlor and Mitchell (2000) suggest that a yield increase of about 10% per 100 µmol [CO_2] increase could occur provided there is no nutrient or water stress. However, an increase in temperature of 1°C would offset any such gain by a change in crop growth; thus, a variety breeding programme would be required to derive benefit from changing CO_2 levels. Increasing temperatures should make maize more viable (Young and Long, 2000) provided that periods of low temperature do not cause inhibitions. Water stress in maize should not be a major problem in Ireland in the future. Miglietta *et al*. (2000) suggest that there has been too little research into root/tuber crop biology to be sure of the impact of climate change other than to suggest that increased water stress may reduce yields and that elevated CO_2 may increase yields. Peet and Wolfe (2000), on the other hand, suggest that increased atmospheric CO_2 will enhance photosynthesis and improve water-use efficiency in vegetable crops provided there is no water or nutrient stress. It is unlikely that the climate of Ireland will change sufficiently to cause temperature stress for such crops. Nösberger *et al*. (2000) indicate that elevated CO_2 with increased temperature should lead to improved grass yields, but that the nature of sward management will change as the varying ability of different plants to utilise the extra CO_2 becomes important. These processes have yet to be fully understood. The interaction of factors involved in livestock farming based on grass and forage production is of central concern to Irish agriculture and needs investigation *before* the impacts of climate change hit farmers.

The nine defined agro–climatic classes (Fig. 3.5, Table 3.2) are strictly agricultural ones linked to specific crop types and their expected performance. The performance of the five crops studied for this project will be analysed with respect to the agro–climatic classes defined. In general, it is probably reasonable to say that the change in climate is not likely to induce temperature stress in any of the regions defined, that plant growth response may increase, but that plant maintenance effort will not be affected. Water stress may become an issue, particularly with drier summers. Maize, being a C_4 crop, will show little response to elevated CO_2, but the increase in temperature will make the Irish climate more suited for its growth.

3.3 Background to Crop Production Simulations

3.3.1 Crop selection

With the exception of the pasture model, which is the Johnstown Castle Grass model (Brereton *et al*., 1996), as used in previous work (Government of Ireland, 1991), the models used in this project are part of a suite of models assembled under US government sponsorship since 1980 as the Decision Support System for Agricultural Technology Transfer (DSSAT). (See http://www.icasa.net/dssat/ for information or Tsuji *et al*., 1994.) In the present project, the most recently updated version of DSSAT, version 3.5, was used. All of the models are well known from the scientific literature or are more recent adaptations based on established models to extend their use to alternative crops (e.g. the original CERES model for wheat is modified and applied to barley and to maize). All models have been thoroughly tested and incorporate the most recent information on each of the crops (Tsuji *et al*., 1994).

The crops selected represented the three main systems of production in Irish agriculture at present. Permanent pasture is the main source of livestock feed for milk, beef and sheep production. Barley represents the cereals sector and the root-crops sector is represented by potato. Two other crops were selected to act as more sensitive indicators of climate change effects. Currently, maize is grown widely in Ireland as a source of high energy feed for livestock. Although it is grown in many parts of the country, it may nevertheless be regarded as a marginal crop under present climate conditions. In some seasons, maize fails to produce the seed which is the source of the high energy. The performance of maize is more reliable in Munster than elsewhere in Ireland. Imported soybean is an important element in livestock rations in Ireland, and because of its potential value to the livestock industry it was selected as an exotic crop that has been grown in Ireland under experimental conditions. However, the yield of seed is poor under the present climate and it has no commercial potential at present. Soybean is a short-day plant which flowers after mid-summer. In recent decades, a major effort has been made to breed cultivars more suited to the higher latitudes and the critical day length for inflorescence initiation has been increased from approximately 12 h to greater than 14 h, and it is from among these latter cultivars that a selection was made for this study.

3.3.2 The crop simulation models

Barley

The CERES models are a family of mechanistic, deterministic crop growth models developed mainly in the United States of America for many of the world's key agricultural crops. Inputs for all these models consist of a detailed environmental database. The CERES–Barley model has been developed from the CERES–Wheat model (Otter-Nacke *et al.*, 1991) primarily by altering the parameter values. Model variables are updated daily on the basis of weather data. The growth cycle of the crop is divided into developmental phases each with its own parameter values for growth rate and dry matter partitioning modified by cultivar, weather or other environmental factors. The developmental stage is linked to the emergence of main-stem leaves whose rate of appearance depends on thermal time. Growth rate is calculated as the product of absorbed radiation, which is a function of leaf area, using a constant rate of dry matter yield per unit radiation absorbed. Leaf area is incremented daily on the basis of available assimilate and specific leaf area. At each stage, deficits of soil water or nitrogen can affect the growth of the modelled crop. Cultivar-specific data are taken account of in terms of genetic coefficients (Table 3.3) for cold tolerance, photoperiod sensitivity, vernalisation requirement and rate of grain growth (Hunt, 1988). The variety used in the simulation was 99002 High Latitude Spring IB001.

Maize

The CERES–Maize model (Jones *et al.*, 1984) differs from CERES–Barley in the simulation of the reproductive structures. In maize, the male and female (cob) inflorescence undergo separate development both in time and space. As in the case of barley, crop development and growth, soil water and nitrogen conditions are calculated on a daily basis. Growth and partitioning of assimilate between the different plant organs is modified by calculated water and nitrogen stresses. Germination is controlled by soil moisture. Otherwise, development from one phenological stage to the next is controlled by cumulative temperature. The initiation of the male inflorescence is determined by day length. The growth sub-model controls the rate of leaf appearance and death and the rate of assimilate distribution to the leaves, stem, roots and to the cob. The parameters of the model are modified for different cultivars that are broadly classed as long season, medium season, short season and very short season. The variable genetic parameters (Table 3.4) include, for example, the cumulative temperature that determines the length of the juvenile phase following germination and that determines the duration of grain filling (maturity). Where the rate of grain filling fails due to low ambient temperatures, the simulation is terminated before the cob fully matures which was found to be frequently the case for the present climate in Ireland. The variety used in the simulation was 990003-Short Season.

Potato

The potato simulation uses the model SUBSTOR which is the DSSAT generic model for root and tuber crops (Singh *et al.*, 1998). The model shares many of the basic features of the CERES family of models. The principal differences are associated with the fact that flowering and seed production are of little importance in potato and these aspects are replaced by algorithms that describe tuber formation. As with the CERES models, the phenological development of the crop (tuber initiation) is controlled by cumulative temperature. Crop parameters are modified for different cultivars. The variable

Table 3.3. Barley genotype coefficients options (99002 was selected for this project).

VAR ID	Name	P1V	P1D	P5	G1	G2	G3	PHINT
990001	Mediterranean	5	2.0	–2.0	4.0	4.0	2.0	75.00
990002	High Latitude Spring	0	0.0	5.0	7.0	10.0	3.0	55.00
990003	High Latitude Winter	6	0.0	5.0	7.0	10.0	3.0	65.00
IB0101	Abiad	5	2.0	–2.0	4.0	4.0	2.0	75.00
IB0102	Beecher	5	2.0	–2.0	4.0	4.0	2.0	75.00
IB0030	Maris Badger	6	0.0	5.0	7.0	10.0	3.0	55.00

P1V: Relative slowing of development for each day of unfulfilled vernalisation, assuming that 50 days of vernalisation is sufficient for all cultivars.

P1D: Relative slowing of development when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h).

P5: Relative grain filling duration based on thermal time (degree days above a base temperature of 1°C), where each unit increase above zero adds 40 degree days to an initial value of 300 degree days.

G1: Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (1 g^{-1}).

G2: Kernel filling rate under optimum conditions (mg day^{-1}).

G3: Non-stressed dry weight of a single stem (no leaf blades and sheaths) and spike when elongation ceases (g).

PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

Table 3.4. Genetic parameters for maize. (The first four cultivars represent generic types and the short-season type was selected for the present project.)

VAR ID	Name	P1	P2	P5	G2	G3	PHINT
990001	Long Season	320.0	0.520	940.0	620.0	6.00	38.90
990002	Medium Season	200.0	0.300	800.0	700.0	8.50	38.90
990003	Short Season	110.0	0.300	680.0	820.4	6.60	38.90
990004	Very Short Season	5.0	0.300	680.0	820.4	6.60	38.90

P1: Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.
P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h).
P5: Thermal time from silking to physiological maturity (expressed in degree days above 8°C).
G2: Maximum possible number of kernels per plant.
G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}).
PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

parameters are adjusted according to the cultivar to be simulated (Table 3.5). The cultivar King Edward was chosen for the present project.

Soybean

The basis of the simulation of soybean is the DSSAT generic model CROPGRO which describes the growth of grain legumes (Hoogenboom *et al*., 1992). As with the other models, the core routine of calculating biomass production as a function of leaf area and the partitioning of biomass between leaf, seed, root and shoot and the use of cumulative temperature and day length to control phenological development is similar in SOYGRO. The principal difference is the inclusion of a sub-routine to describe nitrogen fixation. As with the other crops, parameters vary between cultivars (Table 3.6). The cultivar used in the present work was 990011-Group 000.

Grass

The main objective of the DSSAT pasture model is to allow for biomass cover crop simulation in crop rotation and sequence applications. The pasture model is a very

Table 3.5. Genetic parameters for potato. (The cultivar King Edward was chosen for the project.)

VAR ID	Name	G2	G3	PD	P2	TC
IB0001	Majestic	2000	22.5	0.8	0.6	17.0
IB0002	Sebago	2000	22.5	0.7	0.8	15.0
IB0003	Russet Burbank	2000	22.5	0.6	0.6	17.0
IB0004	Kathadin	2000	25.0	0.7	0.6	19.0
IB0005	Atlantic	2000	25.0	0.9	0.6	17.0
IB0006	Maris Piper	2000	25.0	0.8	0.4	17. 0
IB0007	King Edward	2000	22.5	1.0	0.6	17. 0
IB0008	Desirée	2000	25.0	0.9	0.6	17.0
IB0009	LT-1	2000	25.0	0.9	0.8	21.0
IB0010	C14-343	2000	25.0	0.9	0.4	21.0
IB0011	Norchip	2000	25.0	1.0	0.4	17.0
IB0012	Shepody	2000	25.0	0.7	0.6	19.0

G2: Leaf area expansion rate in degree days.
G3: Potential tuber growth rate.
PD: Index that suppresses tuber growth in the period following tuber induction.
P2: Index that relates photoperiod response to tuber initiation.
TC: Upper critical temperature for tuber initiation.

Table 3.6: Genetic parameters for soybean. The first 13 cultivars are generic types. (The cultivar used in the present work was 990011-Group 000.)

VAR ID	NAME	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XFRT	WTPSD	SFDUR	SDPDF	PODUR
990011	GROUP 000	14.60	0.129	15.5	5.0	12.0	29.50	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990012	GROUP 00	14.35	0.148	16.0	5.0	12.0	30.00	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990013	GROUP 0	14.10	0.171	16.8	6.0	13.0	31.00	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990001	GROUP 1	13.84	0.203	17.0	6.0	13.0	32.00	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990002	GROUP 2	13.59	0.249	17.4	6.0	13.5	33.00	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990003	GROUP 3	13.40	0.285	19.0	6.0	14.0	34.00	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990004	GROUP 4	13.09	0.294	19.4	7.0	15.0	34.50	26.00	1.030	375.0	180.0	1.00	0.19	23.0	2.20	10.0
990005	GROUP 5	12.83	0.303	19.8	8.0	15.5	35.00	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
990006	GROUP 6	12.58	0.311	20.2	9.0	16.0	35.50	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
990007	GROUP 7	12.33	0.320	20.8	10.0	16.0	36.00	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
990008	GROUP 8	12.07	0.330	21.5	10.0	16.0	36.00	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
990009	GROUP 9	11.88	0.340	23.0	10.0	16.0	36.50	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
990010	GROUP 10	11.78	0.349	23.5	10.0	16.0	37.00	18.00	1.030	375.0	180.0	1.00	0.18	23.0	2.05	10.0
IB0003	WAYNE (3)	13.45	0.245	19.5	7.9	14.8	28.00	26.00	1.020	380.0	180.0	1.00	0.18	21.0	2.20	14.0

CSDL: Critical short day length below which reproductive development progresses with no day-length effect (for short-day plants) (hour).
PPSEN: Slope of the relative response of development to photoperiod with time (positive for short-day plants) ($1\ h^{-1}$).
EM-FL: Time between plant emergence and flower appearance (R1) (photothermal days).
FL-SH: Time between first flower and first pod (R3) (photothermal days).
FL-SD: Time between first flower and first seed (R5) (photothermal days).
SD-PM: Time between first seed (R5) and physiological maturity (R7) (photothermal days).
FL-LF: Time between first flower (R1) and end of leaf expansion (photothermal days).
LFMAX: Maximum leaf photosynthesis rate at 30°C, 350 vpm CO_2, and high light (mg CO_2 m^{-2} s^{-1}).
SLAVR: Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1}).
SIZLF: Maximum size of full leaf (three leaflets) (cm^2).
XFRT: Maximum fraction of daily growth that is partitioned to seed + shell.
WTPSD: Maximum weight per seed (g).
SFDUR: Seed filling duration for pod cohort at standard growth conditions (photothermal days).
SDPDV: Average number of seeds per pod under standard growing conditions (no. pod^{-1}).
PODUR: Time required for cultivar to reach final pod load under optimal conditions (photothermal days).

simple model that predicts vegetative growth and development only. It is based on the CROPGRO model, in which all reproductive development phases have been switched off. In its current format, it does not predict flowering. The experimental data for model development are based on several Bahia grass experiments. The simulation of vegetative growth and development of the pasture model is identical to the simulation of vegetative growth of the grain legume crops. It is recommended that this model should not be used as a stand-alone model.

In the present project, therefore, the simulation of pasture production uses the Johnstown Castle Grass Growth model. This model simulates the production of Perennial Ryegrass dominated pasture which is the common basis of livestock production in Ireland. The model is described in Brereton *et al*. (1996). It was originally created as a basis for evaluating the gross effects of year-to-year differences in weather conditions on herbage production in grazing systems. It does not, and was not intended to, explain the nature of grass growth. Instead, the intention was to provide a means to understand the dynamics of a grazing management system subject to a variable feed (herbage) supply. The approach is very simple, but the variation between the reproductive and vegetative states of the grass crop are taken into account. Reflecting the simple empirical nature of this model the description of the system is reduced to a few simple equations. The increase in herbage mass for a period is calculated from the radiation received at the crop surface in the period:

$$\Delta W = \varepsilon \frac{\Delta J}{Q} \qquad \text{(eqn 3.1)}$$

where ΔW is the mean daily herbage dry matter yield increase (kg ha^{-1}), ΔJ is the mean daily light received at the crop surface (J cm^{-2}), Q is the heat of formation of plant matter (18.81 MJ kg^{-1}), and ε is the efficiency of conversion to plant energy of the radiation received at the crop surface.

According to Equation 3.1, yield is proportional to the radiation received. However, it is assumed that the capacity of the crop to utilise light is saturated at a flux density of 144 J cm^{-2} h^{-1}. The effects of leaf area on light interception are implicit in the model assumption that the efficiency parameter is affected by temperature. Efficiency varies with temperature in a sigmoid relationship:

$$\varepsilon = \varepsilon_{max}\left[\frac{(T/K)^n}{1+(T/K)^n}\right] \qquad \text{(eqn 3.2)}$$

where T is the mean daily temperature (°C), ε_{max} is the maximum efficiency at high temperatures, K is the temperature at which ε is half maximum (°C), and n is a constant.

For the present project, the parameters of Equation 3.2 were selected to represent a reproductive crop harvested after 28 days re-growth, fertilised with N at a rate equivalent to 600 kg N year^{-1} and adequately supplied with water and other nutrients (i.e. growth not restricted by soil nutrients or by soil water deficit). For other conditions, the daily yield increase is modified using multiplicative functions of ontogeny, nitrogen use, soil water status and rest interval. The model has been tested against measured production over a wide geographical range in Ireland (Brereton, 1995). It is important to note that the model was designed to simulate grass production in permanent pasture. In the first 2 years of a re-seeded pasture, yields are approximately 25% greater than the yields of permanent pasture so that the model's production estimates tend always to be less than the production measured in short-term grass cultivar trials. The parameters of the soil water-balance component of the pasture model vary according to soil type. The profile is not described in as great detail as the DSSAT models. All of the soils are assumed to have 120 mm available water at field capacity. The water deficit at which growth becomes restricted varies according to the texture of the soil and the distribution pattern of the roots.

3.3.3 The soil sub-model (DSSAT)

While the crops are modelled in considerable detail, the soil sub-model is a relatively simple water-balance model. The parameters of the soil sub-model (Table 3.7) vary between soil types (Table 3.8) in regard to albedo, drainage rate, number, depth, textural composition and moisture characteristics of horizons. The moisture characteristics include water content at saturation, at field capacity and at the limit of extractable water. Root distribution between horizons is a soil characteristic. Whereas the crop models simulate root growth, the

Table 3.7. Soil parameters used in the DSSAT model.

SALB	Albedo, fraction	SLCL	Clay (<0.002 mm), %
SBDM	Bulk density, moist, g cm^{-3}	SLDR	Drainage rate, fraction day^{-1}
SCEC	Cation exchange capacity, cmol kg^{-1}	SLHB	pH in buffer
SCOM	Colour, moist, Munsell hue	SLHW	pH in water
SDUL	Upper limit, drained, cm^3 cm^{-3}	SLLL	Lower limit, cm^3 cm^{-3}
SLB	Depth, base of layer, cm	SLNF	Mineralisation factor, 0–1 scale
SLCF	Coarse fraction (>2 mm), %	SLNI	Total nitrogen, %
SLOC	Organic carbon, %	SLRO	Runoff curve no. (Soil Conservation Service)
SLSI	Silt (0.05–0.002 mm), %	SLU1	Evaporation limit, mm
SMHB	pH in buffer determination method, code	SMKE	Potassium determination method, code
SMPX	Phosphorus determination code	SNH4	Ammonium, KCl, g elemental N Mg^{-1} soil
SNO3	Nitrate, KCl, g elemental N Mg^{-1} soil	SRGF	Root growth factor, soil only, 0.0–1.0
SSAT	Upper limit, saturated, cm^3 cm^{-3}	SSKS	Sat. hydraulic conductivity, macropore, cm h^{-1}

distribution of roots between horizons is determined by the soil parameter.

Each model in DSSAT uses a common soil sub-model to estimate soil moisture changes during growth. The soil model requires a profile description and the soil properties that affect soil water balance. A digitised version of the General Soil Map of Ireland (Gardiner & Radford, 1980) was used to determine the dominant soil type of each 10 km square used for the simulations. The soils were then further simplified by grouping into seven classes: (i) Grey Brown Podzolic; (ii) Brown Earth; (iii) Acid Brown Earth; (iv) Podzol; (v) Gley; (vi) Peats; and (vii) urban/water. The parameter values for the five groups used are presented in Table 3.8 and the resulting soil map (Fig. 3.9) was very similar to the 1969 soil map of Ireland (see Cruickshank, 1972) from which the descriptive terminology was derived. Grid cells dominated by peats and urban/water were excluded from the crop yield calculations.

3.3.4 Daily weather data generation

All of the crop models require daily values of solar radiation, maximum temperature, minimum temperature and rainfall. The climate data available for this project were in the form of monthly average values for these elements for the baseline climate and two future scenarios (2055 and 2075). The baseline data, covering the 30-year period 1961–1990, were statistically interpolated to a 10 × 10 km grid over Ireland (see Chapter 2). DSSAT includes a facility, called Weatherman/Simmeteo (Richardson, 1985; Geng et *al*., 1986), which enables the generation of the daily values from the monthly means. The approach taken for this simulation of the impact of climate change was to create 30 years worth of daily data from the monthly mean values which could be used to simulate the crop growth on a daily basis. The resulting 30 years worth of crop data were then averaged for each site and the mean values reported.

The weather data file included the altitude for each 10 × 10 km square. For the tillage crops, squares at altitudes greater than 150 m were excluded from the analysis. The altitude limit was 300 m in the case of pasture.

The monthly means of the 10-km squares were modelled at NUI, Maynooth, from data from the weather stations of the Met Éireann network. The generation of daily weather data from monthly means was a critical aspect of the project. Simmeteo generates daily values of radiation, temperature and rainfall from monthly means of radiation, maximum temperature, minimum temperature and precipitation. As well as the means of these weather elements Simmeteo requires monthly means of the number of rain days. The number of rain days per month was not available for each 10 km square. However, these data were available for some Met Éireann weather

Table 3.8. The parameters of the five general soil types.

DUDU02DU02Grey Brown Podzolic (Soil 1)

SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE
BN	0.13	9.4	0.60	76	1.00	1.00	IB001	IB001	IB001

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
40	0.112	0.234	0.360	1.00	–99.0	1.30	2.40	18.0	35.0	5.0	–99	5.5	5.5	16.0
75	0.147	0.269	0.369	0.75	–99.0	1.40	0.50	26.0	35.0	5.0	–99	6.8	6.8	16.0
100	0.151	0.272	0.365	0.20	–99.0	1.45	0.40	27.0	32.0	5.0	–99	8.0	8.0	16.0

DUDU03DU02 Brown Earth (Soil 2)

SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE
BN	0.13	9.0	0.60	76	1.00	1.00	IB001	IB001	IB001

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
20	0.086	0.203	0.331	1.00	3.0	1.30	3.60	12.0	24.0	5.0	–99	6.0	6.0	20.0
65	0.074	0.189	0.322	0.75	3.0	1.40	1.00	9.0	23.0	5.0	–99	5.5	5.5	18.0
100	0.053	0.171	0.296	0.70	2.0	1.45	0.40	4.0	17.0	5.0	–99	6.0	6.0	15.0

DUDU04DU02 Acid Brown Earth (Soil 3)

SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE
BN	0.13	9.2	0.60	76	1.00	1.00	IB001	IB001	IB001

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
30	0.099	0.211	0.326	1.00	3.0	1.30	5.00	15.0	15.0	5.0	–99	5.5	5.5	25.0
90	0.052	0.166	0.313	0.75	3.0	1.40	2.00	10.0	10.0	5.0	–99	6.0	6.0	22.0
100	0.047	0.151	0.338	0.20	2.0	1.45	0.40	10.0	7.0	5.0	–99	7.0	7.0	20.0

DUDU05DU02 Podzol (Soil 4)

SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE
BN	0.13	8.2	0.20	76	1.00	1.00	IB001	IB001	IB001

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
35	0.047	0.163	0.304	1.00	3.0	1.30	8.00	3.0	23.0	5.0	–99	5.5	5.5	38.0
60	0.091	0.204	0.324	0.75	3.0	1.40	4.00	13.0	17.0	5.0	–99	5.8	5.8	35.0
100	0.058	0.187	0.308	0.20	2.0	1.45	0.60	7.0	17.0	5.0	–99	5.7	5.7	30.0

DUDU06DU02 Gley (Soil 5)

SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE
BN	0.13	25.4	0.05	76	1.00	1.00	IB001	IB001	IB001

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
40	0.190	0.318	0.387	1.00	2.0	1.40	3.00	35.0	40.0	1.0	–99	5.5	5.5	23.0
65	0.213	0.340	0.390	0.20	1.9	1.40	0.40	40.0	40.0	1.0	–99	6.8	6.8	20.0
100	0.190	0.313	0.368	0.10	1.0	1.40	0.30	35.0	30.0	1.0	–99	8.0	8.0	18.0

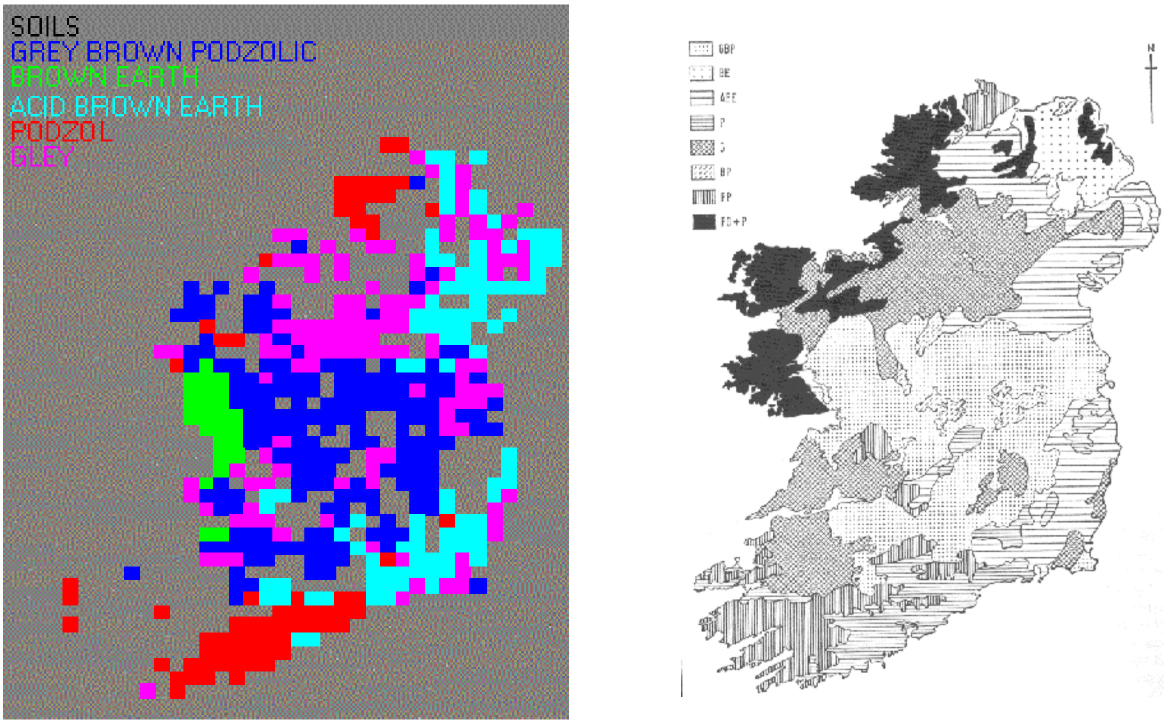


Figure 3.9. Left: Map of the soil type distribution used for DSSAT simulations (urban and peat soils omitted); details of the soil descriptions are presented in Table 3.8. Right: The soil map of Ireland published in 1969 (see Cruickshank, 1972) shows a very similar distribution of soils to those used for this work.

stations. An analysis of the relationship between the average total monthly rainfall (P) and average number of rain days per month (N) suggested that a general extrapolation could be achieved using the equations:

$$N = 0.26 \times P \qquad \text{(where } P < 100 \text{ mm)} \qquad \text{(eqn 3.3)}$$

and

$$N = 24.0 + 0.0189 \times P \qquad \text{(where } P > 100 \text{ mm)} \qquad \text{(eqn 3.4)}$$

for each month for each of the 100-km^2 grid squares. Simmeteo uses random numbers to generate the data. The primary objective of Simmeteo is to generate a sequence of yearly data that reflects the real year-to-year variation in weather. As a result, the monthly means of the output for 1 year may deviate significantly from the input and it is necessary to generate data for a sequence of years to obtain a set of data in which the monthly means reduce to the input means. A 30-year period was used in the present project. Each crop model was run for each of the 30 years and the yield for each 10 km square represents the average of 30 simulations. Thirty years represents a compromise between the need to economise on run time and the need to accurately reflect crop production for the climate of the 10 km square. A comparison between input and output means are presented here for three contrasting sites (Table 3.9).

The comparisons show that the 30-year period provides an adequate weather data set and that the use of an empirical relationship to estimate rain days from total monthly rainfall gives a very good rain data set. In initial work with Simmeteo, rainfall was underestimated in summer months and a recurring feature of the generated data is the overestimate of July radiation. However, the relationship between photosynthesis and radiation takes the form of a rectangular hyperbola. In mid-summer, photosynthetic activity occurs mainly at the upper end of the relationship where photosynthesis is effectively independent of variation in radiation and, therefore, the July overestimate may be regarded as unimportant. An important feature of the comparison is that although there are differences between input and output means these are small compared to the differences between sites and, especially, compared to the climate changes that are anticipated.

Table 3.9. Comparison of input and mean output data from the daily weather generator for three test sites.

Month	Input data					Output data			
	Radiation	T_{max}	T_{min}	Rain	Rdays	Radiation	T_{max}	T_{min}	Rain
Site at latitude 55° N, altitude 231 m (North-East)									
1	2	5.4	0.1	152.5	28.0	1.68	6.11	0.01	146
2	4.2	5.4	–0.1	121.7	27.0	4.05	6.19	–0.11	118
3	7.6	7.3	0.8	116.8	27.0	8.54	7.25	0.28	120
4	13.3	10.0	2.2	94.2	24.0	13.05	10.11	1.69	96
5	16.4	12.7	4.4	86.9	23.2	16.43	13.78	4.34	81
6	17.0	15.5	7.3	89.7	23.6	17.93	16.50	7.77	96
7	15.0	16.8	9.2	91.6	23.9	16.93	17.53	9.42	91
8	13.3	16.7	9.0	108.6	25.9	13.92	16.50	8.47	104
9	9.2	14.5	7.4	129.1	27.4	9.50	15.19	7.73	124
10	5.4	11.7	5.7	144.2	27.8	5.22	12.41	6.05	147
11	2.7	7.8	2.1	148.3	27.8	1.83	8.89	1.95	139
12	1.5	6.3	1.2	143.4	27.7	1.04	6.90	1.12	140
Site at latitude 54° N, altitude 64 m (North-East)									
1	2.1	6.8	1.6	112.3	26.3	1.76	7.09	1.31	112
2	4.4	6.8	1.4	87.0	23.2	4.46	7.22	1.04	82
3	7.8	8.6	2.3	88.5	23.4	9.10	8.51	1.74	82
4	13.3	11.0	3.6	68.3	19.9	13.67	12.25	3.80	65
5	16.9	13.7	5.9	65.9	19.4	17.26	14.91	5.75	63
6	17.5	16.5	8.7	71.3	20.5	18.05	16.72	8.39	76
7	15.5	17.9	10.6	70.9	20.4	17.98	18.52	10.55	67
8	13.4	17.8	10.4	87.1	23.2	13.84	17.54	10.21	89
9	9.2	15.8	8.9	100.9	25.1	9.22	16.08	9.24	97
10	5.4	13.0	6.9	110.8	26.1	5.08	13.75	7.42	121
11	2.7	9.3	3.5	112.0	26.2	1.90	9.74	2.95	110
12	1.5	7.7	2.5	102.8	25.3	1.42	8.46	2.66	91
Site at latitude 53° N, altitude 76 m (Midlands)									
1	2.4	7.1	1.3	90.4	23.7	2.14	6.84	0.63	89
2	4.6	7.3	1.2	63.9	19.0	5.36	7.74	0.80	58
3	8.2	9.5	2.2	69.9	20.2	9.28	9.91	2.41	68
4	13.0	12.1	3.4	57.3	17.5	13.43	12.63	3.12	56
5	16.3	14.6	5.7	71.5	20.5	16.09	15.71	5.66	71
6	16.9	17.9	8.7	64.7	19.1	17.59	18.08	8.71	68
7	15.4	19.4	10.6	59.7	18.0	17.60	19.80	10.80	58
8	13.2	19.0	10.3	80.7	22.2	13.37	18.92	10.68	81
9	9.8	16.6	8.5	82.0	22.4	9.91	17.15	9.03	72
10	5.8	13.4	6.5	89.6	23.6	5.22	13.03	6.10	85
11	3.1	9.5	2.9	87.0	23.2	2.65	10.31	2.39	81
12	1.9	7.9	2.1	89.9	23.6	1.68	8.71	2.30	91

3.3.5 Model operation: starting conditions and crop management

The DSSAT simulation package is designed to facilitate the execution of conventional field experiments as desk exercises. Simulation events are controlled by the experimental protocol entered in a control file – the FILEX. Experiments may be run as normal single-season exercises. The facility is also provided to replicate the experiments at different locations. The locations are defined by the particular soil and climate characteristics. In this project, the 10 km square was considered a treatment and the 30-year weather sequences were regarded as replicates. The number of treatments possible in one experiment is 99 and replication is limited to 30. For each crop, six FILEX experiments were set up for successive groups of 10-km squares. This provided coverage for the entire set of 10-km squares. There are 845 10-km squares but with the elimination of sites at higher altitudes and sites dominated by peat and urban/ water the number of squares to be processed was reduced to less than 600. Prior to each of the six experiments for each crop, a climate file was created for each of the 99 squares, or sites, of that experiment. The climate files were created using the monthly means of weather elements and the calculated number of rain days per month for each 10 km square. The generation of 30 years replicated daily data for each site was effected from the FILEX.

The FILEX is a text file composed of an initial section that lists the treatments to be simulated and indicates the soil, climate and cultivar files to be used for each (details are presented for each crop in Table 3.10). It also gives the initial soil water status, details of date and method of planting, of the date and rate of fertiliser application and of harvest. At the end of the FILEX, the control section determines the number of replicates, the simulation start date, the method for weather generation and the form of output. For all crops, a FILEX contains:

- Number of replicates: 30 years (variable weather in site climate)
- Soil: site variable
- Climate: site variable

Table 3.10. FILEX for the five crops being simulated.

Spring barley	
Cultivar:	High Latitude Spring
Planting:	Seed, DOY 75, 225 seeds m^{-2}, rows 15 cm apart, depth 2 cm
Fertiliser:	50 kg N ha^{-1} in two equal applications, DOY 65 and DOY 105
Harvest date:	At maturity
Soybean	
Cultivar:	Group 000
Planting:	Seed, DOY75, 21.5 seeds m^{-2}, rows 91 cm apart, depth 4 cm
Fertiliser:	None
Harvest date:	At maturity
Maize	
Cultivar:	Short Season
Planting:	Seed, DOY 75; 7.1 seeds m^{-2}, rows 50 cm apart, depth 4 cm
Fertiliser:	200 kg N ha^{-1} in three equal applications DOY 65, 125 and 155
Harvest date:	At maturity
Pasture	
Cultivar:	Permanent pasture (Perennial Ryegrass dominant)
Planting:	Simulation started DOY 315
Fertiliser:	500 kg N ha^{-1} in monthly applications from DOY 35
Harvest date:	First harvest DOY 75 and at 28-day intervals subsequently
Potato	
Cultivar:	King Edward
Planting:	Seed, DOY 75; 5.1 seeds m^{-2}, rows 86 cm apart, depth 20 cm, sprout 8 cm
Fertiliser:	200 kg N ha^{-1} in two equal applications DOY 65 and DOY 145
Harvest date:	DOY 315

- Initial soil conditions: profile at field capacity
- Output format: summary at end of simulation

Data were obtained from Teagasc advisory guidelines.

A program in Visual Basic, an interface with DSSAT, was created to interrogate the primary weather/soil/ altitude database and copy the relevant weather data to the climate files. The interface discarded sites that did not meet the altitude and soil criteria. It also edited the soil classification in the FILEX of the 99 sites to be processed and created a record of the longitude, latitude, altitude and soil type of the sites that were processed. The interface then transferred control to the DSSAT FILEX and the simulation was initiated manually. When the simulation was completed, control returned to the Visual Basic interface where the output file of the simulation was renamed to avoid its being over-written in the following experiment.

3.3.6 Baseline crop production data for model evaluation

Crop models, however detailed the treatment of growth and development may be, are always a simplification of reality. Ideally they are used to obtain greater understanding of the way biological systems work and how they respond to environmental change or parameter changes introduced by crop breeding. Precise agreement between model and field data is not expected (for instance, national mean yields predicted by this simulation exercise will include locations not currently used for a specific crop's production. Therefore, the values will not necessarily be comparable with measured values) but there should be general agreement in terms of the order of magnitude and the round values being predicted with those found in the field. This was the case in the present study. For comparison with the output of the DSSAT models, data for current crop production in Ireland are presented here.

Spring barley

In European surveys Irish barley production is estimated at 5.4 t ha^{-1} with a coefficient of variation of 11.4% (Russell, 1990; Hough, 1990). The trends in barley yields during the period from 1955 to 1985 indicate that yields may be increasing by 0.7 t ha^{-1} per decade so that current yields may exceed 6 t ha^{-1}. In current practice, 6.1 t ha^{-1} is regarded as normal but may vary from a moderate yield of 4.9 t to a 'good' yield of 7.3 t (O'Sullivan, 1999). In experimental trials by Teagasc in 1980–1981, barley (cv. Idri) yields ranged from 5.1 to 8.5 t ha^{-1} between different locations (Table 3.11) (Conry, 1985). Note that spring barley yields are reported at 18% water content and the DSSAT output discussed is dry matter. National mean yield predicted for the baseline climate was 6.3 t ha^{-1} (dry matter (dm), values reported here are 18% water content).

Maize

Maize silage production in the variety trials of the Department of Agriculture, Food and Rural Development varies between 11.4 and 12.5 t ha^{-1} dm currently (Anonymous, (a) no date). The variety trials were conducted in areas considered suitable for maize production. In 1988, the trials were located in Counties Cork, Waterford, Wexford and Kildare. In the following years, the trials were extended to include Counties Tipperary, Meath and Louth. In the year 2000, silage yield varied from 11.54 to 16.33 t ha^{-1} between sites. In farm practice, 9.8 t ha^{-1} is considered normal but yields vary between 8.6 and 10.8 t ha^{-1} (O'Sullivan, 1999). Grain yields are not given. However, in the regions of Northern Europe (Brittany) that may be regarded as experiencing a similar climate to the most southern parts of Ireland, grain yields are approximately 6 t ha^{-1} (Bignon, 1990) and it may be assumed that grain yields in Ireland would be 6 t ha^{-1} or less. The levels of production of maize silage and grain in trials conducted between 1994 and 1998 by Teagasc, Oakpark, for The Maize Growers Association (J. Crowley, personal communication, 2001) are presented in Table 3.12. The silage yield varies from 6 to 19 t ha^{-1} and the percent grain from 10 to 50%. The inter-site and inter-year variations are both significant. Reported and DSSAT data are both dry matter values. National mean yield predicted for the baseline climate was 1.6 t ha^{-1} grain (dm).

Potato

In a European survey of crop production (Hough, 1990), maincrop potato yields for the late 1980s in Ireland is

Table 3.11. Spring barley yield variations for Ireland.

Location	Soil texture	Soil classification	Yield
Screen, Wexford	Very light sand	Brown Podzolic/Podzol	5.1
Oak Park, Carlow	Light gravel limestone	Brown Earth	6.5
Athy, Kildare	Medium textured limestone	Grey Brown Podzolic	7.5
Mulhuddart, Dublin	Heavy limestone	Grey Brown Podzolic	8.5

Table 3.12. Maize yields for Ireland.

Site	Year	Silage (t ha^{-1} dm)	% grain
Oakpark, Carlow	1994	9.4	11.0
Carrick-on-Suir, Tipperary	1994	10.8	11.4
Newcastle, Wicklow	1994	11.0	24.3
Lyons Estate, Kildare	1995	12.2	47.0
Newcastle, Wicklow	1995	15.2	42.0
Oakpark, Carlow	1995	12.4	47.8
Carrick-on-Suir, Tipperary	1995	18.2	44.3
Bandon, Cork	1995	14.3	40.6
Lyons Estate, Kildare	1996	11.1	36.0
Bandon, Cork	1996	14.6	38.6
Newcastle, Wicklow	1996	15.3	32.9
Carrick-on-Suir, Tipperary	1996	17.1	43.5
Dromore, Down	1996	11.5	14.1
Lyons Estate, Kildare	1997	15.2	51.6
Newcastle, Wicklow	1997	17.9	50.7
Blarney, Cork	1997	14.7	40.0
Newcastle, Wicklow	1998	18.7	42.2
Blarney, Cork	1998	14.6	33.0
Banbridge, Down	1998	6.2	9.3

given as between 30 and 35 t ha^{-1}. In current farm practice, 29.4 t ha^{-1} is regarded as a normal yield (saleable yield) for maincrop with yields ranging from moderate yields of 25.5 tonnes to good yields of 34.3 t ha^{-1} (O'Sullivan, 1999). In potato variety comparisons by The Department of Agriculture, Food and Rural Development carried out between 1996 and 1999, average yields of marketable potatoes (ware 40–80 mm in size) varied between varieties from 43.6 to 55.8 t ha^{-1} (Anonymous, (b) no date). In 2000, total yield varied from 60.26 to 69.55 to 73.49 t ha^{-1} for Midleton, Co. Cork, Oldtown, Co. Dublin and Raphoe, Co. Donegal, respectively. DSSAT values reported are dry matter and are thus about a factor of 5 less than reported values. National mean yield predicted for the baseline climate was 36 t ha^{-1} tuber yield.

Soybean

Soybean has been grown experimentally at Teagasc, Oakpark, Carlow. However, the grain yield was not significant (J. Crowley, personal communication, 2001). In Europe, soybean is grown commercially in Spain, Italy and Greece. In the cultivars used in the highest latitudes of the area (North Italy), the effects of day length are small and the principal limiting factor is temperature. In north-west Italy, economic seed yields of 2.5 to 3.0 t ha^{-1} are normal. National mean yield predicted for the baseline climate was 0.4 t ha^{-1} seed (dm).

Pasture

In trials at 26 sites throughout the Republic of Ireland over 4 years, mean yields of permanent pasture receiving 300 kg N ha^{-1} year^{-1} varied from 13 t ha^{-1} dm in the south-west to 11 t ha^{-1} in the north-east (Ryan, 1974). Yields on poorly drained soils were 2 t ha^{-1} less in the high rainfall western sites and 1 t ha^{-1} less in the east. Model estimates of production under the same conditions provided similar trends and indicated that in the extreme south-west yields exceeded 13 t ha^{-1} (Brereton, 1995). Similar levels and pattern of production were projected by Lee and Diamond (1972), though their primary basis was soil survey data. The annual production of grass varieties in experimental variety trials exceeds these yields significantly. In the current Irish Recommended

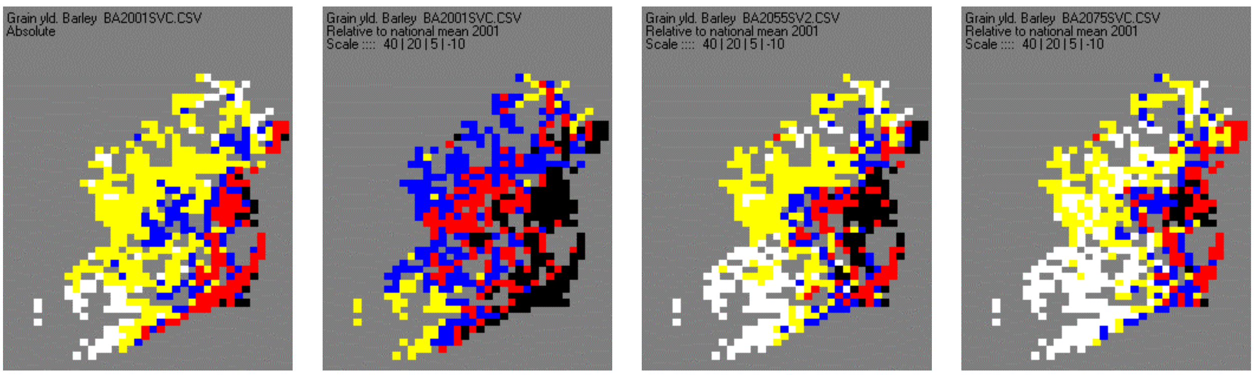
List of Herbage Varieties, yields are given as approximately 19 t ha^{-1} dm (Anonymous, (c) no date). These yields are obtained using new re-seeds grown with a non-limiting nitrogen supply. Several studies have shown that in new re-seeds grass yields decline progressively by approximately 20% over the first 2–3 years (Culleton and McGilloway, 1994). The production of grass at the moderate levels of nitrogenous fertiliser used in farm practice would be expected to be reduced by a similar amount (Prins, 1983). The model used in the present work was calibrated for permanent pasture and it normally gives estimates of annual production that are less than the production measured in experimental trials on re-seeds, but may be regarded as more representative of production in Irish commercial livestock farms. National mean yield predicted for the baseline climate was 12.9 t ha^{-1} annual production.

3.4 Baseline and Future Crop Yields in Ireland

Spring barley

According to the simulation modelling, there was no limitation on the establishment of spring barley either under the baseline or future climates. The baseline grain yields of spring barley vary between 4 and 6 t ha^{-1} (dm) in the areas of the midlands and the east and south coasts where cereals are currently located. Elsewhere, in the north, west and south-west, the estimated potential yield is between 6 and 8 t ha^{-1} (dm) (Fig. 3.10). These yields are similar to reported values. In 2055 and 2075, this geographical distribution of yield potential is not expected to change but the grain yield in all areas is expected to increase with possibly a greater increase towards the west. Along the east and south coasts, where present yields are more than 25% less than the baseline national mean, yields are expected to approach the baseline mean. In the north, west, and south-west potential yields are expected to increase by more than 25% of the baseline national mean in 2055 and by more than 40% greater in 2075. The impact of climate change is to increase the spring barley biomass and to increase grain yield so the grain/biomass ratio remains similar.

The baseline date of harvest of spring barley varies by 3 weeks between the south coast (222 DOY) and the North coast (204 DOY). In 2055, the harvest date is expected to be earlier with a further advance in 2075 when the harvest date, generally, will by earlier by about 3 weeks. The change in spring barley grain yield and harvest date by agro-climatic class (Table 3.13) shows that yield is currently related to precipitation rather than to temperature and that warm sites are ready to harvest earlier in the year. This means that as sites get (overall) wetter, yields increase and harvesting can occur earlier in the year. An evaluation of rainfall during crop growth and final yield revealed that under the baseline climate, yield



Baseline – absolute *Baseline – relative* *2055 – relative* *2075 – relative*

[Note: 2001 is only a coding for baseline climate data and output files].

Figure 3.10. Spring barley yield in Ireland under baseline climate, and its relative change under 2055 and 2075 scenarios. For the relative yield maps compared to baseline national mean yield (6.254 t ha^{-1} dm), black: < –10%; red: –10 to 5%; blue: 5–20%; yellow 20–40% and white >40%.

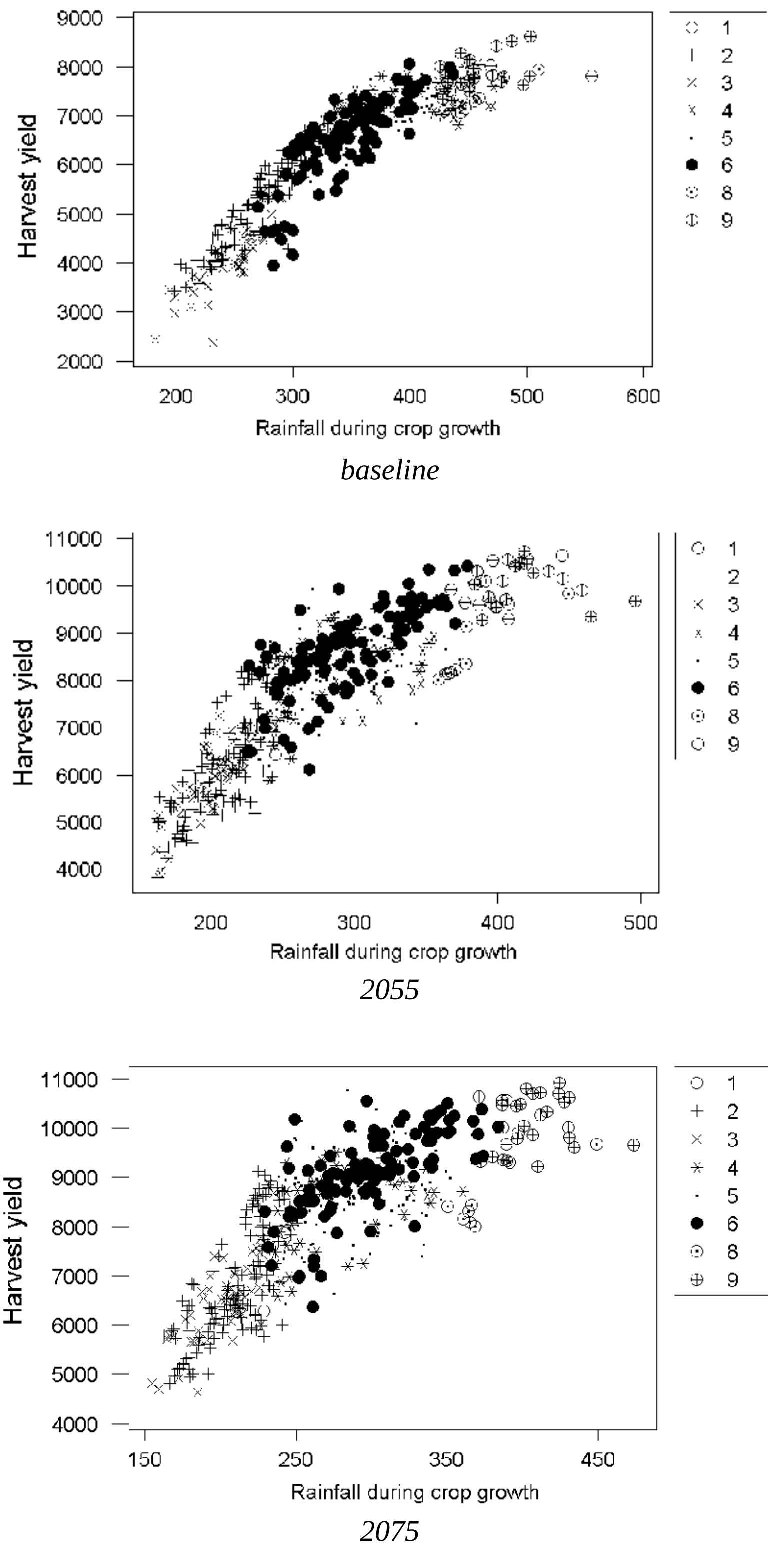
Table 3.13. Distribution of harvest weights and day by agro–climatic class (Fig. 3.5, Table 3.2), and the impact of climate change.

	Class	Harvest weight			Day of harvest		
		N	Mean	S.D.	N	Mean	S.D.
Baseline	**1**	2	6940.5	327.4	2	216.50	0.71
	2	142	5404.9	924.8	142	212.80	1.68
	3	49	4134.9	745.7	49	208.78	1.58
	4	49	7282.7	290.0	49	218.08	1.34
	5	152	6799.4	469.6	152	213.16	1.88
	6	107	6566.3	832.4	107	208.56	1.96
	8	9	7388.0	294.4	9	213.44	1.74
	9	29	7857.5	322.3	29	209.62	1.97
2055	**1**	2	6761	479	2	204.93	0.14
	2	142	6261	1164	142	201.27	1.49
	3	49	5929	847	49	198.35	1.37
	4	49	8187	882	49	205.39	1.29
	5	152	8171	735	152	201.77	1.51
	6	107	8622	881	107	198.92	1.55
	8	9	8681	803	9	201.95	0.67
	9	29	10008	441	29	199.69	1.32
2075	**1**	2	7084	1118	2	202.37	0.33
	2	142	6832	1089	142	198.85	1.29
	3	49	6483	840	49	196.54	1.64
	4	49	8396	880	49	202.83	1.17
	5	151	8652	777	151	199.51	1.40
	6	107	9087	869	107	196.50	1.64
	8	9	8780	883	9	199.84	0.92
	9	29	10121	523	29	197.40	1.20

Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.

is not quite at the maximum possible, but with climate change, the straight-line relationship starts to curve off to a maximum grain yield and indicates no further response to rainfall (Fig. 3.11).

The data suggest that the effects of water deficit by 2055 are significant in the case of grain production in spring barley. Water deficit effects appeared to operate where precipitation was less than 400 mm, and the majority of sites were affected to some extent. At the most affected sites, grain yield was reduced to about 4.5 t ha^{-1} (at 150 mm precipitation) which represents a reduction of about 4.5 t ha^{-1} compared to the general level of yield at 400 mm precipitation during growth. The irrigation required to recover the loss would be about 250 mm. The agro–climatic classes clearly relate well to the production of spring barley. The timing of the harvest is important when considering the impact of the relatively sudden onset of winter rain with change in climate; when the harvest is earlier relative to the onset of winter rain there will be less risk to the farmer of not being able to harvest crops.



[Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.]

Figure 3.11. Relationship between spring barley grain yield and rainfall during crop growth. It can be seen that by 2075 the yield reaches a maximum controlled by a different limiting factor.

It can be concluded that:

- barley remains a viable crop in yield terms with the predicted climate change
- the impact of the change in winter and autumn precipitation on harvesting will not be a major problem due to the harvest becoming earlier in the year
- spring barley yield is most closely linked to precipitation
- barley will remain an option as a forage crop.

Maize

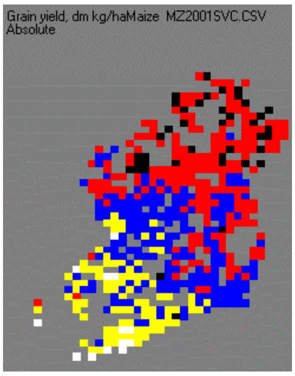
With the baseline climate maize biomass production is greatest in the south-west where production is more than 25% greater than the baseline estimate of national mean (6.4 t ha^{-1}). This biomass is substantially lower than the values reported in Table 3.12 (10–12 t ha^{-1}) but it must be remembered that the data presented there are only for sites thought to be suitable, while the national mean reported here is for all possible locations. In most western areas, the biomass yield is at least 5% greater than the baseline national mean and yields improve towards the west. Elsewhere, yield is generally within ±5% of the mean but the dry areas of the east and south-east coasts appear to be an influence. In 2055 and 2075, biomass yields are expected to increase substantially – in 2055, yields in western areas are expected to be more then 70% greater than the baseline national mean. In the north, biomass yield is expected to be about 40% greater than the baseline national mean. In the south-east, yields may be about 25% greater. Further increases are expected to 2075. The pattern of geographical distribution of yield is expected to reflect the changed rainfall patterns. The dry south and south-east depress the yields in 2055 and by 2075 grain yields are noticeably decreased in the south-east, probably due to summer water stress, compared to the rest of the country (but they are still substantially greater than baseline yields).

In 2055 and 2075, the smallest increases are expected in the south-east, in an area roughly corresponding to the area of greatest drought effect in permanent pasture. The climate change effects on maize grain yield follow essentially the same pattern (Fig. 3.12); however, relatively speaking, the increases are greater. The increases in yield are expected to be more than 150% greater than the present national mean in the west, and about a 75% increase elsewhere in 2055. By 2075, these responses are expected to extend significantly over the country.

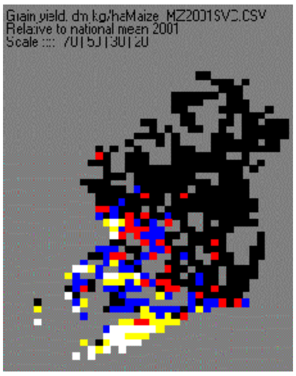
The greater increases in grain yield compared to the increases in biomass (the ratio almost doubles) are expected to result in a significant improvement in the grain content of the harvested crop. At present, grain yield displays an approximately normal distribution around 1.2 t ha^{-1}. Few locations have a more than 35% greater yield, and a relatively high proportion have 25% or less than average yield. In 2055, in contrast, it is expected that, at the majority of sites, grain content will be at least 50% more than the baseline levels, and few sites will have less than baseline national estimated averages (Fig. 3.13). By 2075, it is predicted that most sites will yield around 5.5 t ha^{-1} of grain which would be a viable commercial crop for farmers as high-energy forage.

The harvest date suggests a tendency to become about a week later in 2055 and 2075 (Table 3.14) which has implications with respect to the change to winter rainfall because the harvest date becomes very close to the predicted timing of the winter rainfall occurrence which may increase the risk of the farmer losing the crop. The relationship between grain yield and agro–climatic class (Table 3.14) reveals that warmer sites have higher yields and there is also an increased yield where there is more rainfall.

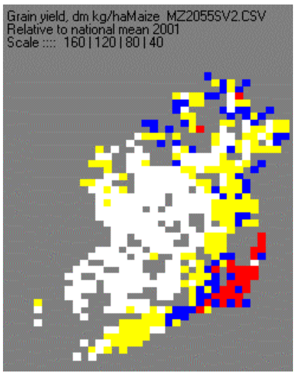
There is a changing relationship between agro–climatic class and the pattern of harvest yield and rainfall during crop growth. While there is clearly a rainfall effect, it appears to be moderated by a drought effect in some locations (Fig. 3.14, 2055, Class 6 is clearly split into two sections). It is assumed that the impact is a soil effect causing drought stress due to a lack in water-holding capacity (a further discussion of this point is presented later). With climate change in 2055, maize appears likely to be less affected by precipitation then the other crops. Grain yield may be reduced at sites where precipitation is less than about 400 mm in the growing season. Thus, only a relatively small proportion of the sites is expected to be



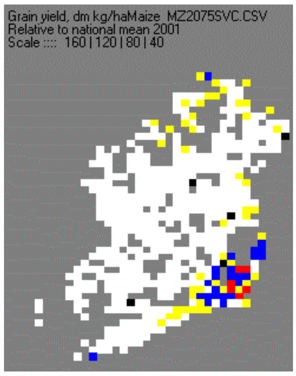
Baseline – absolute



Baseline – relative



2055 – relative



2075 – relative

[Note: 2001 is only a coding for baseline climate data and output files].

Figure 3.12. Maize grain yield in Ireland under baseline climate, and its relative change under 2055 and 2075 scenarios. In the relative grain yield maps compared to the baseline national mean yield (1.636 t ha^{-1} dm), black: <40%; red: 40–80%; blue: 80–120%; yellow 120–160% and white >160%.

Table 3.14. Distribution of maize harvest weights and harvest day by agro–climatic class (Fig. 3.5) and the impact of climate change.

	Class	Harvest weight			Day of harvest		
		N	**Mean**	**S.D.**	**N**	**Mean**	**S.D.**
Baseline	**1**	2	1114.0	251.7	2	283.5	7.78
	2	141	1392.1	352.6	141	280.5	4.18
	3	49	1839.9	322.6	49	286.9	4.34
	4	49	756.2	297.9	49	284.1	6.74
	5	151	1469.8	468.0	151	281.3	4.70
	6	106	2355.2	438.2	106	285.3	4.33
	8	9	1285.1	363.0	9	282.7	5.68
	9	29	2544.8	569.5	29	289.3	4.03
2055	**1**	2	4178.3	105.4	2	288.6	5.12
	2	142	4227.9	552.7	142	285.6	5.58
	3	49	3319.2	684.4	49	275.4	8.35
	4	49	3704.7	448.6	49	289.1	5.42
	5	152	4421.4	543.6	152	288.2	5.10
	6	107	4585.1	663.7	107	285.6	5.00
	8	9	4309.2	388.7	9	291.5	4.15
	9	29	4712.3	490.2	29	291.6	4.08
2075	**1**	2	4886.4	334.4	2	284.6	6.55
	2	142	4857.8	876.1	142	279.5	15.55
	3	49	3854.8	938.9	49	267.0	15.84
	4	49	4573.5	458.9	49	290.1	4.39
	5	152	5045.3	500.2	152	283.7	6.65
	6	107	5105.6	765.2	107	278.3	12.08
	8	9	4896.8	391.5	9	289.3	2.15
	9	29	5215.9	425.1	29	284.5	4.81

Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.

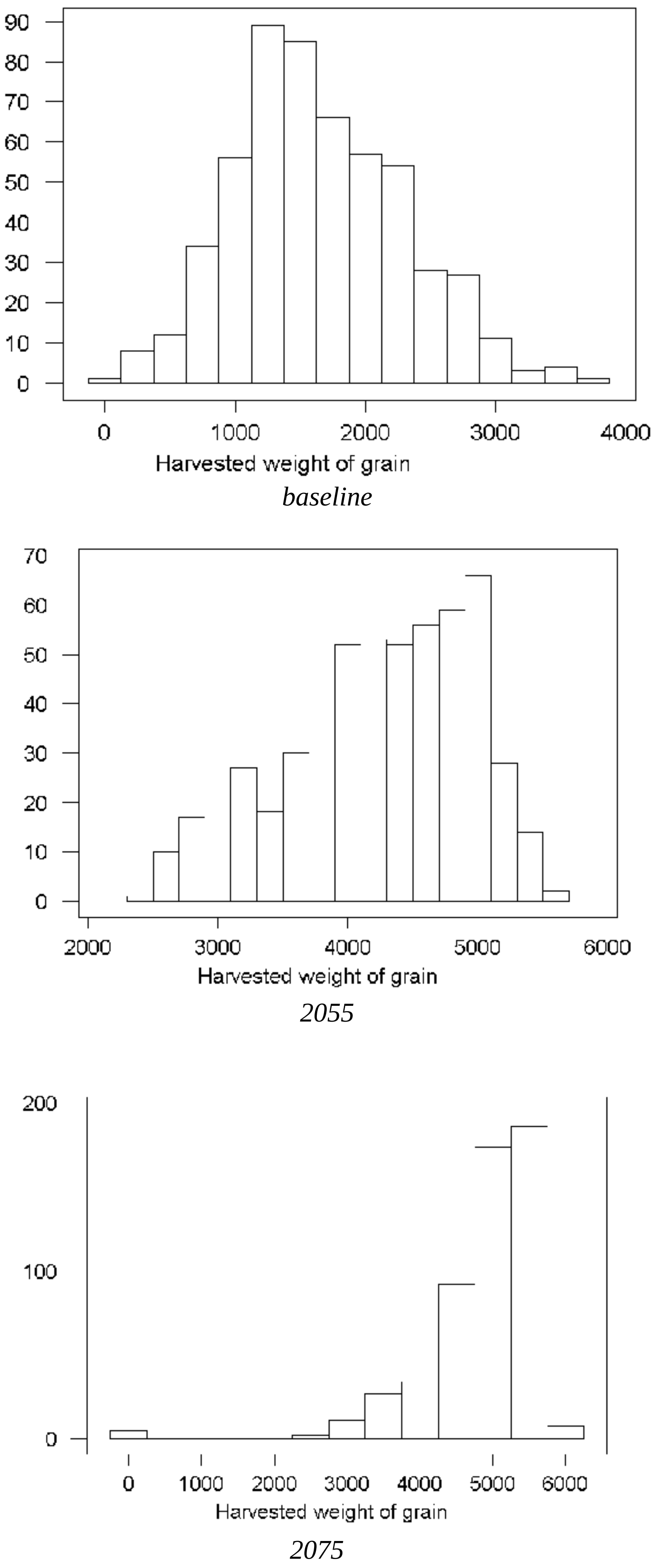
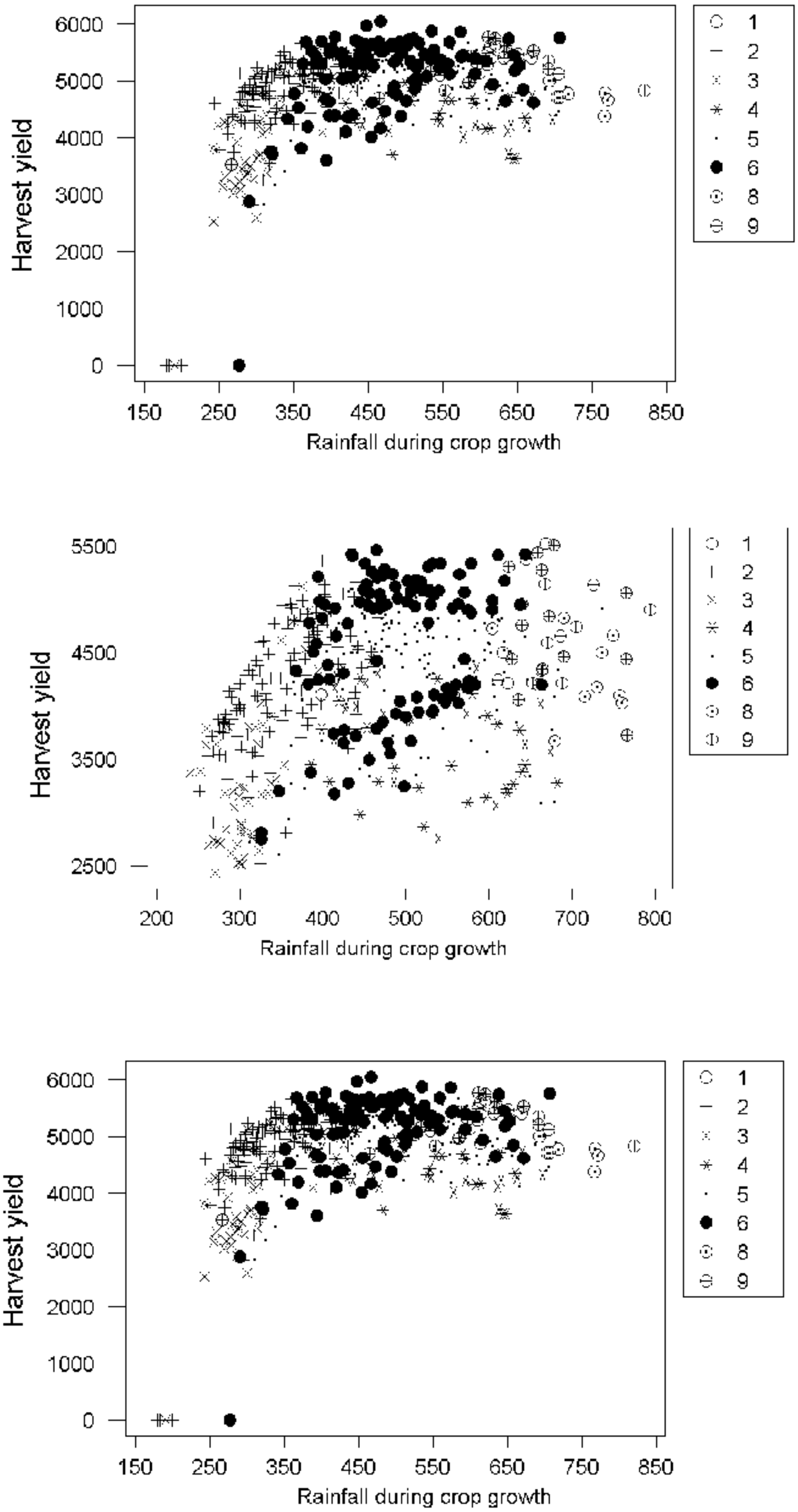


Figure 3.13. The frequency distribution of maize grain yield with change in climate.



[Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north west of the country.]

Figure 3.14. Relationship between maize grain yield and rainfall during crop growth. It can be seen that by 2075, rainfall is not the growth-limiting factor.

affected. Grain yield varies between 3 and 5 t ha^{-1} where expected precipitation is greater than 400 mm. At about 250 mm rainfall during growth, grain yield varies between 2.5 and 3.5 t ha^{-1}. The comparison indicates that in the drier areas a response of more than 1 t ha^{-1} may be expected from the application of about 150 mm irrigation.

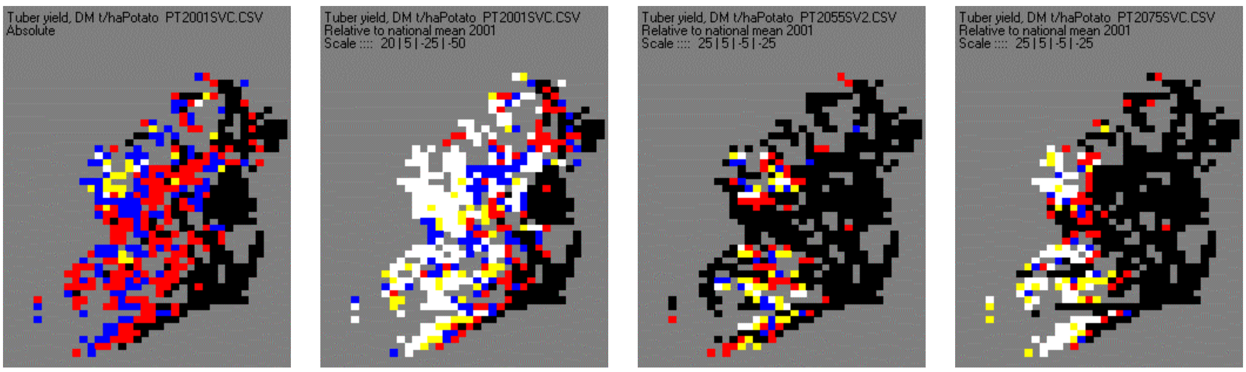
It can be concluded that:

- the performance of maize as a grain-yielding crop significantly increases with climate change
- maize becomes a very valuable crop suitable for high energy forage
- maize starts to show indications of summer water stress but will still yield a significant grain output
- with climate change, grain production increases drastically making maize more valuable than it is currently.

Potato

The geographical distribution of baseline tuber yield of non-irrigated maincrop potato reflects the high sensitivity of the crop to water deficiency (Fig. 3.15) but the estimated national average yield is still very close to that expected, based on the findings of Hough (1990). In the humid western areas, the estimated non-irrigated tuber yields vary between 25 and 50 t ha^{-1} (fresh weight *ca* 23% dm). Biomass yields are currently highest in the west, and are likely to remain that way. In the lower rainfall areas of the east, non-irrigated yields are estimated at less than 15 t ha^{-1} (fresh weight). Tuber production closely follows total biomass, being about 86% of total biomass, and this ratio remains fairly constant even with climate change. In 2055 and 2075, with the expected fall in summer and autumn rainfall, yields of non-irrigated tubers are expected to decrease further. The impact can only be regarded as a significant, almost catastrophic, loss of yield over most of the country by 2055 with a slight yield recovery by 2075. In the west, in 2075, baseline production levels are expected to be maintained. This impact is seen because the simulation was for non-irrigated potato.

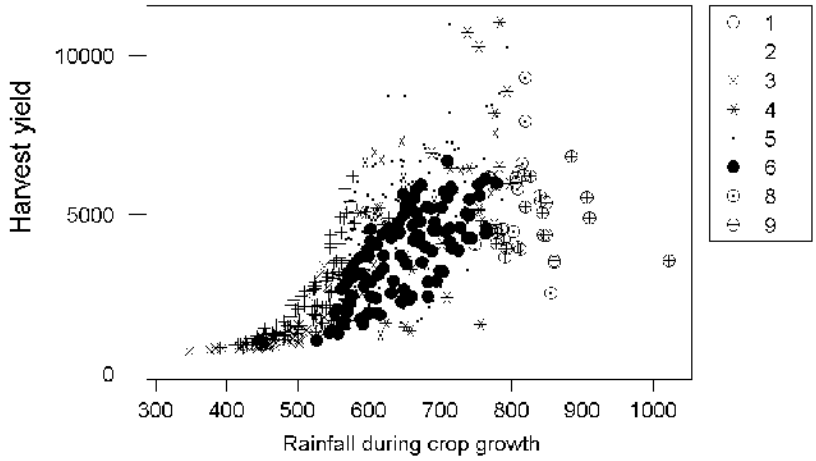
The impact of rainfall during the growing season can be seen in Fig. 3.16 where the low rainfall agro–climatic classes have markedly lower yields than those classified as high rainfall under the baseline climate, and the impact of water stress moves to those classes currently defined as average to high rainfall. Potato tuber yield is particularly sensitive to water deficit and this appears to be reflected in the data. All sites were affected in 2055 but it is not possible to estimate the full scale of the effect. With irrigation, 12 t ha^{-1} (tuber dry weight) would be a normal yield for the baseline climate. The data for 2055 then suggest that at 800 mm precipitation during growth, tuber yields of 6 t ha^{-1} were only 50% of the potential yield. At



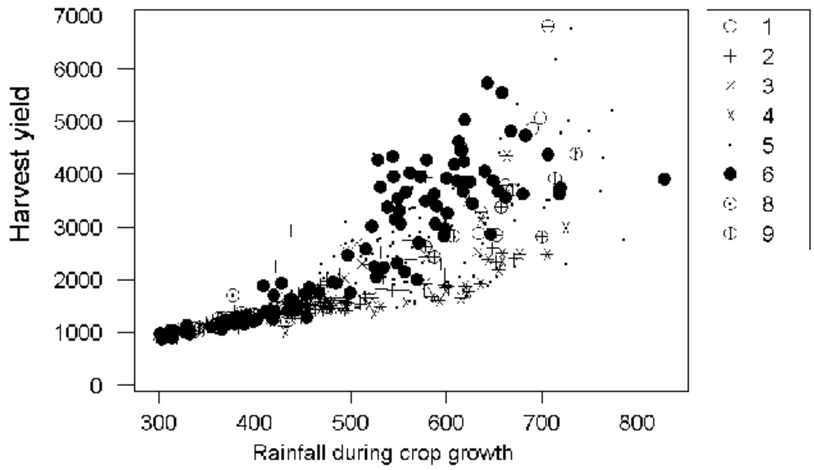
Baseline – absolute | *Baseline – relative* | *2055 – relative* | *2075 – relative*

[Note: 2001 is only a coding for baseline climate data and output files.]

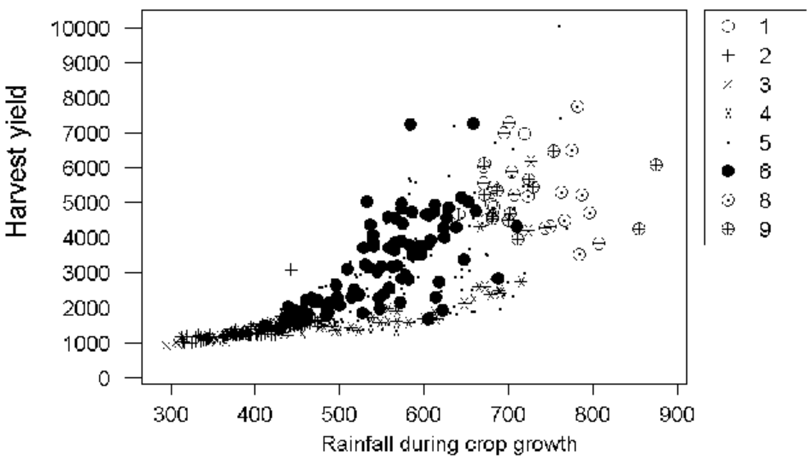
Figure 3.15. Potato tuber yield in Ireland under the baseline climate, and its relative change under 2055 and 2075 scenarios. For the relative yield maps compared to baseline national mean yield (35.9 t ha^{-1} dm), black: > –25%; red: –25 to –5%; blue: –5 to 5%; yellow 5 to 25% and white >25%.



baseline



2055



2075

[Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.]

Figure 3.16. Relationship between potato tuber yield and rainfall during crop growth. It can be seen that by 2075, the yield reaches a maximum control by a different limiting factor.

the extreme, 300 mm of rainfall during growth resulted in negligible tuber yields. The data indicate that the irrigation requirement of the potato crop in 2055 would be very substantial. The distribution of yield with agro–climatic class clearly supports this finding (Table 3.15) where, by 2075, only the very wettest areas can support a reliable non-irrigated potato crop which indicates that the impact of increased seasonality in precipitation will be very important in the future.

Table 3.15. The distribution of tuber yield with agro–climatic class (Fig. 3.5), and the impact of climate change.

	Class	N	Mean	S.D.
Baseline	**1**	2	3820	2024
	2	142	2178	1241
	3	49	1219	576
	4	49	5155	2335
	5	152	4685	1904
	6	107	3746	1339
	8	9	5950	2004
	9	29	4869	989
2055	**1**	2	1460.0	58.1
	2	131	1515.9	443.5
	3	47	1380.2	412.1
	4	49	1789.0	652.5
	5	148	2441.4	1113.6
	6	93	2731.8	1290.7
	8	9	1210	231
	9	28	2689.7	1530.1
2075	**1**	2	1381	132
	2	129	1354	250
	3	45	1269	200
	4	49	1992	976
	5	147	2854	1484
	6	86	3218	1279
	8	9	5243	1235
	9	27	5303	945

Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.

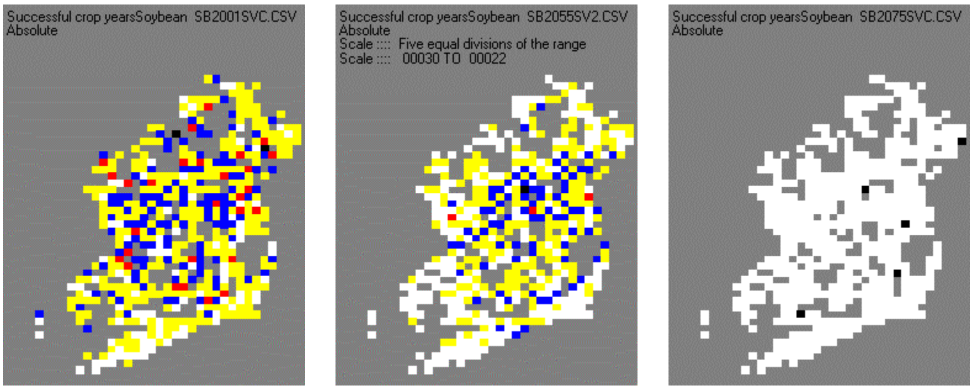
It can be concluded that:

- potato will be a difficult crop to grow with climate change because of water stress in the summer
- it is necessary to investigate how much impact an irrigation system would have on yields
- viability as a commercial crop may be maintained with irrigation, but this would require water storage from the increased rainfall in winter to survive the drier summer
- it is very likely that potato will cease to be a commercially productive crop in Ireland because of (i) the reduced yield due to drought stress, (ii) difficulties with harvest due to the onset of winter rain in October, (iii) difficulties with tillage and planting due to very wet soils in spring, and (iv) a possible increase in pest and disease problems.

Soybean

Under baseline climate conditions, the establishment (Fig. 3.17) and successful seed production (Fig. 3.18) of soybean is significantly affected by low temperatures early and late in the growth of the crop. Under baseline conditions, soybean will establish about 85% of the time resulting in a successful seed harvest, and provide about 25% seed as a proportion of total biomass (nationally). In many locations, principally coastal, the crop successfully produced seed regularly but in inland areas there were more failures. In 2055, with the expected increase in temperature, fewer failures are expected (94% establishment, 40% seed as a proportion of biomass) and, in 2075, the establishment rate remains at nearly 94%, but the seed proportion of the biomass rises to 41%.

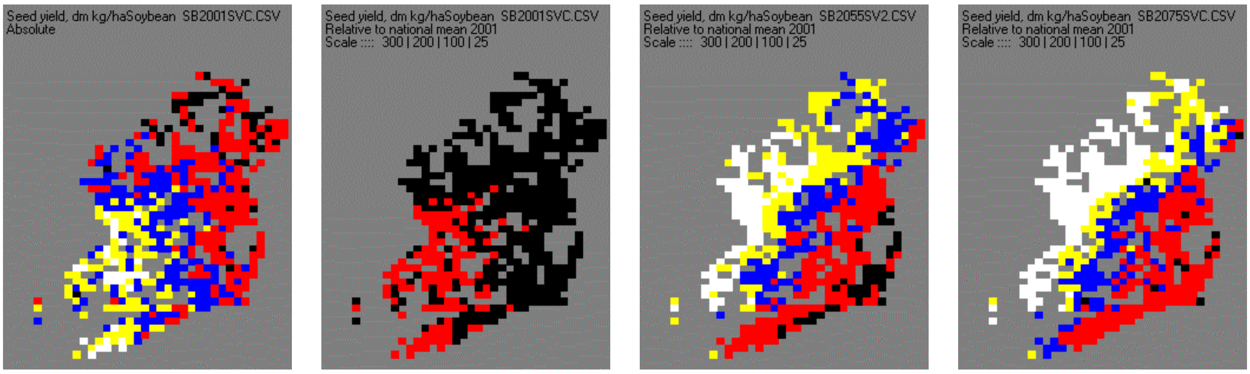
At present the estimated seed yield potential varies from a maximum of 0.7 t ha^{-1} in the south-west to only about 0.2 t ha^{-1} in the north and east with a national mean value of about 0.38 t ha^{-1}. In 2055 and 2075, the seed yield is expected to increase significantly and its geographical distribution is expected to change significantly. This would reflect the effects of reduced rainfall in the east and south-east where low yields of 0.6 t ha^{-1} will remain common but maximum yields will rise to 2.1, then 2.3 t ha^{-1}. In general, however, seed yields in the west and north-west are expected to increase to at least four times



Baseline – absolute *2055 – absolute* *2075 – absolute*

[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.17. Soybean establishment in Ireland under baseline climate (mean value is 8.5/10 years it is grown), and its change with change in climate (2055: 9.4/10 years; 2075: 9.3/10 years).



Baseline – absolute *Baseline – relative* *2055 – relative* *2075 – relative*

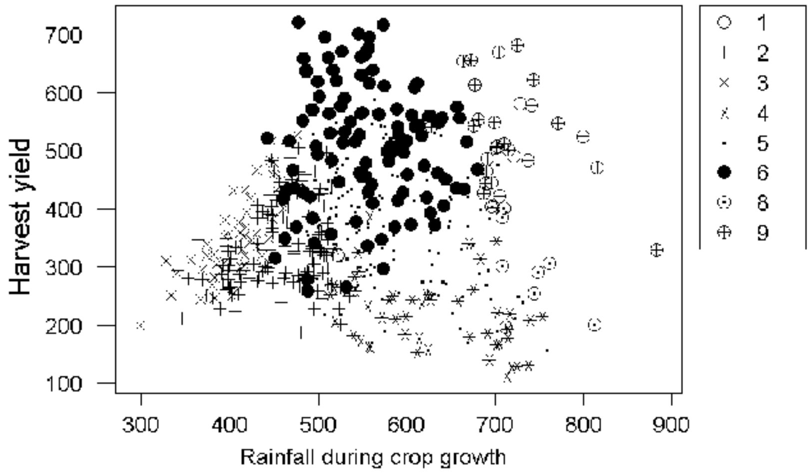
[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.18. Soybean seed yield in Ireland under baseline climate, and its relative change under 2055 and 2075 scenarios. For the relative yield maps compared to the baseline national mean yield (0.38 t ha^{-1} dm)– black: <25%; red: 25–100%; blue: 100–200%; yellow 200–300% and white >300%.

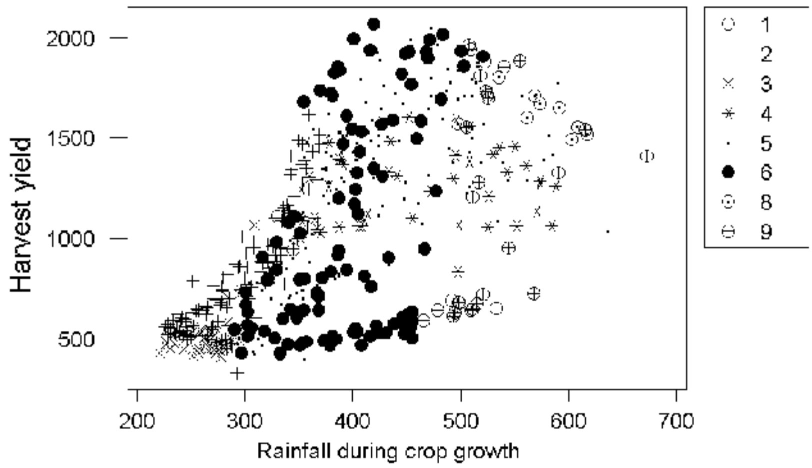
the present national mean yield to about 1.6 t ha^{-1} (Fig. 3.18). These results suggest that soybean may have the potential to reach economic levels of seed development, but that its actual value to the farmer will depend on the wider economic picture in Europe and worldwide.

It is possible in southern areas of Europe where soybean is grown that heat and water stress will make a potential Irish crop more valuable, thus lower yields may be economically acceptable. A further consideration is the possibility of plant breeders developing a variety more suitable for Irish conditions.

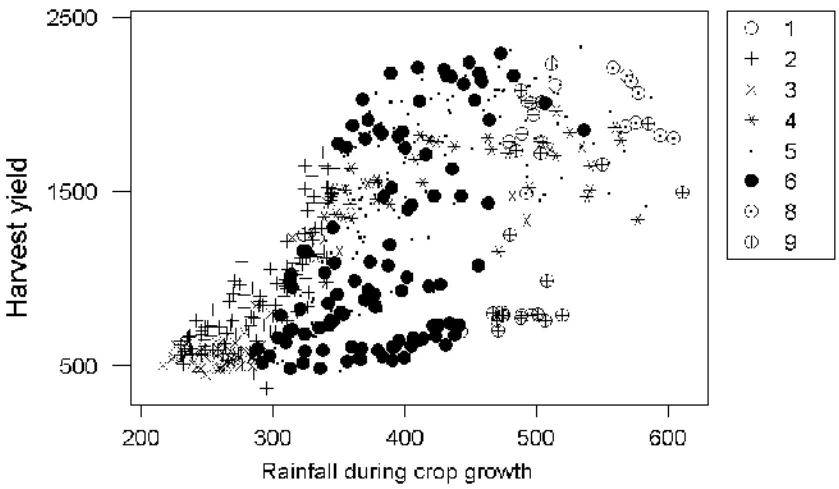
Looking at the difference between agro–climatic classes and the relationship between rainfall during crop growth and harvest yield (seed) (Fig. 3.19), there is a clear temperature and rainfall interaction. Classes 6 and 9 have similar yield levels that are greater than Class 3, which indicates that water stress suppressed yield in the warm, low-rainfall areas. Classes 2, 4 and 8 all show depressed yields, which suggests a relationship with temperature, i.e. average and cool sites are currently not adequate for



baseline



2055



2075

[Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.]

Figure 3.19. Relationship between soybean seed yield and rainfall during crop growth.

seed development. In 2055, the effect of water stress becomes very clear. Class 6 sites still support high yields but there is a clear division in the class that suggests that soil water storage and supply to the plant during dry spells is a limiting factor. The relatively poor performance of the crop at Class 2 and Class 3 sites (low rainfall) clearly illustrates that with elevated temperature, rainfall becomes the limiting factor. Classes 4 and 8 become good yielding sites due to their relatively high rainfall. In 2075, the picture remains the same. In soybean the critical precipitation was again approximately 400 mm. Where precipitation was greater then 400 mm, the seed yield varied very widely. The variation was more than in maize or barley indicating large effects of other factors. The data indicate that seed yield was reduced generally by about 1 t ha^{-1} where precipitation was reduced to 200 mm. Given that Ireland is not, and does not become an ideal location for soybean, it is difficult to assess the potential gain of irrigation.

The relationship between soybean yield, temperature and rainfall is outlined in Table 3.16. In the baseline climate, the warmer sites provide the highest yield because the plant is temperature limited, but with the change in climate the wetter sites provide the highest yields when the plant becomes water stress limited. The day of harvest

Table 3.16. Distribution of harvest weights and day by agro–climatic class (Fig. 3.5), and the impact of climate change.

	Class	Harvest weight			Day of harvest		
		N	Mean	S.D.	N	Mean	S.D.
Baseline	**1**	2	291.34	41.94	2	282.99	5.29
	2	142	332.90	72.21	142	281.05	2.83
	3	49	354.45	76.61	49	276.63	1.88
	4	49	222.15	62.71	49	286.45	4.08
	5	152	386.47	99.71	152	281.65	3.77
	6	107	509.08	107.50	107	276.63	2.27
	8	9	304.60	79.64	9	282.73	2.44
	9	29	524.71	85.28	29	277.84	2.17
2055	**1**	2	1025.3	114.6	2	266.17	4.84
	2	142	815.9	293.1	142	262.38	2.63
	3	49	511.6	107.3	49	258.05	1.77
	4	49	1253.7	192.8	49	270.58	3.41
	5	152	1284.5	411.9	152	264.19	4.06
	6	107	1023.8	531.2	107	259.65	2.32
	8	9	1619.5	99.6	9	266.33	1.81
	9	29	1183.1	528.9	29	262.38	1.54
2075	**1**	2	1243.5	13.5	2	260.20	2.55
	2	139	919.1	340.5	140	256.95	15.99
	3	48	578.7	122.3	49	250.05	27.09
	4	49	1549.5	216.6	49	265.74	3.29
	5	152	1485.3	510.1	152	260.05	4.31
	6	106	1148.9	573.0	107	253.95	16.64
	8	9	1941.7	228.5	9	262.60	2.41
	9	29	1338.8	571.8	29	257.25	1.27

Note that there are no Class 7 sites included because this agro–climatic class corresponds to the geographical distribution of peat soil and high ground (>150 m) in the north-west of the country.

(Table 3.16) becomes earlier with the change in climate, ensuring that risk of winter precipitation influencing harvest operations is minimal. By 2075, the day of harvest is simulated as being nearly 3 weeks earlier than for the baseline climate.

It can be concluded that:

- soybean remains a marginal crop even given a change in climate
- soybean will replace maize which is currently marginal but becomes viable
- soybean remains temperature limited but may also become rainfall limited.

Grass

The present geographical distribution of permanent pasture production displays a south-west to north-east trend in all seasons (Fig. 3.20). In the extreme south-west, annual yield is about 16 t ha^{-1} and falls progressively to about 11 t ha^{-1} in the extreme north. A diagonal from Belmullet in the north-west to Wexford in the south-east represents the approximate position of the 13 t ha^{-1} iso-yield line. These data are consistent with measured production (Ryan, 1974) and previous model estimates (Brereton, 1995). In 2055, as a result of the general increase in temperature and the decrease in summer rainfall in the east, the distribution of yield displays a more east–west trend which is clearly visible in the summer and autumn production (Fig. 3.20).

In Mayo, Sligo and Donegal, where the present yield is at or below the national mean, it is expected that by 2055 yields will have increased to between 5 and 25% greater than the present mean. Similarly, the means in mid-Ulster are expected to increase from below the national mean to equal the mean. These changes reflect the general increases in temperature throughout the year. Although the radiation environment in these areas is expected to decrease, the present data indicate that the effect of the higher temperatures outweighs any radiation effect. In east Munster and south Leinster, the effects of decreased precipitation are evidenced by falls in annual yield. The situation in 2075 is basically the same as in 2055. The annual yield of grass is greatest in the warm areas regardless of precipitation (Classes 3, 6 and 9). However, with the onset of climate change there is a tendency for the difference between average and warm sites to be less marked. Similarly, turnout date is closely related to temperature with an earlier turnout in the areas defined as warm (Table 3.17) which corresponds to the south of the country (Fig. 3.21). The area of the country that is suitable for early turnout increases with climate change (which should be beneficial for low-cost livestock production). But the occurrence of heavy rainfall in the winter until March (Fig. 3.8) probably means that the turnout could not happen in practice for many sites due to soil damage risk and flooding.

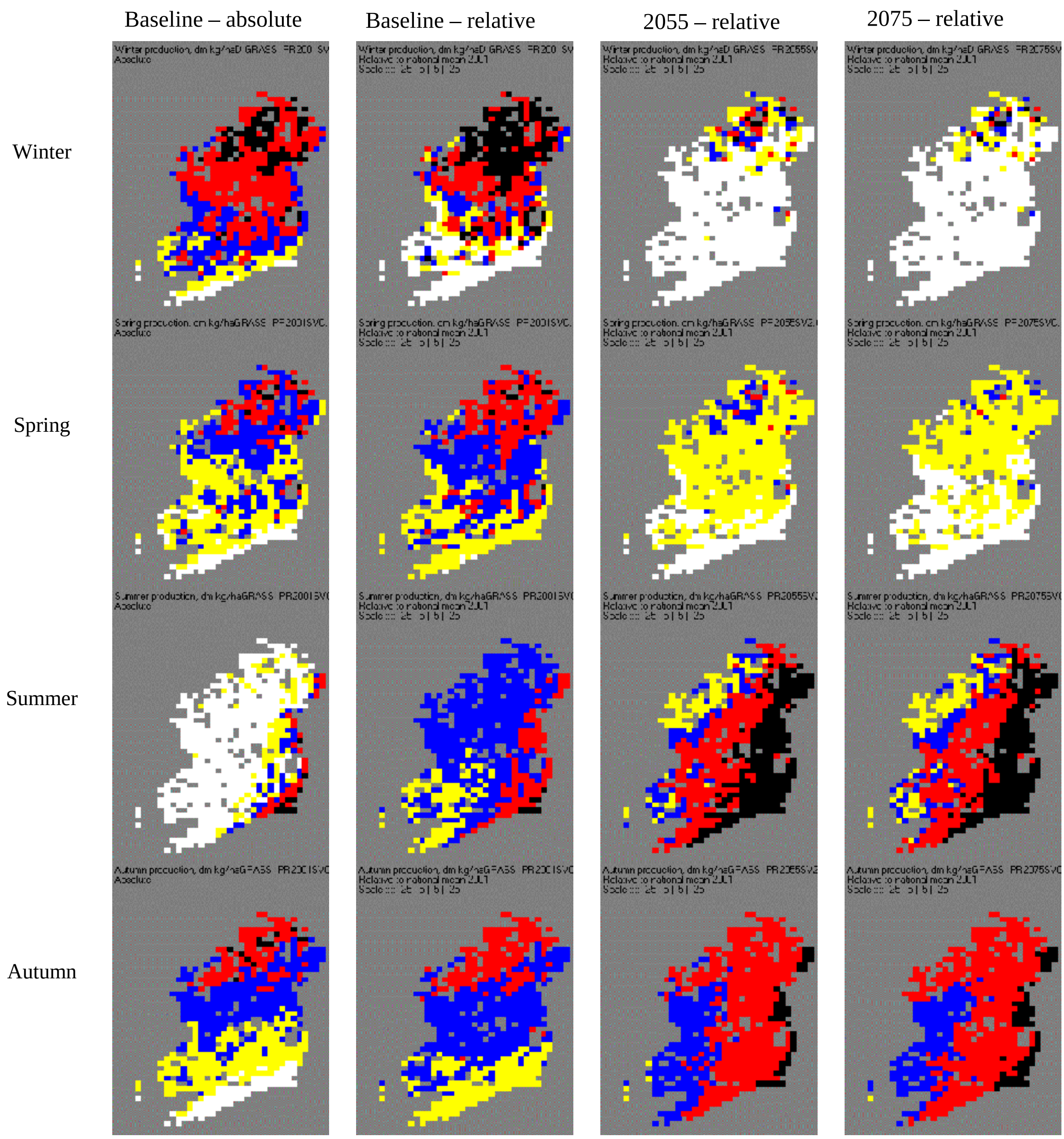
At present, annual losses to summer drought in the south-east reach between 2 and 2.5 t ha^{-1}. Previous estimates of the scale and distribution of these losses were similar (Brereton & Keane, 1982). In 2055 and 2075, the area where drought losses become significant increases substantially, to include the entire east of the country. In this area, drought losses are expected to increase to an average annual loss of more than 2 t ha^{-1} which represents more than 14% of potential annual yield (Fig. 3.22).

It can be concluded that:

- grass may cease to be a viable crop in the south-east and east if it requires irrigation to compensate for loss of biomass due to drought
- turnout date may become earlier in the season, but if rainfall is still at high winter levels stock will have to remain housed.

3.5 The Effect of Soil Type on Crop Yield with Climate Change

The modelling of soil water processes in DSSAT is performed as a simpler expression of knowledge than the modelling of the plant growth (Bouma, 2001). It was considered interesting to evaluate how much impact the soil model aspect of the simulations of crop production had compared to the climate impact. A further issue was to address whether the impact of climate change could be reduced simply to a change in agro–climatology or whether it should be considered in terms of the soil types in Ireland. The inclusion of a soil sub-model in the crop simulations was to objectively incorporate precipitation effects as longer-term interactions with the plant. In other



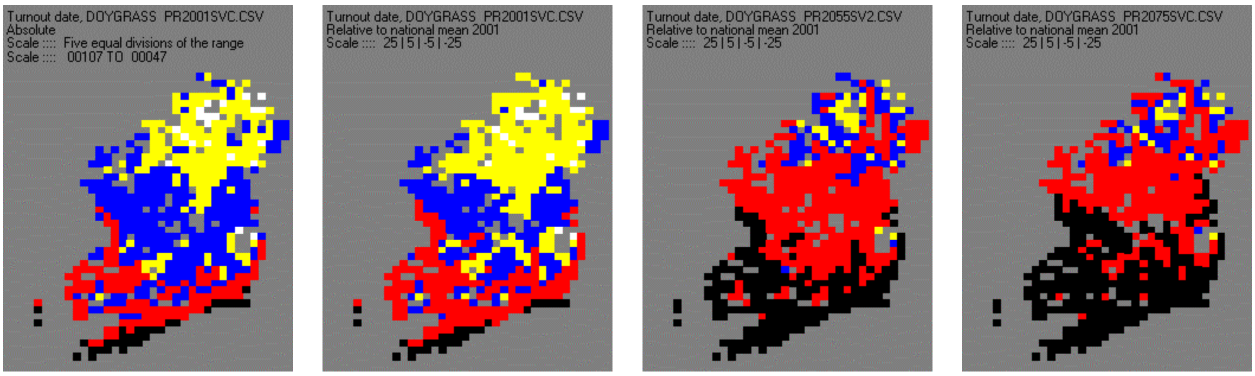
[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.20. Grass yield in Ireland under baseline climate, and its relative change under 2055 and 2075 scenarios. For the relative yield maps compared to baseline national mean yield (winter: 0.52 t ha^{-1} dm; spring: 4.95 t ha^{-1} dm; summer: 4.91 t ha^{-1} dm; autumn: 2.49 t ha^{-1} dm; national mean annual production: 12.88 t ha^{-1} dm), black: <25%; red: 25–100%; blue: 100–200%; yellow 200–300% and white >300%.

words, soil water storage capacity is very important, particularly if summer drought is a possible consequence of climate change. The limitations to crop production arising from accessibility or trafficability problems or water logging were ignored. A comparison of selected yield indicators for cereals revealed that there was relatively little difference between soil types (Table 3.18) in terms of national average production now or in the future. The simulation modelling was repeated for all sites assuming a fixed soil type for the whole country.

Table 3.17. Distribution of annual grass yield and turnout day by agro–climatic class (Fig. 3.5) and the impact of climate change.

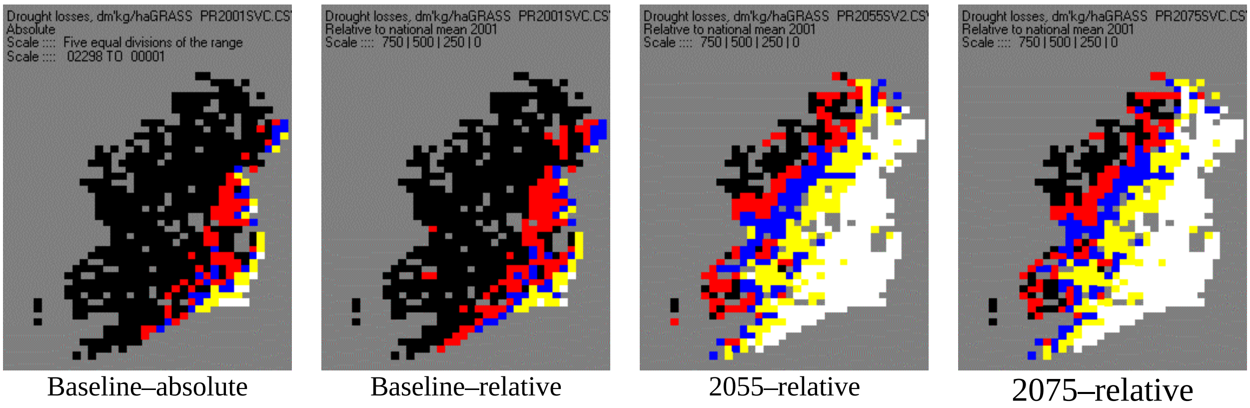
	Class	Annual yield			Turnout day		
		N	Mean	S.D.	N	Mean	S.D.
Baseline	**1**	2	12173	97	2	87.00	0.00
	2	142	12610	336	142	79.03	3.86
	3	49	13126	458	49	65.08	5.66
	4	100	11704	423	100	90.93	3.74
	5	175	12856	383	175	78.73	3.89
	6	107	14035	458	107	64.87	5.86
	7	12	10837	666	12	97.75	6.00
	8	20	12993	321	20	75.60	3.55
	9	31	14335	553	31	60.58	6.57
2055	**1**	2	11731	629	2	72.00	1.414
	2	142	12022	726	142	64.28	4.198
	3	49	12013	724	49	50.51	5.197
	4	100	12407	701	100	76.67	5.005
	5	175	13343	692	175	63.80	5.026
	6	107	13862	589	107	50.73	4.649
	7	12	12561	629	12	84.58	7.937
	8	20	14258	342	20	60.30	3.962
	9	31	14827	392	31	48.36	3.738
2075	**1**	2	12543	494	2	64.5	7.778
	2	142	12871	623	142	62.65	10.580
	3	49	14196	720	49	54.39	8.311
	4	100	12190	872	100	62.11	10.940
	5	175	13009	1099	175	59.73	10.520
	6	107	14268	757	107	55.80	7.921
	7	12	12065	1086	12	60.25	12.490
	8	20	13905	948	20	54.95	8.525
	9	31	14855	435	31	51.16	6.497



Baseline–absolute Baseline–relative 2055–relative 2075–relative

[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.21. The distribution of turnout date for the baseline climates, 2055 and 2075. For the relative turnout date, black represents about 3 weeks before baseline national mean, red represents about 1 week, blue represents about the national mean, yellow 1 week later and white up to 3 weeks later.



[Note: 2001 is only a coding for baseline climate data and output files.]

Figure 3.22. The distribution of grass yield drought loss for the baseline climate, 2055 and 2075. Black: <0%; red: 0–250%; blue: 250–500%; yellow 500–750% and white >750%.

The soil chosen was the Grey Brown Podzolic which is perhaps typified by the Elton series found in north Munster. This is a deep soil with good water holding capacity and was found in crop productivity trials in the late 1960s to be the best performing soil for grass, cereals and root crops. A comparison of the national mean production against that simulated using possibly the best soil revealed that there was very little effect of soil type at a national scale (Table 3.19).

It was assumed when looking at the relationship between rainfall during crop growth and harvest yield (Figs 3.11, 3.14, 3.16 and 3.19) that the range of values found for a given agro–climatic class was related to soil type or some other variable. A closer examination of soybean and maize yield data which has an obvious split in Class 6 yields (Fig. 3.14), revealed that the results were only partially related to soil type (Fig. 3.23). For soybean, the Podzol and Acid Brown Earth soil had low yields while the Brown Earth in the west of Ireland had the highest yields. This is somewhat misleading because there are no sites where a Brown Earth soil has relatively low rainfall during crop growth.

An examination of maize grain yield at Class 6 sites revealed that the Grey Brown Podzolic soil was able to sustain high yields with relatively low rainfall input while this was not the case for the Acid Brown Earth. The podzol soil clearly cannot support a high crop yield. A similar analysis of Class 5 (average temperature, average rainfall) showed that other processes were also influencing yield (Fig. 3.23). The range of yields found with rainfall on the Grey Brown Podzolic soil type suggests that another factor must be important. It can be concluded from these data that soil type will be important with respect to plant utilisation of water, particularly where summer water stress becomes significant.

The objectives of this soil effect simulation exercise were to determine if soil impact on crop primary production was significant when compared to the meteorological impact and to determine if the soil impact was modified by climate change. While it is clear that soil has a significant moderating effect on the meteorological impact, it proved impossible to abstract the soil effect with respect to climate change. This was because of variation in the values of the meteorological input data between simulations, i.e. the stochastic nature of the daily weather generation used to drive the models from monthly mean data. The Simmeteo weather generator does not generate exactly the same sequence of daily data over the 30 years of each simulation (fixed soil type/ variable soil type). The same random number seed was used for each 30-year simulation, and although this ensured a repeat of the same sequence of weather element values in single-year experiments, it did not give a constant sequence for 30 years. The effects of these variations in the generated daily weather between the 30-year simulations on the crop outputs were not great but

Table 3.18. Variation in cereal yield indicators by soil type as produced by modelling using DSSAT and a simplified description of the soils of Ireland (Fig. 3.9).

	Maize grain		Barley grain		Barley biomass	
	Baseline	**2075**	**Baseline**	**2075**	**Baseline**	**2075**
Brown Earth	2130	5381	6825	7463	10006	12893
Podzol	2003	4711	6661	8660	11284	13757
Grey Brown Podzolic	1733	5042	5616	7099	9807	12280
Acid Brown Earth	1446	4293	5597	8770	10687	13436
Gley	1266	4773	6364	8365	10493	13224
COV%	21.2	8.3	10.4	9.3	5.6	4.3
Range	864	1088	1228	1671	1477	1477

Table 3.19. The deviation in national production under baseline and 2075 climates, as indicated by barley grain, maize grain, potato tubers, soybean seed and annual grass production as compared to an 'ideal' soil.

	Barley grain	Maize grain	Potato	Soybean seed	Grass
Baseline	+0.34	–0.12	+0.6	+0.06	+0.03
2075	–0.35	+0.06	+0.3	–0.07	+0.05

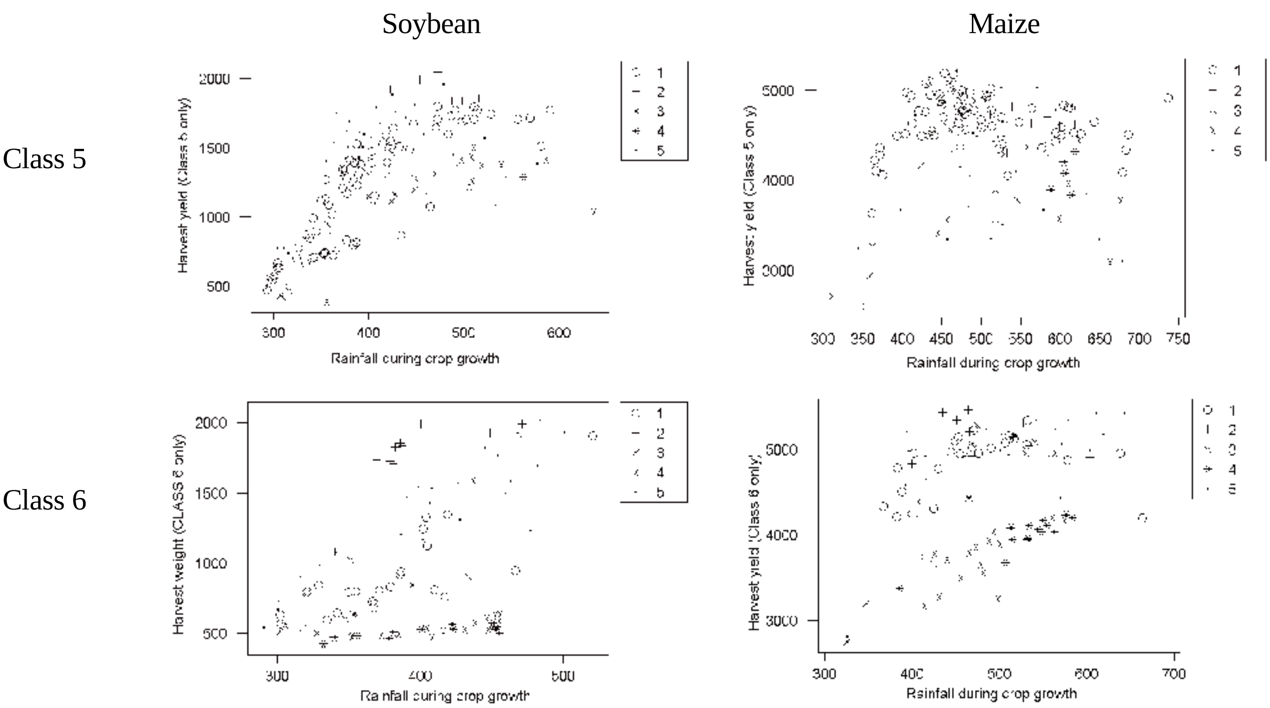


Figure 3.23. The relationship between rainfall during crop growth and harvest yield for agro–climatic Classes 5 and 6 for soybean seed and maize grain. 1, Grey Brown Podzolic; 2, Brown Earth; 3, Acid Brown Earth; 4, Podzol; and 5, Gley. It should be noted that these are descriptions of convenience related to approximate distributions throughout the country and are not related to any particular real soil at any given location in Ireland.

they were sufficient to obscure any soil effects on the production estimates (Table 3.19). This indicated that the soil effects were small relative to the weather effects on production. Comparison of the differences in output values for the soil-variable case and the soil-constant case for barley and maize illustrate the relatively minor scale of the effects of the variations in weather input (Fig. 3.24).

The differences for the majority of sites were close to the means, but crop responses to environmental variation are not linear and very large differences did occur when the site soil was replaced by the Grey Brown Podzolic type. The difficulty of abstracting soil effects was compounded by the fact that although some of the soil groups are widely distributed geographically (Group 1, the Grey Brown Podzolics for example) others were not (e.g. Group 2, the Brown Earths). Apart from the crop yield data, the comparison shows consistently in all four data sets that when poorly drained Podzols (Group 4) and Gleys (Group 5) (note that the pedological implication of these soil class names should not be thought of as exact with respect to the simulation modelling) were replaced by the better-drained Grey Brown Podzolic (Group 1), runoff was decreased and drainage was increased. This was not an unexpected result. These responses to the soil change were not affected by climate change.

3.6 Discussion on the Implications of Change in Yield of Irish Crops

The simulation results show that the expected climate changes will have a major impact on Irish agriculture by the year 2055. Further changes up to 2075 are expected to be relatively slight compared to the impact over the next 50 years. The impact of the climate change on Irish agriculture has been assessed in terms of primary crop production. However, it is clear from the nature of the impacts determined that the operation of whole farm systems will be affected. Although the expected impacts are significant, they cannot be regarded as potentially catastrophic.

Livestock production is the main farming enterprise in Ireland at present and the data do not suggest that this will cease to be the case. Livestock production systems are closely tied to the seasonal pattern of grass production and relatively little supplementation with purchased feed is required. The expectation of summer drought over a much greater area than at present may be expected to introduce the need for significant supplementation of

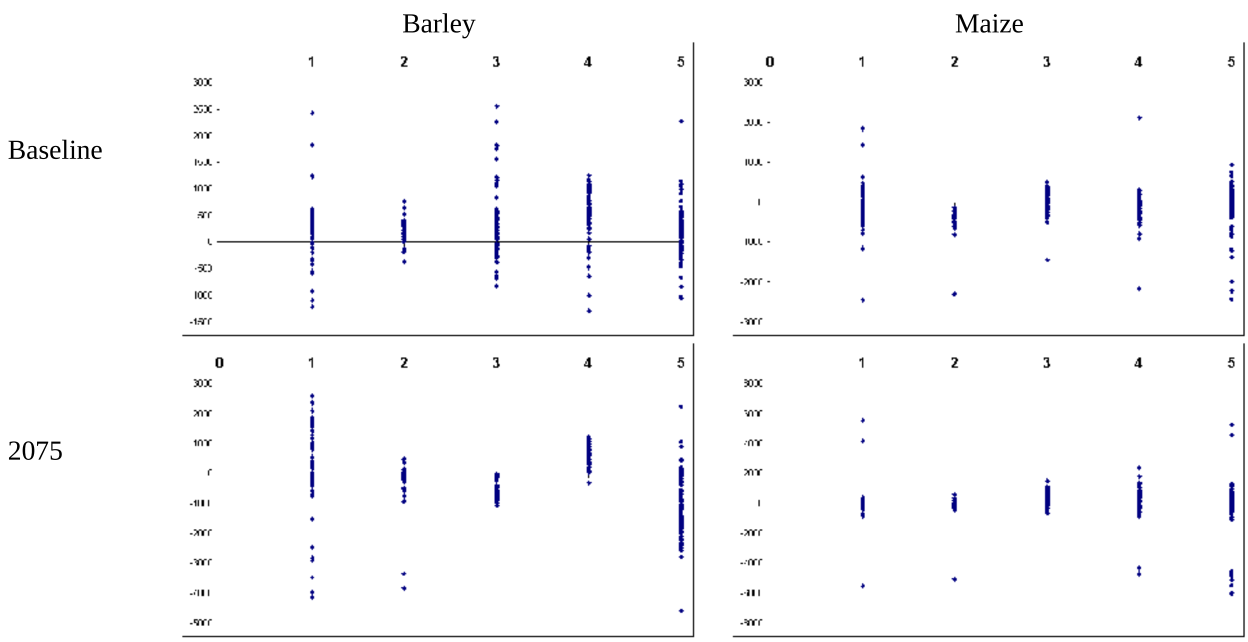


Figure 3.24. Difference in yield achieved at each site for the five soil types compared with using a constant Grey Brown Podzolic soil type for the whole country. No systematic soil effect is seen which suggests that the impact of soil is significantly less than the impact of the daily weather data generation from the climatic values.

grazed grass. At the same time, a very substantial increase in production of maize is expected. The very significant increase in grain percentage and the elimination of the risk of crop failure that currently limits the geographical distribution of maize may be expected to allow livestock systems to be less rigidly geared to the grass crop. This would become possible because maize silage may replace grass silage so that, on farms, the land currently reserved for grass silage production would become available for grazing. Barley is another potentially important source of energy for supplemental feeding of livestock. The expected increases in cereal grain production may be expected to reduce the cost of feed barley. However, the extra costs associated with irrigation may offset this if it proves necessary, thereby bringing the economic viability into question, especially if barley is in competition with maize as a forage crop.

Protein supplementation is an important feature in livestock production systems. Soybean is an important source of this protein and is currently imported into Ireland. At present, a seed yield of 2.5–3.0 t ha^{-1} is sufficient to make the crop viable commercially in other parts of Europe. The simulated results for 2055 indicate that soybean seed yields approach these levels in some areas which suggest that soybean has the potential to replace maize as the marginal crop in Irish agriculture. The increase in recent years in the cultivation of maize in Ireland was made possible at least partly by the introduction of new short-season varieties. In recent years, a major breeding programme for soybean has succeeded in extending the geographical range of this crop northwards and it is now well established in the north of Italy. The present results show that these northern varieties would produce significant seed in the expected climate of 2055. It is not unreasonable to suggest that further developments may occur in soybean. The issue of plant breeding is of significance for all the crops considered. There is potential to better utilise enhanced CO_2 concentrations and to optimise for change in climatic characteristics. This may be very important for crops subject to competition from weeds.

The exact impact of the change in seasonality of rainfall is not clear. It is likely that the sudden onset of winter rainfall will require the removal of livestock from all but the most well-drained land, and the high rainfall rates may mean that access is limited until the end of March while the soil dries out. This, therefore, has implications for slurry storage and spreading. Figure 3.8 (monthly rainfall distributions for the nine agro–climatic Classes defined in Fig. 3.5) suggests that winter rainfall starts around October and lasts until March for all the Classes. It appears that for the drier locations (the east of the country and parts of the midlands, Classes 1, 2, and 3) 20 weeks storage will be required (part of October (2), November (4), December (4), January (4), February (4) and part of March (2) – totalling 20 weeks). For the average rainfall (Classes 4, 5 and 6) and high rainfall (Classes 7, 8 and 9) sites, this period may be extended because of the excess rainfall and soil saturation of anything up to 26 weeks. Suggestion of a shorter winter rainfall period (Government of Ireland, 1991) is not supported by these data where February clearly becomes much wetter than under the baseline climate.

The major effects of climate change are due to temperature and precipitation. Not unexpectedly, all crops were affected significantly. Whereas the increase in temperatures raised the potential for production in the existing cereal and grass crops, the achievement of this potential was limited by reduced summer rainfall. In the high water demand crop, potato, potential yields did not appear to be increased, but the effect of water deficit was very significant. The effects might be described as catastrophic but for the fact that the crop is normally irrigated in the present climate. The other major effects were that maize, currently a marginal crop, became established and soybean, which is not grown in Ireland at present, replaced maize as a marginal crop with possible economic potential. The fact that day of harvest appeared to be earlier in the year for most crops means that the risk of harvest loss due to lack of field access or excess water content is somewhat mitigated.

In general, potential production was greater in the more humid western areas where the water deficit was minimal. The assessment of potential depends to a great extent on the changes in production found in the more humid western areas. The estimates of the scale of yield reduction due to water deficit and the amount of irrigation required to overcome these deficits indicate that in the eastern half of the country irrigation will become important for all crops. Although it was not possible to consider the impacts on the operation and economics of production systems (in the more general sense) in any detail, the analysis provides clear indications that irrigation will become important. This will have a major impact on the economics, machinery requirement and labour demand in both tillage and livestock systems. In recent years, it was estimated that irrigation for dairying in the drought-prone south-east is justified economically only if water is available without charge and without the construction of farm reservoirs. With the projected scenarios, a much greater area of agricultural land will be affected by drought loss, and the quantities of water involved to compensate by irrigation will be large. Given that agriculture may have to compete for scarce summer water extraction with other users, the consequent economic effects may make crops with good potential uneconomical. The DSSAT package provides a facility to simulate crops with optimal irrigation, but within the time frame of this project (12 months) it was not possible to use this facility. However, the data have provided a reasonable estimate of expected irrigation need and they clearly highlight the need for further investigation for medium- to long-term rural environmental planning.

At the present time, tillage farming tends to be concentrated in the south and east. Even though the analysis indicates very much greater production potential in western areas than in the east it is unlikely that the distribution of land use will change. The primary reason for the present concentration of tillage in the south and east is more to do with the suitability of soils for tillage – the land quality is better suited to tillage in these areas. The soils generally are better drained and are more easily tilled. It is most likely that grass-based livestock will continue to dominate in western areas but the potential production may be significantly increased.

3.7 Conclusions

The main conclusions of this project are:

1. Major changes in the crops grown and their performance can be expected but there will be no catastrophic effects
2. The distribution of land use will alter. Livestock production will probably dominate more to the west and arable production will dominate east of the Shannon.
3. Maize will become a major crop.
4. Soybean may become a marginal specialist crop.
5. Planning for irrigation is needed to ensure that water costs are acceptable and summer surface and ground water resources are not over used.

Some crop-specific conclusions are:

Spring barley

- remains a viable crop with the predicted climate change
- will remain an option as a forage crop
- yield is most closely linked to precipitation.

Maize

- yield significantly increases with climate change
- becomes a very valuable crop suitable for high energy forage
- may suffer summer water stress but will still yield significant grain contents
- earlier harvests should reduce the risk of harvest loss due to the onset of winter rainfall.

Potato

- will suffer water stress in the summer with climate change
- will have a large irrigation requirement
- viability as a commercial crop may be maintained only with irrigation
- irrigation systems will possibly require investment in infrastructure to store winter rain because of competing demands from ground and surface waters
- it is very likely that potato will cease to be a commercially productive crop in Ireland because of (i) the reduced yield due to drought stress, (ii) difficulties with harvest due to the onset of winter rain in October, (iii) difficulties with tillage and

planting due to very wet soils in spring, and (iv) a possible increase in pest and disease problems.

Soybean

- remains a marginal crop with change in climate but in some areas becomes viable
- remains temperature limited but may also become rainfall limited with climate change.

Grass

- will suffer drought loss over large parts of the south and east of the country with climate change.
- Maize may become a viable forage crop and replace grass silage in livestock systems.
- Grassland livestock production may migrate west in terms of intensity. Total numbers may stay the same but stock per unit area will increase in the west.
- Problems with slurry storage and spreading in the wetter western part of the country may emerge unless it is transported east. This would also move water to drier parts, but possibly not in significant amounts.

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4 The Impact of Climate Change on Water Resources in Ireland

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4.1 Introduction

4.1.1 Water resources in Ireland

In comparison with much of Europe, Ireland is relatively well endowed with water resources, although regional shortages can occur at certain times of the year. The rapid expansion of urban areas, such as Dublin, Cork and Limerick, associated with present economic conditions, is putting an increasing strain on the water supply infrastructure. The increased demand for water comes mainly from the industrial and domestic sectors, with domestic demand increasing both as a result of population growth and rising water consumption per capita. Most of the present water supply in Ireland comes from surface water, with between 20% and 25% coming from groundwater. In some counties, the groundwater proportion is much greater, and in many rural areas with no access to a public or group supply scheme, groundwater from wells provides the only source of water (Daly and Warren, 1998).

Water availability fluctuates through space and over time and is dependent on the balance between precipitation and evapotranspiration. The runoff yield from an area, usually that of a catchment, over a period of time can be calculated using the water balance equation

$$R.O. + P - AET \pm \Delta S \qquad \text{(eqn 4.1)}$$

where *R.O.* is runoff, *P* is precipitation, *AET* is actual evapotranspiration and ΔS is change in storage.

The storage term includes water stored as groundwater, in lakes and reservoirs and soil moisture. The volume of water held in storage fluctuates through time in response to changes in the balance between rainfall inputs and evaporative losses. For instance, over the course of a year the various stores tend to become depleted during the relatively dry summer months and are partly or fully recharged over the wetter winter months.

The available volume and type of storage in a particular catchment is determined by the physical and land-use characteristics of that catchment, with each catchment having a unique response to rainfall inputs. Water takes a number of pathways in travelling to the stream channel from where it falls as rainfall within the catchment. Travel times vary considerably and are dependent on the pathway(s) taken and the overall distance travelled. The rates at which water flows over the surface as overland flow or through the upper layers of the soil as shallow subsurface flow are relatively fast, whereas flow can be orders of magnitude slower in the lower soil and in the saturated zone. However, in aquifers dominated by fissure permeability, especially those that have been karstified, groundwater flow rates can be much higher and under some circumstances may be comparable to those observed in river channels.

The flow in a river can be divided into two components, quick flow and base flow. Many rivers respond rapidly to rainfall inputs. This is because water falling near the channel and that taking the faster flow pathways both reach the channel as quick flow. After the peak flow has occurred in the channel the flow recedes and it is water that has taken the slower pathways that forms the greater proportion of channel flow. Catchment characteristics such as soil permeability, geology and topography all determine the response to precipitation as well as the flow recession characteristics and duration of base flows. The base flow contribution is particularly important in the context of climate change predictions that indicate dryer summers, as the frequency and duration of low flows are likely be greater than at present.

When considering the impacts of climate change it is also important to consider changes within the catchment. Land use and human activity within the catchment can have major impacts on hydrology and response to precipitation, as is the case for urbanisation. As the land surface is covered with impermeable surfaces such as streets and car parks, less water is able to infiltrate, meaning that a greater proportion is contributed to the channel as quick flow. In addition, drains and sewers act as efficient conduits to transfer water to the channel with the result that a greater proportion of flood flow is quick flow, increasing the flood risk as rivers respond more rapidly to rainfall and peak flows are increased.

4.1.2 Observed linkages between climate change and water resources

A number of studies have been carried out to examine the linkages between climate variables, especially circulation types and precipitation, and subsequent runoff. A close correlation was found by Shorthouse and Arnell (1999) who concluded that precipitation and the resultant runoff are strongly correlated with the North Atlantic Oscillation index (NAO). Increased rainfall caused by powerful westerlies (positive NAO) has been observed for northern and western Europe, while at the same time southern and central Europe has experienced drying. The importance of circulation–rainfall relationships has also been stressed by a number of authors for Britain (Hulme and Barrow, 1997; Conway, 1998; Lovelace, 2000) and Ireland (Houghton and O'Cinnéide, 1976; Sweeney, 1985; Sweeney and O'Hare, 1992). Irish studies have found changes in the synoptic patterns of Irish precipitation, identifying a reappearance of westerly circulation frequencies along the northern and western parts of Britain and Ireland during the 1980s and 1990s (Sweeney, 1997). These westerly winds, together with a decrease in easterly anticyclones, are thought to be responsible for the rise of autumn and winter storm events in Dublin in the latter half of the 20th century (Sweeney, 2000). Increases in annual precipitation and streamflow have been observed by Kiely (1999) who tested observations from selected sites for climatic and hydrological change. Streamflow was found to show similar trends to precipitation data with the increase occurring after 1975 and being most noticeable in the west of the island.

Future changes in climate are likely to have major impacts on regional and local runoff patterns. This may influence the annual and seasonal availability of water resources, with significant implications for water resource use, water quality management and strategies and flood/drought hazard indices in Ireland.

4.1.3 Predicting runoff under future climate change scenarios

Although a number of studies have investigated the impact of future predicted climate scenarios on water resources for Britain (Arnell 1992, 1996; Arnell and Reynard, 1993, 1996; Boorman and Sefton, 1997; Pilling and Jones, 1999), little work has so far been carried out for Ireland, with the exception of a study carried out by Cunnane and Regan (1991). Cunnane and Regan investigated the effect of four climate scenarios on the catchment of the River Brosna, a tributary of the Shannon, for the year 2030. The scenarios were produced by modifying the observed precipitation and/or evaporation data. Under these scenarios, precipitation and evaporation were increased on an annual basis, or seasonally on the basis of increased winter and decreased summer precipitation. The results indicated that although the magnitude of high and low flows would be only slightly greater than those observed within the range currently experienced, the frequency of flood and drought events would be likely to increase within that catchment. The authors suggested that similar studies be carried out to examine such changes in the major catchments in Ireland. One of the main aims of the present study is to examine likely spatial patterns of change across Ireland associated with future climate scenarios for different time periods. This will enable identification of those areas where the greatest changes are predicted to occur.

Recent research in Britain has examined the spatial pattern of changing runoff for the whole land area of Britain (Arnell, 1992, 1996; Arnell and Reynard, 1993; Pilling and Jones, 1999). Although the grid squares used do not represent actual catchments, such studies allow changing spatial patterns of annual and seasonal runoff to be considered and provide a valuable starting point for further research focusing on selected catchments. Advances in downscaling techniques have allowed hydrological modelling to be carried out at increasingly higher spatial resolutions, with the 10 × 10 km resolution used by Pilling and Jones (1999) constituting the highest resolution to date. Pilling and Jones used downscaled GCM predictions for 2050 (UKHI) and for 2065 (transient UKTR) to drive a hydrological model and simulate annual and seasonal effective runoff for Britain.

(Effective runoff is the total depth of runoff yielded by an area over a given time period, e.g. annually or seasonally. It is normally expressed as a depth of water in millimetres covering the area under consideration.) Whereas this had previously been carried out using water balance models (Arnell, 1992, 1996; Arnell and Reynard, 1993) Pilling and Jones used a physical process-based hydrological model to simulate runoff, which allowed a more detailed representation of the land surface through the use of physically realistic parameters and processes. The results of these simulations allowed detailed spatial analysis of variations in water resource availability in Britain to be made with one of the main findings being an accentuated north-west to south-east imbalance.

Since there has not been any previous attempt to model runoff for the whole land area of Ireland under future climatic scenarios, the present study is an initial investigation. A grid-based approach, based on that of Pilling and Jones, was adopted. It has been necessary to make some simplifying assumptions, and certain aspects, such as the representation of storage, are somewhat crude. However, in addition to giving a first-pass indication of spatial changes in runoff for Ireland, the study also provides a useful learning experience in the application of various techniques and in assessing the validity of the approaches used.

4.1.4 Research outline

Three sets of hydrology simulations were carried out for the baseline (1961–1990) climatology and downscaled future climate scenarios for the 2041–2070 and 2061–2090 periods established by Sweeney and Fealy (Chapter 2). The 10 × 10 km grid covering the land area of Ireland that was used in downscaling was also used as the 'hydrological grid'. The reasons for adopting a grid-based rather than a catchment-based representation of the land area are discussed in the following paragraph. For each grid square, monthly mean values for precipitation and evapotranspiration were calculated for each scenario. These values were used to drive each of the three sets of hydrological model runs, using a hydrological simulation period of 1 year. Squares were assigned individual values for each of the hydrological parameters on the basis of information derived from digital map sources. Model predictions of effective runoff for the baseline period were validated for selected catchments. The squares that fell partly or wholly within the boundary of each of these catchments were identified and the effective runoff predicted over the area of each catchment was compared with runoff calculated from observed data for the same period.

The relative advantages of using a grid-based, as opposed to a catchment-based, approach to hydrological modelling were considered in the context of this particular application. The catchment is the most logical management unit for water resource planning and management, as recommended in the EU Water Framework Directive. This investigation aims to provide a starting point for future work by identifying spatial variations in effective runoff over the whole land area. Since the timescale of the downscaled climate data is relatively coarse for hydrological applications – monthly rather than daily or hourly values of precipitation for example – it is only possible to produce annual and seasonal predictions of runoff at this stage. Although a catchment-based approach would allow a more accurate representation of certain aspects such as topography or channel hydraulics, this becomes less critical when considering runoff over longer timescales, especially since it is effective runoff, not streamflow, that is being considered here. In parameterising the model, time constraints also had to be taken into account. The parameterisation of individual catchments would have taken considerably longer than the semi-automated processes used for grid squares that is outlined in Section 4.3 and would not have been possible in the time available. In fact, since the selected process-based hydrological model is a spatially 'lumped' model, the grid square-based approach would in some cases have represented parameters at a finer resolution than if actual catchments had been modelled. This is because the model usually represents the catchment as a number of sub-catchments, each of which is parameterised separately. For the larger catchments in Ireland, several sub-catchments have an area greater than the 100 km^2 covered by one of the grid squares used here.

There are also disadvantages. While the grid square approach may provide a finer spatial representation of soil properties (and hence moisture storage) than the catchment-based approach, the accurate representation of groundwater, lake and reservoir storage presents problems. Streamflow records are required to derive some of the parameters relating to these and are obviously not available for grid squares. Even if a number of catchments had been considered instead of grid squares, the derivation of these parameters would have been a lengthy process and may not have been possible in the time available. It was, therefore, necessary to simplify the representation of some of the storage terms. Despite this, it should be possible to gain some insight into possible spatial and temporal changes in storage under future climate scenarios.

4.2 Hydrological Simulation

4.2.1 The HYSIM model

The hydrological simulation model HYSIM (Manley, 1978, 1993) was selected for this study. This is a versatile model that has previously been used in a number of different applications including those examining the effects of climate change on hydrological water resources (Pilling and Jones, 1999) and is the standard rainfall-runoff model used by the UK Environment Agency. HYSIM uses rainfall and potential evaporation data to simulate river flow and parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. This means that the model is more likely to perform well under climatic conditions that are more extreme than those for the calibration period. HYSIM has a number of advantages for this type of application. It is flexible in its data requirements and provides a range of output data which include simulated streamflow, simulated storage in each conceptual reservoir (e.g. upper and lower soil moisture, groundwater) and simulated transfers between these reservoirs.

The structure of HYSIM is shown in Fig. 4.1. The model consists of several conceptual stores between which water is transferred by means of numerical algorithms. The parameters define the whole river basin from a hydrological point of view. Runoff is then routed in

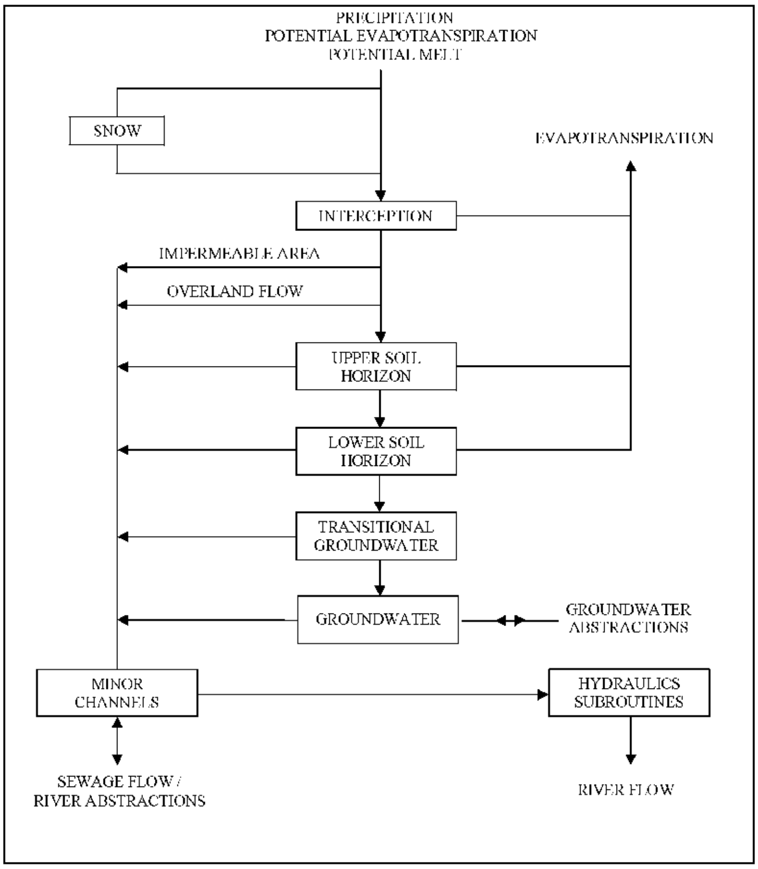

Figure 4.1. HYSIM model structure.

channels using hydraulic routines. A full list of HYSIM parameters is given in Appendix 4.1.

4.2.2 Data requirements and model outputs

At the minimum, HYSIM requires daily rainfall and monthly potential evaporation. The model also accepts other inputs including snowmelt, abstractions from and discharge to surface water and pumping from groundwater. The data can be daily or any other shorter time step and the time step for different types of data and for calculations does not need to be the same. The model provides a number of outputs that include:

- total surface runoff
- soil moisture storage
- groundwater recharge
- groundwater storage.

4.3 HYSIM Parameterisation

4.3.1 Soil parameters

HYSIM has been designed to enable quantitative values for the soil hydrological parameters listed in Appendix 4.1 to be derived using soil survey data (Manley, 1993). These values are assigned on the basis of the soil textural characteristic which is determined from the relative proportions of sand, silt and clay sized particles (USDA, 1951). Soil data were obtained from a digitised 1:575 000 map of the 44 soil associations for Ireland. This map was originally produced by the Soil Survey of Ireland together with the accompanying bulletin (Gardiner and Radford, 1980). The digital map was converted to a grid format with a 1 × 1 km resolution in ArcView, and the 44 soil associations were reclassified into 11 soil textural groups, according to the relative proportions of sand, silt and clay reported by Gardiner and Radford for typical depth profiles for each soil association. A soil texture was derived for each soil horizon (layer) and from this an overall soil texture was allocated for each soil association. If the different soil horizons for a particular soil association fell into separate textural classes the dominant texture and that of the upper horizons were taken into account.

The 1 × 1 km grid shown in Fig. 4.2 was then upscaled to a 10 × 10 km resolution whereby the dominant soil textural class represented by the 100 1 × 1 km squares comprising each 10 × 10 km square was given as the texture for that square. Where more than one textural class was dominant, texture was defined manually by considering the textural classification of the adjoining grid squares and their corresponding land-use classification, indicated by the CORINE (Coordination of Information on the Environment) land-use map.

Two additional hydrological classes were included to represent the extensive areas of blanket and raised peat. These parameter values were not assigned on the basis of texture but by using the field and laboratory observations of raised and blanket peat made by Galvin (1976) and Feehan and O'Donovan (1996).

4.3.2 Land use and vegetation

Parameters related to vegetation and land-use characteristics are shown in Appendix 4.1 and include the rooting depth of vegetation, impermeable areas, permeability of the soil surface and the rainfall intercepted by different types of vegetation. Values for these parameters were obtained using CORINE (O'Sullivan, 1994). CORINE classifies land use into 44 categories, although many of these are not relevant to Ireland (e.g. vineyards, olive groves and glaciers) or occur over such a small area that they did not occur on the 1 × 1 km grid. As a result 11 land-use classes exist on the 1 × 1 km grid map (Fig. 4.3).

The 1 × 1 km grid was then upscaled to a 10 × 10 km resolution on the basis of the majority occurrence in each cell, and reclassified into seven classes:

- urban areas
- arable land
- pasture
- forests, including shrubs and herbaceous plants
- peat bogs
- inland water bodies
- little or no vegetation.

As with the soil textural classes, one land-use classification value based on majority was assigned to

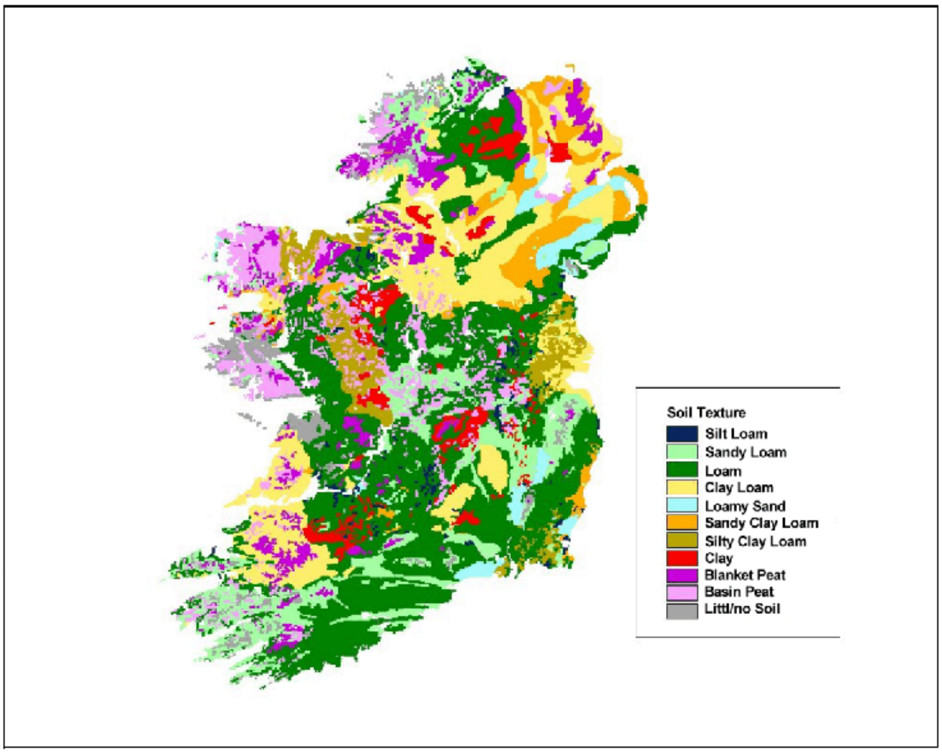

Figure 4.2. Map of soil texture based on the digitised map of soil associations derived from Gardiner and Radford (1980) and converted to a grid format at a resolution of 1 × 1 km.

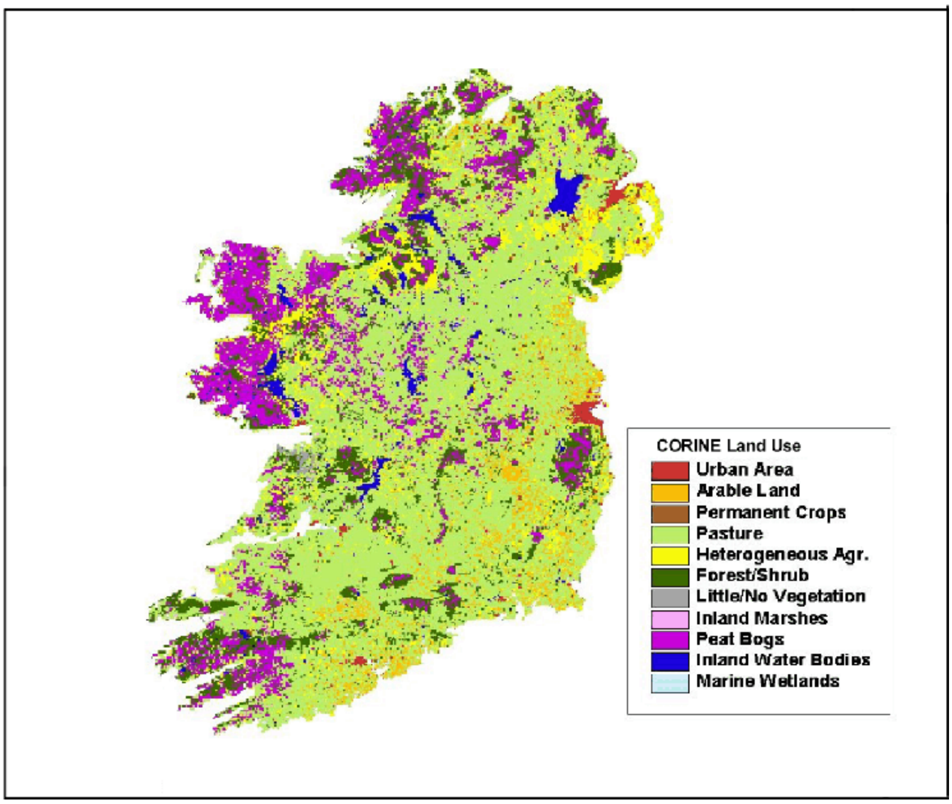

Figure 4.3. 1 × 1 km map of CORINE land-use classes for Ireland.

each of the 10 × 10 km squares. It was also necessary to reclassify some squares by hand where a similar number of 1 × 1 km squares represented two or more land-use classes. The land use of neighbouring squares was taken into consideration when doing this.

Standard values were assigned to different vegetation classes for interception storage, the interception factor and rooting depth. The impermeable proportion was calculated from the percentage urban area and bare rock for each 10 × 10 km square and included areas of bare rock, urban areas, roads, mines, airport, etc. As recommended by Manley, it was assumed that 25% of these areas were impermeable. Other areas were assigned a value of 2%, which is typical for rural areas (Manley, 1993).

4.3.3 Groundwater

Most of the groundwater in Ireland occurs in fissured shallow aquifers, many of which show some degree of solutional enlargement or karstification of fissures characteristic of certain limestones (Daly and Warren, 1998). The grid-based approach used in this study presented some problems for the representation of groundwater. These were anticipated but since one of the main aims of this first-pass study was to examine changes in effective runoff for the whole land area, it was necessary to make simplifying assumptions. HYSIM would normally be applied to a catchment or a number of sub-catchments with the groundwater parameters derived from analysis of observed records of streamflow. During a dry period, river flows are usually dominated by groundwater, and the recession of flow in a river over time is affected by aquifer characteristics. A ‘recession coefficient’ determined from hydrograph analysis integrates these aquifer characteristics. For the approach used in this study, it was not practical to do this as it would have involved obtaining and analysing streamflow records for most of the rivers in Ireland. A sensitivity analysis was carried out to determine the sensitivity of the model to changes in the recession coefficient. This showed that the value assigned to the recession coefficient was significantly less critical over the relatively long time periods examined in this study than for the much shorter time periods used in the simulation of, for example, individual storm events. It was thus decided that the time required to derive groundwater parameters from hydrograph analysis would not have been justified.

A simpler approach was adopted by assigning each square with a groundwater reservoir and using an ‘average’ value for the recession coefficient suggested by Manley (1993). Although many of the 10 × 10 km squares do not include significant aquifers it was felt that assigning groundwater to all squares made fewer assumptions than allocating ‘groundwater’ and ‘no groundwater’ to squares. This was because there is much heterogeneity, even in a single aquifer, due to complex geological structures and complex flow pathways and hydraulic conductivity may vary over several orders of magnitude, especially where fissure permeability exists. When validation of the model predictions was carried out catchments with significant aquifers underlying all or part of their area and those without significant aquifers were selected. The results of the model validation are discussed in Section 5.2.

4.3.4 Channel hydraulics

Runoff simulated by HYSIM for a catchment or its sub-catchments is usually routed through channels using hydraulics routines, with channel dimensions and hydraulic characteristics defined in the parameter file. In this study, changes in effective runoff (expressed as a depth of runoff per unit area) rather than in streamflow were examined and the hydraulic routines were not employed. In addition, the coarse time resolution of the input climate data meant that a water budget approach was more appropriate. This meant that it was not possible to simulate lakes and reservoirs using the hydraulic routines, although it would be possible to make an estimate of the water balance of a particular lake by aggregating the water balance of the component grid squares. For squares covered partly or wholly by lakes or reservoirs, the riparian proportion (the proportion of the square where evaporation takes place at the potential rate) was increased. As a result of these simplifications the groundwater storage term actually represents groundwater, lake and reservoir storage. Catchments selected for validation included those with and without lakes and aquifers.

Although the hydraulic routines were not used, it was necessary to include a value for a catchment parameter to control the simulation of the response of minor channels within the catchment that would not have been large enough to be simulated within the flow routing routines. This parameter is defined as the average time to peak for minor channels and is derived using a UK Institute of Hydrology Flood Studies Report (NERC, 1975) equation:

$$T_p = 2.8(L/\sqrt{S})^{0.47} \qquad \text{(eqn 4.2)}$$

where T_p is time to peak (h), L is stream length (km) and S is stream slope (m km^{-1}).

This parameter is important when considering short time periods of hours or days but its value is less critical for seasonal and annual time periods. In this case, an 'average' value recommended by Manley (1993) was used.

4.4 Input for Rainfall and Evaporation

For each of the baseline, 2041–2070 and 2061–2090 simulations, the downscaled monthly precipitation and PE data were converted to input files in HYSIM format. Two sets of 852 input files were created as input for each of the simulations carried out. This was done by means of a program that divided the mean monthly precipitation for each 10 × 10 km square by the number of days in each month to provide a daily precipitation input file in HYSIM format. Monthly values of PE were written to separate input files. The input files each contained two identical years of precipitation or PE data to allow 1 year as a run-in period for the model before the actual simulation. Longer run-in periods were tried but did not produce a significant improvement in model predictions.

4.5 Model Validation

4.5.1 Selection of catchments for validation

The process of validation is carried out to assess model performance by comparing observed and predicted flows for the same time period. Although the grid squares did not represent actual catchments it was possible to validate HYSIM predictions by comparing observed runoff for selected catchment areas with the runoff predicted for the squares corresponding to these areas.

As far as possible, catchments were selected to represent the diverse range of climatological and hydrological conditions found in Ireland. Streamflow is recorded at a number of river gauging stations operated by the Office of Public Works, the Electricity Supply Board, county councils and the Environmental Protection Agency, as well as private bodies. Within larger catchments there are usually a number of gauging stations recording flow in the main river and its tributaries. Gauging stations upstream from dams and reservoirs were selected on the basis of the quality and availability of data for the 1961–1990 baseline period. Naturalised flows, adjusted to compensate for abstractions from and discharges to the river were used. The catchments selected are shown in Fig. 4.4 and Table 4.1. It was hoped to include the Liffey in the validation exercise but this was not possible, as naturalised flows were not available for this regulated river for the baseline period.

Mean monthly observed flows in m^3 s^{-1} for the 1961–1990 period were converted to an annual effective runoff in mm by calculating the mean annual total volume of flow and dividing this volume over the catchment area to give a depth of flow. This process was repeated to provide seasonal runoff totals for summer (June, July and August) and winter (December, January and February). The locations of grid squares in relation to the selected catchment areas were found by using OS 1:250,000 and 1:50,000 maps to plot each catchment boundary and then by identifying the squares that fell wholly or partly within the catchment area. The percentage contribution made by squares was used as a weighting factor in these calculations.

Table 4.1. Catchment areas selected for HYSIM validation.

River and location of gauging station	Catchment area (km^2)
Feale at Listowel (Q997333)	646
Suir at Clonmel (S208222)	2173
Slaney at Scarawalsh (S983450)	1036
Shannon at Athlone weir (N039412)	4597
Brosna at Ferbane (N115243)	1207
Bonet at Dromahair (G805308)	294

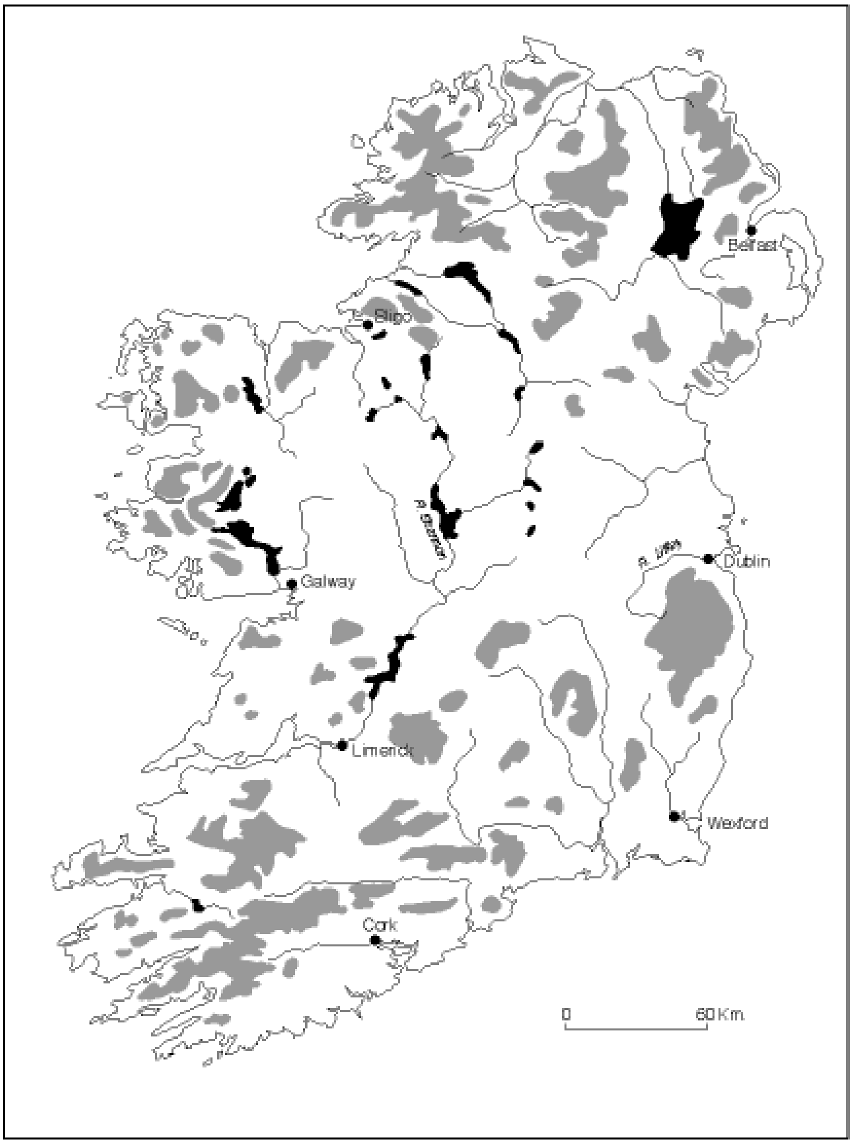

Figure 4.4. Rivers selected for validation.

4.5.2 Results of HYSIM validation

Table 4.2 shows the annual observed and predicted effective runoff for each of the selected catchments under baseline conditions. From this it can be seen that the Feale, Slaney and Brosna all fall within ±10% of the observed values, with the percentage error for the Suir being just over 10%. However, the predicted runoff is underestimated by over 18% for the Shannon and almost 23% for the Bonet.

The winter and summer runoff from these catchments were also compared in order to see if there was a seasonal imbalance in the predictions. An insufficient volume of water entering storage during the wetter winter months could result in the predicted winter runoff being too high and too low in the summer. Conversely, too much water entering storage during the winter months could lead to over-predicted winter flows and under-predicted summer flows. The Shannon catchment, upstream from Athlone, is the largest catchment considered in this study. It is also the most complex hydrologically, with extensive areas covered by lakes, wetlands and peat, complex interactions with groundwater and a very low channel gradient. Despite the simplifying assumptions made in this first-pass investigation, comparison of the winter and summer runoffs for the Shannon and Bonet revealed that

Table 4.2. Predicted and observed values of annual effective runoff for validation catchments.

Effective runoff	Feale	Suir	Slaney	Shannon	Brosna	Bonet
Predicted (mm)	1058.93	617.27	566.55	645.86	475.88	950.12
Observed (mm)	1070.69	697.00	565.63	787.97	441.82	1232.20
% error	–1.10	–11.44	0.16	–18.03	7.71	–22.89

runoff was under-predicted throughout the year. The overall change in each of the storage reservoirs was examined for selected squares over the time period of the simulation but the small changes observed at the end of the simulated year were insufficient to account for the annual shortfall in runoff.

Since the upper Shannon drains an upland area, it is possible that the low predicted runoff is due to the under-prediction of precipitation for upland areas brought about by the areal averaging techniques used in downscaling the precipitation data. As was described in Chapter 2 (Section 2.4) the high-resolution topographic data may result in some under-representation of high altitude areas (and thus of precipitation). This would also be consistent with the low runoff predicted for the Bonet and, to a lesser extent, the Suir, which also drain upland areas. In general, the results of the HYSIM validation are encouraging given that this is a first pass, and mean that a certain degree of confidence can be held in the hydrological predictions made for future climate scenarios.

4.6 Predicted Changes in Hydrology and Water Resources

4.6.1 Baseline simulation

Figure 4.5 shows the predicted annual effective runoff for the 1961–1990 baseline period together with the seasonal effective runoff for winter (December, January and February) and summer (June, July and August).

The spatial distribution of runoff for this period reflects precipitation patterns, with an east–west gradient along which a decrease in runoff is observed. Higher runoffs

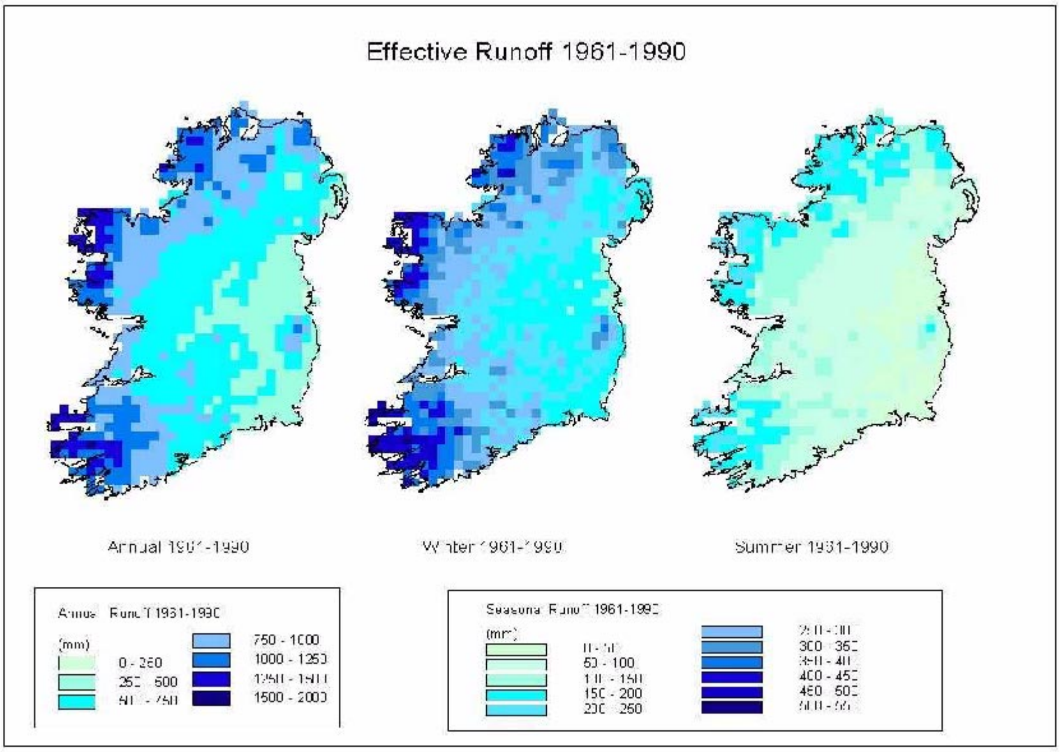

Figure 4.5. Effective runoff in mm for baseline (1961–1990) period.

from upland areas are associated with localised increases in precipitation caused by orographic effects. On an annual basis the driest areas are found in the east and south-east and include the counties from Louth to Wexford, inland to Kildare, and parts of Westmeath and Offaly. Within this broad area, higher runoffs are associated with higher ground, most notably the Wicklow Mountains.

The highest values of effective runoff are found along the western seaboard. This effect is again enhanced by topography, with Co. Clare being relatively dry compared to the more mountainous parts of the west coast. Similar patterns are observed for the seasonal runoff over the winter and summer periods. The mean runoff predicted for the 852 grid squares is 748.36 mm annually, 266.47 mm in winter and 105.53 mm in summer.

4.6.2 Changes in runoff for 2041–2070

Figure 4.6 shows maps of percentage change in runoff for 2041–2070 relative to the baseline simulation for the annual, winter and summer periods. On an annual basis, an overall decrease in runoff is predicted for most of the land area, with the exception of western Mayo for which a slight increase in runoff is observed for a small number of squares. The percentage change in runoff is more marked in the east, although this is affected to some extent by the magnitude of the baseline runoff for a given square, as the same absolute change in runoff would produce a higher percentage change for squares with a relatively low baseline runoff.

The absolute differences between baseline and 2041–2070 runoff are shown in Fig. 4.7. From this it can be seen that an east–west trend exists, similar to that seen for percentage change, with maximum drying occurring in the east.

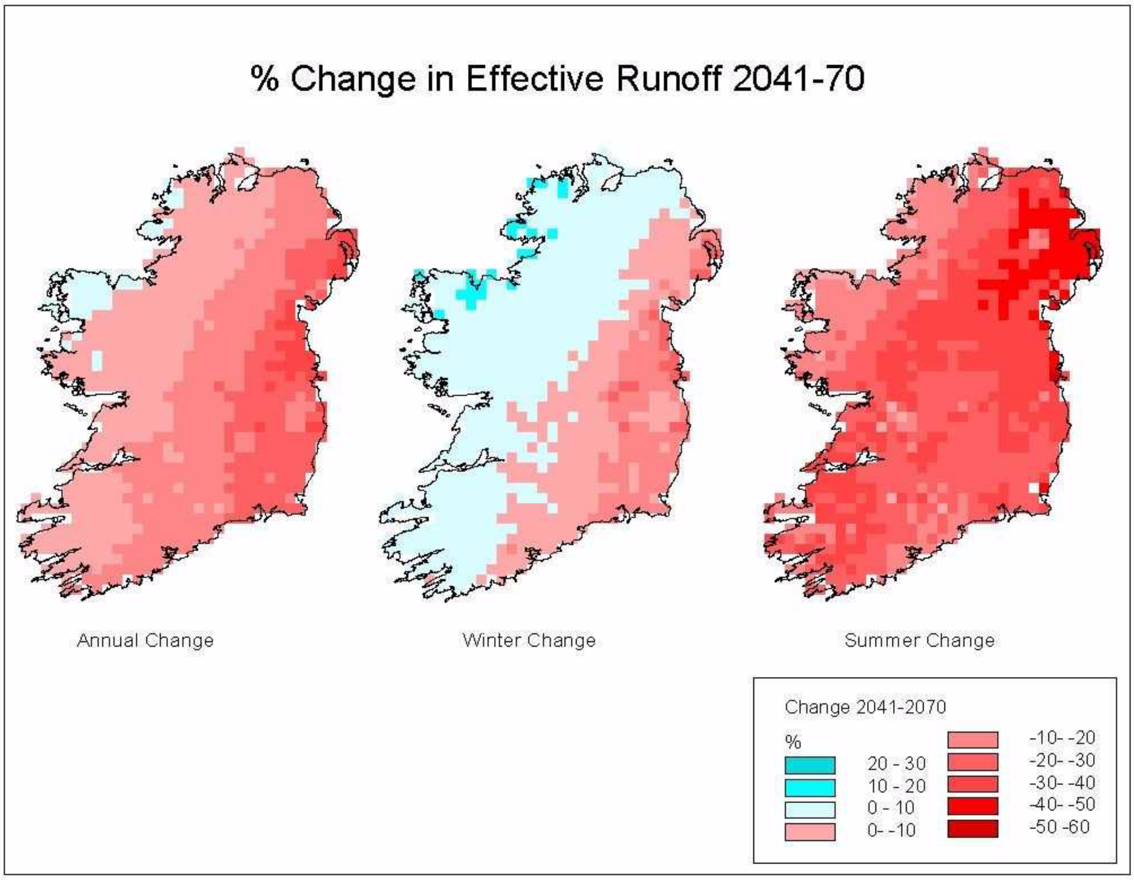

Figure 4.6. Annual and seasonal change for 2041–2070 simulation expressed as the percentage difference with the 1961–1990 baseline.

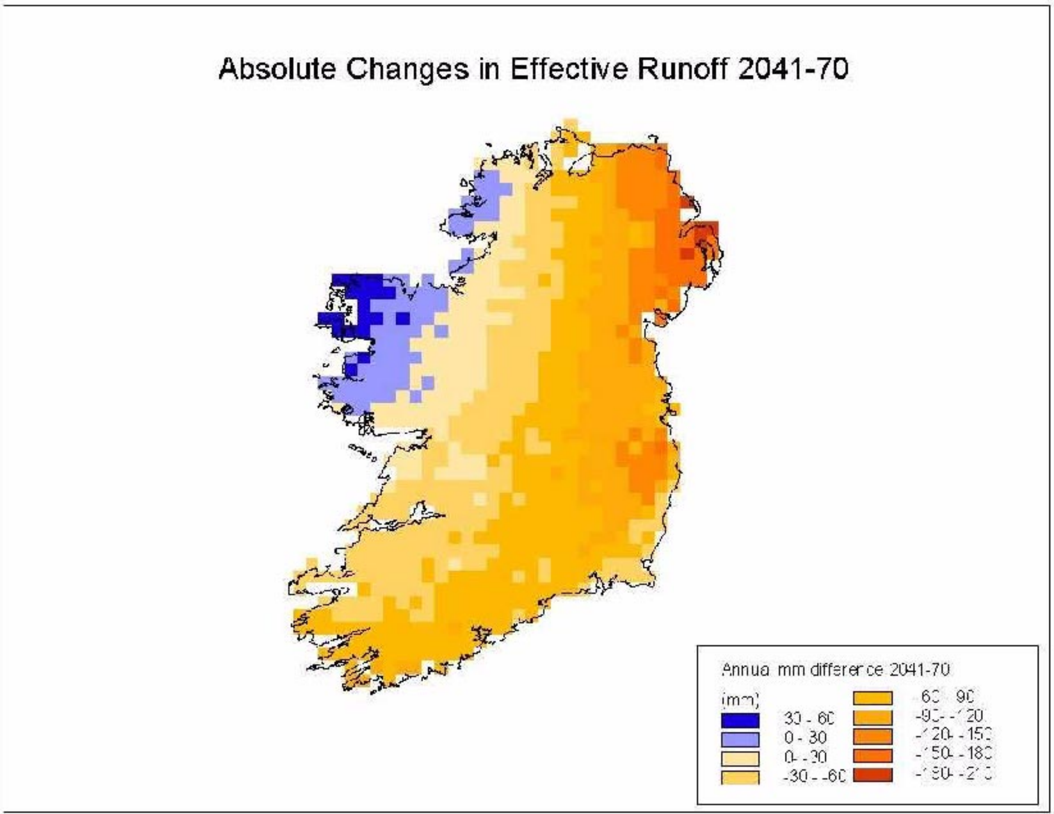

Figure 4.7. Absolute change in annual runoff between baseline and 2041–2070 scenario.

It is in some of the areas where the greatest percentage change is predicted that present demand for water is highest and most likely to increase in future. These areas include the Dublin region and the east coast between Dublin and Belfast. A large proportion of the water supplied to Dublin is abstracted from rivers draining the Wicklow Mountains, including the upper Liffey. The reduction in rainfall in the winter months to recharge stores within these catchments could exacerbate problems caused by reduced summer rainfall and increased evaporation rates. Reduced storage would mean that less water would be available during the drier months to sustain low flows and could result in water shortages.

The annual change in runoff for the validation catchments was examined and is shown in Table 4.3. The predicted runoff for 2041–2070 was compared with the predicted runoff from the baseline period rather than the observed runoff. The greatest change, an annual reduction in effective runoff of approximately 25% of the baseline flow, was observed for the Slaney. The area drained by this river is in the south-east of the country where the some of greatest reductions in predicted runoff occur. The predictions indicate that the Brosna and Suir will experience an annual reduction of between 10 and 20% and the Shannon, Feale and Bonet less than 10%.

Over the winter months, 57% of the grid squares show an increase in runoff. The land area can be roughly divided into two zones by an axis running from the north-east to the south-west. To the west of this an increase in winter runoff, of between 0.1 and 11%, is seen and to the east runoff decreases by up to 25%. The changes in winter runoff for the validation catchments are less marked than annual and summer changes, although the Slaney shows a considerably greater reduction in winter flow than the other catchments. There is also a decrease in winter runoff of between 3 and 4% for the Suir and Brosna. The winter runoff from the Feale, Shannon and Bonet catchments is predicted to increase by between 3 and 7%. This could have consequences for river basins that already have a history of winter flooding, most notably the Shannon. Although it is not possible at this stage to comment on the frequency and magnitude of individual flood events, higher winter rainfalls and the resultant higher levels of saturation in catchments stores such as soil and lakes would increase the likelihood of flooding.

Decreases in summer runoff are spatially quite varied and similarities between precipitation distribution and predicted runoff patterns are less clear than for annual and winter runoff (Fig. 4.6). This is due to the fact that during summer, when flows are low, runoff from storage (e.g. lakes, groundwater and the lower soil) forms a much higher percentage of total runoff. This means that in summer the hydrological characteristics relating to storage and rate of movement between stores is an important factor in runoff generation. For the summer months, with the exception of the Bonet and Suir rivers, the predicted reduction in runoff is between 28% and 32%. Overall, lower precipitation and higher evapotranspiration will probably lead to a depletion of soil moisture and groundwater storage and to a later and more prolonged recharge period in the autumn and winter. This situation would impact in return on runoff conditions in the following spring. The issue of storage is examined in more detail in Section 4.6.4.

4.6.3 Changes in runoff for 2061–2090

If a comparison is made between the percentage change maps for the 2041–2070 scenario (Fig. 4.6) and those for 2061–2090 (Fig. 4.8), it will be seen that the predicted hydrological change is less marked between these two future scenarios than the changes observed between the baseline and the 2041–2070 scenario. In fact, compared to the baseline simulation, the overall hydrological impacts are greater for the 2041–2070 scenario than for 2061–2090. This can also be seen from examination of Tables 4.3 and 4.4.

Compared to the 2041–2070 scenario (Fig. 4.6), the difference between baseline predicted annual runoff and that for 2061–2070 (Fig. 4.8) indicates that, while the east–west trend is still evident, drying is less marked for

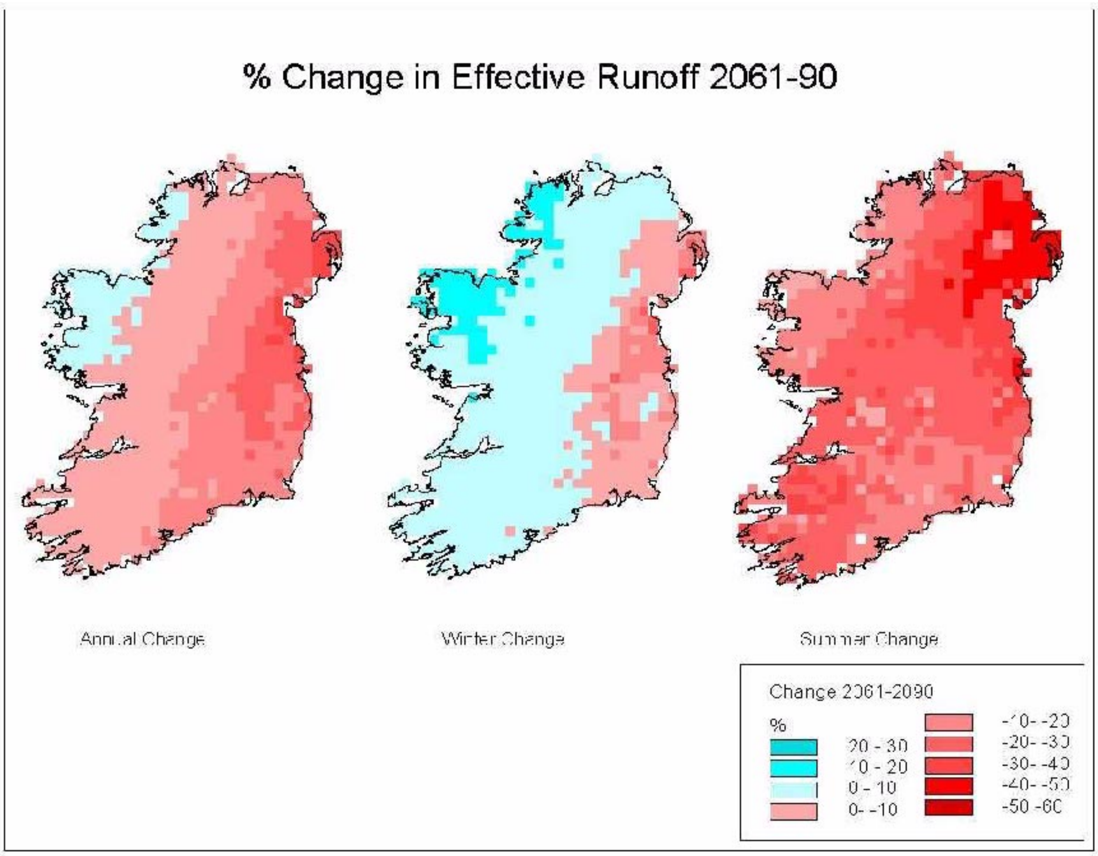

Figure 4.8. Change in annual and seasonal runoff for the 2061–2090 scenario expressed as a percentage of the 1961–1990 baseline.

Table 4.3. Percentage change in effective runoff for the 2041–2070 scenario relative to baseline simulation for catchments selected for validation.

2041–2070	Annual	Winter	Summer
Feale	–7.18	3.49	–31.29
Suir	–15.86	–3.91	–22.59
Slaney	–24.93	–11.37	–31.50
Shannon*	–9.05	4.15	–29.10
Brosna	–17.99	–3.49	–28.05
Bonet*	–4.14	7.28	–19.88

*Catchments for which percentage error exceeds percentage change.

Table 4.4. Percentage change in effective runoff for the 2061–2090 scenario relative to baseline simulation for catchments selected for validation.

2061–2090	Annual	Winter	Summer
Feale	–4.19	7.24	–29.02
Suir	–11.29	1.05	–16.94
Slaney	–20.81	–6.24	–26.59
Shannon*	–6.69	5.83	–26.82
Brosna	–14.59	–0.26	–23.73
Bonet*	–1.62	7.95	–18.82

*Catchments for which percentage error is greater than the observed changes.

2061–2090. In the north-west, a greater number of squares show an overall increase in runoff throughout the year. This includes parts of Galway, Mayo, Sligo and Donegal.

It is during the winter months that the greatest difference can be seen between the two future scenarios. The number of squares for which an increase in winter runoff is predicted increases to include much of the west midlands and Co. Cork. An increase is also observed for the Wicklow Mountains. The increase in winter runoff is predicted to be greater than 10% in some parts of the north-west.

It is during the summer months that the greatest spatial variation occurs since effective runoff for this period is more strongly influenced by variations in storage characteristics than for winter and annual flows.

4.6.4 Changes in storage

Three main stores were defined for each square: groundwater, upper soil and lower soil. These were in addition to minor stores such as interception storage. It was necessary to simplify the representation of storage for the reasons discussed in Section 4.2. Because of this the groundwater store represented lakes and reservoirs as well as groundwater. Changes in storage were observed from hydrographs produced by HYSIM for squares located within the validation catchments. These showed variations in moisture storage and the transfers between different stores that occurred during each simulation period. From these hydrographs, it was possible to make some general observations.

For the baseline simulation, spatial variations in soil moisture, groundwater storage and effective runoff were found to be predominantly influenced by patterns of precipitation and evapotranspiration. During the summer months, when storage levels were depleted and a soil moisture deficit developed, runoff patterns were less clearly influenced by the climatic variables. This was partly due to the influence of different soil properties on rates of movement through the soil and on water retention. Soil properties would also have had some control on rates of recharge to the groundwater store, although the groundwater parameters themselves were identical for each square. As might be expected, recharge to storage began during the autumn and winter months with peak levels occurring during late winter and early spring, depending on location and the type of storage. In the west, north-west and west midlands the onset of recharge was between 2 and 4 weeks earlier than in the drier east and south-east of the country, where recharge commenced in early September. Peak groundwater levels were predicted to occur in mid-January in the west, north and midlands and 2 weeks later in the east. Soil moisture levels showed a similar west–east variation. In reality, there would be much greater spatial variation in groundwater levels because aquifers are highly heterogeneous in properties and extent and do not underlie all areas. As a result, the predicted variations in soil moisture are probably more meaningful.

A slight depletion in soil moisture storage was observed during the summer months under the 2041–2070 scenario in the west and north-west. This was accentuated in the midlands and severe in the east and south-east, with a temporal delay in recharge of up to 6 weeks. There was an increase in the length of time over which a deficit developed, from 1 to 4 weeks in the case of the Brosna. The maximum soil moisture deficit was up to 45% greater (dryer) in the midlands and almost 85% in the south-east. A delay in the onset of recharge was also observed for groundwater and this was again most marked in the east and south-east of the country. While the delay in the onset of recharge was between 1 and 2 weeks in the west of the country, this was up to 6 weeks in the east and south-east. In the north-west, where an increase in winter runoff was predicted, there was a corresponding increase in groundwater storage. During the summer months a decrease in groundwater storage was observed across the country. For the Brosna, this reduction was approximately 20%, and for the Shannon, up to 50%.

Although a number of assumptions were made in representing storage, the results of the validation for annual effective runoff predictions were acceptable. A degree of caution should obviously be applied to the observations made above which can only give a general idea of changes in annual and seasonal patterns of storage under the future climate scenarios considered. The implications of these changes are discussed in the next section.

4.7 Implications of Climate Change for Future Water Supply and Water Resource Management

4.7.1 Water supply and water resource management

Predictions of effective runoff for 2041–2070 and 2061–2090 indicate that most of the island will experience a decrease in annual runoff. Evaporative losses are likely to increase during the summer months and will have a significant effect on reservoir yields. Seasonal fluctuations in flow are likely to increase in western areas, with wetter winters and dryer summers. In the east and south-east, lower flows than at present are predicted for both the winter and summer months. It is in these areas that demand is highest and there is a rapid increase in demand where urban expansion is occurring. The most notable example is the Greater Dublin region, where the water supply infrastructure is likely to come under growing pressure in the near future (Department of the Environment, 1996), especially during the summer months. In order to meet future demand, careful planning will be required to maximise the available supply and further research to provide more accurate predictions of future water availability are essential. The supply could potentially be enhanced on a seasonal basis by increasing the operational limits of the Poulaphuca dam to increase winter storage in the reservoir and allow greater drawdown in the summer months (Department of the Environment, 1996).

It will be necessary to increase the available supply of water in some areas by constructing new reservoirs, transferring water between drainage basins and the conjunctive use of groundwater. There are considerable supplies of groundwater that are currently unused for water supply at present (Daly and Warren, 1998) and that could be exploited. In doing this, it would be necessary to consider the role of groundwater in maintaining low flows, especially under the climate change scenarios considered. The availability of groundwater in karst areas, where there is a rapid throughput of water, could be significantly reduced during the dryer months. Karst aquifers are also extremely vulnerable to contamination from landfill sites, agricultural pollution and septic tanks (Daly and Warren, 1998). Another option is the transfer of water between drainage basins. A relatively small-scale transfer has already been proposed to pump water from the upper Barrow to the Liffey in order to enhance flow into the Poulaphuca reservoir, the main reservoir supplying Dublin. Future climate-induced reductions in runoff could result in a flow deficit in both catchments, especially if the available runoff was underestimated on the basis of the current flow regime. Transfers over longer distances are also feasible, and supplying Dublin with water from the Shannon catchment has been suggested as a possibility (Department of the Environment, 1996). Again, changes in runoff would need to be considered as the results of this investigation suggest that all regions will experience drying during the summer months when demand is highest.

As well as developing new sources of supply, attention should also be given to demand management, which could postpone the need to develop new sources of supply in the short- to medium-term. At present up to 30% of the water supplied to Dublin is lost through leakage from the ageing supply network (Department of the Environment, 1996). This problem is currently being addressed although the location and repair of leaking pipes is a time-consuming and expensive process. Regular monitoring and maintenance would make substantial savings. Programmes to educate and encourage water conservation through greater public awareness, incentives for installing water-efficient appliances or more aggressive strategies such as compulsory water metering should also be given serious consideration.

4.7.2 Water quality

Water quality control is an essential component in the planning and operation of water management systems. Contamination of the water in rivers, aquifers, lakes and reservoirs can result in a reduction in the available supply and may also have impacts on fisheries and freshwater ecosystems. Most of the water abstracted for domestic, agricultural and industrial use is returned to the environment as waste water, which is discharged to the sea or inland waters. The quality of this waste water is often impaired by substances that are dissolved or suspended in it. In Ireland, the majority of these substances are of an organic and biodegradable nature (Kenny, 1996), but non-organic, non-biodegradable substances are also discharged. Waste water enters watercourses via point sources, for instance where sewage effluent is discharged directly into a river, or non-point sources which include runoff from agricultural areas and leakage from landfill sites and septic tanks. In rural areas, non-point sources are the main cause of contamination; this is already a major problem, not least because of the difficulties associated with the monitoring and control of diffuse pollution.

Under the future scenarios examined, a number of water quality problems may arise, mainly as a result of the widespread reduction in runoff. Although these predictions are for seasonal runoff, it is not unreasonable to assume that the frequency and duration of low flows will increase. This would mean that less water was available to dilute organic effluent, enabling it to be broken down, a bacterial process that reduces the dissolved oxygen content of the water. The biochemical oxygen demand (BOD) is used as an indicator of the pollution potential of organic effluent. The BOD is greatly reduced by the sewage treatment process but a certain volume of flow is required to receive the effluent and, if this drops below a minimum level, there may be serious consequences for downstream users, fisheries and freshwater ecosystems. It is recommended that minimum flow constraints are determined and imposed to ensure that a sufficient volume of flow is available for the needs of downstream users and to dilute effluent. It is essential that this be incorporated into the planning process for the expansion of urban areas to ensure that the volume and quality of flow is maintained. Accurate predictions of changes in future should also be taken into account during this process.

There is considerable potential to increase water supply by developing groundwater resources and, in the future, withdrawals from aquifers may be the only way of meeting demand as surface runoff is reduced. Groundwater is especially vulnerable to pollution as flow processes and contaminant pathways are relatively slow. If an aquifer does become contaminated the problem may persist for many years due to the relatively slow turnover of water. In serious cases of aquifer pollution, it may be necessary to abandon the supply altogether. It is, therefore, of vital importance that aquifers are protected from pollution, including those that are not currently used as a source of supply. Since the early 1980s, the Geological Survey of Ireland has been developing groundwater protection schemes which can be used as a basis for decision-making in land-use planning and environmental protection. For much of the country, the availability of relevant geological and hydrogeological information is currently inadequate for a fully comprehensive scheme, although interim schemes have been implemented on the basis of available information.

4.7.3 Flood management

Although it is not possible to comment on changes in flood magnitude and frequency, the increase in winter runoff indicated for many parts of the west, especially under the 2061–2090 scenario, is likely to have significant implications. River flooding is affected by meteorological, topographical, geological and other factors. It tends to be more common during the wetter winter months when soils are near saturation but can occur at any time of the year. River flooding can be exacerbated in coastal areas when interactions occur between high tides and high flows. This has long been a problem in Waterford and Cork and is likely become more widespread as a result of the combined effects of increased runoff and sea level rise. Many of the rivers draining upland areas have a rapid or 'flashy' response to orographically enhanced rainfall. Steep slopes and thin soils favour rapid flow pathways and water is rapidly transmitted to the channel network. The underlying geology of formations that surround the central lowlands is relatively impermeable which also leads to a flashy response. Such flooding occurs on a number of rivers including the Suir at Clonmel and Carrick-on-Suir, the Nore at Kilkenny and the Blackwater at Fermoy and Mallow.

Land-use change can also increase the flood risk and is especially true of urbanisation. The widespread flooding that took place in November 2000 and November 2002 could have been exacerbated in some cases by urban encroachment onto floodplains, for example the Griffeen at Lucan, the Tolka at Dunboyne and Clonee and the Slaney at Enniscorthy. The impermeable surfaces, drains and sewers efficiently transfer water to river channels increasing flood peaks and reducing the response time. The development of floodplain areas increases the numbers of industrial and domestic properties at risk. It is difficult to separate the relative effects of climate change and urban development of floodplain areas, but the combined effects mean that such flooding is likely to become a more common occurrence. Structural defence schemes are at the design and construction stage, for example at Carrick-on-Suir and Clonmel. It is recommended that further research be carried out to determine changes in the magnitude–frequency range of floods in order to take account of climate change in design flood. It is strongly recommended that a national floodplain zoning strategy is developed to identify and classify at-risk areas and to restrict development in these areas.

Although flooding tends to occur mainly during the winter months it can occur at any time of the year. In August 1986, extreme rainfall associated with 'Hurricane Charley' and centred over the Wicklow Mountains caused widespread damage to parts of south Dublin. It is not possible to say whether such extreme events might increase in frequency under the climate scenarios examined because these were downscaled to a monthly temporal resolution, but it is recommended that this should be considered in future research.

Seasonal flooding affects many parts of Ireland during the winter months. The low-lying central lowlands have large areas of lakes and wetlands and seasonal flooding is a common occurrence for the rivers draining this area as these have shallow gradients along much of their length and a poor carrying capacity. The Shannon dominates the drainage system of the central lowlands and has a long history of flooding. The predicted increase in winter runoff over much of its catchment under both future climate scenarios is likely to increase the extent and duration of flooding, which mainly affects rural areas. From the mid-19th Century onwards, extensive arterial drainage works have been carried out to relieve flooding in rural areas. Cunnane and Regan (1991) suggested that these areas might in future re-experience flooding under climate scenarios where increased winter precipitation occurred.

Seasonal flooding can also be caused by turloughs, seasonal lakes that are a feature of the limestone lowlands of Galway and Mayo. They drain slowly via underground routes which tends to cause a backing-up of water over the winter months, causing the lake to expand. Extensive areas can become inundated if the accumulation of rainfall is greater than average over the autumn and winter months as was the case in the winter of 1994–1995 when severe flooding occurred in the Gort–Ardrahan area. Turloughs present a difficult management problem and which is likely to become worse and any flood alleviation schemes should consider the implications of future climate change.

4.8 Conclusions

This is the first time that downscaled GCM predictions have been used to model effective runoff for the whole land area of Ireland under future climate scenarios. Since this was a first-pass investigation it was necessary to make several simplifying assumptions. Despite this, the results of the model validation carried out were acceptable. The main impacts indicated by the model results are summarised below:

- The predictions made under both future scenarios suggest that there will be a widespread reduction in annual runoff that will be most marked in the east and south-east of the country. A slight increase may be observed over a limited area in the north-west.

- Winter runoff is predicted to increase in the west of the country, especially under the 2061–2090 scenario, where an increase in winter runoff is predicted for over 60% of the land area. The greatest increases are predicted to occur in the north-west.

- All areas will experience a decrease in summer runoff, with the greatest reductions in the east of the country. It is likely that the frequency and duration of low flows will increase in many areas.

- The magnitude and frequency of individual flood events will probably increase in the western half of the country. Seasonal flooding may occur over a larger area and persist for longer periods of time.

- Long-term deficits in soil moisture, aquifers, lakes and reservoirs are likely to develop.

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Appendix 4.1. HYSIM Parameters

Soil parameters

Parameter	Description	Estimation method (typical range)
Pore Size Distribution Index (PSDI)	Controls soil response to ‘moisture/capillary suction’ and ‘moisture/effective permeability’ relationships	Soil hydrology class* (0.09 to 0.25)
Bubbling pressure	Represents the capillary suction at which bubbles appear when the soil is dewatered under increasing negative suction	Soil hydrology class* (80 to 630 mm)
Porosity	Relative volume of pores in soil to total bulk volume of soil	Soil hydrology class* (0.4 to 0.55 mm)
Permeability at horizon boundary	The rate at which moisture moves between the two soil horizons	Soil hydrology class* (5 to >200 mm h^{-1})
Permeability at base of lower horizon	The rate at which moisture leaves the soil layers (0 if no groundwater)	Soil hydrology class* (0 to >100 mm h^{-1})
Proportion of moisture storage in upper horizon	Proportion of the total available soil moisture stored in the upper horizon	Standard value (0.3)
Interflow runoff from upper horizon at saturation	Direct, or lateral runoff from the upper soil horizon	Standard value (10 mm h^{-1})
Interflow runoff from the lower horizon at saturation	Direct runoff from the lower horizon	Standard value (10 mm h^{-1})
Saturated permeability at the top of upper horizon	Controls rate at which water enters the top of the upper soil horizon	Soil hydrology class and land use (up to 1000 mm h^{-1} for cultivated land)

* Values assigned on the basis of soil textural class

Vegetation and land-use parameters

Parameters	Description	Estimation method (typical range)
Interception storage	The proportion of precipitation which is lost to runoff by interception by different types of vegetation	Between 2.0 mm (grassland/urban areas) and 10 mm (woodlands)
Interception correction factor	Weighted factor for evapotranspiration from interception storage. Moisture from interception storage evaporates at the ‘open water rate’ which is higher than the normal evapotranspiration rate	1.1 for grassland to 1.5 for woodland
Impermeable proportion	Proportion of each square that can be defined as being impermeable, such as rocks, roads, urban areas, etc.	0.02 for rural areas and up to 0.2 for urban
Soil rooting depth (mm)	Rooting depth of vegetation for woodland	Normally 1000 mm but can be up to 5000 mm
Riparian proportion	Where permanently swampy riparian areas exist close to rivers or lakes, potential evapotranspiration will continue at the potential rate, even if the catchment is ‘dry’	Typical value is 0.02

Groundwater parameters

Parameters	Description	Estimation method (typical range)
Discharge coefficient for groundwater	Controls the rate of water leaving groundwater storage	'Standard' value used (0.8)
Proportion of catchment without contributing groundwater		Assumed to be 0
Ratio of contributing groundwater catchment area to surface catchment area	This parameter is applied as groundwater and surface water catchments may not be contiguous	Assumed to be 1:1

Hydraulic parameters

Parameters	Description	Estimation method (typical range)
Time to peak – minor channels (h)	This parameter controls the simulation of the response of minor channels within the catchment. As grid cells are not real catchments, a standard value was applied	'Standard' value used (2 h)

Additional correction factors

Parameters	Description	Estimation method (typical range)
Precipitation correction factor	Parameter is adjusted to allow for the fact that rain gauges used under- or overestimate true catchment rainfall	Correction factor for standard rain gauge (1.04)
Potential evapotranspiration correction factor	Measurement of potential evapotranspiration is less accurate than that of rainfall	Adjusted during model calibration

5 The Potential Impact of Climate Change on Irish Forestry

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5.1 Introduction

In Chapter 2, high-resolution statistical downscaling techniques were used to provide future climate scenarios for Ireland for the periods 2041–2070 and 2061–2090. Milder winters and warmer summers are forecast with general temperature increases relative to 1961–1990 averages of 1.5–2°C expected by mid-century (Fig. 2.17). With the exception of low-lying areas in the north-east, east and south-east, winter precipitation is forecast to increase by up to 25 mm per winter month. Summer precipitation is expected to decrease on 1961–1990 levels along a north-west to south-east gradient (Fig. 2.19) with little change in the north-west but potential drought problems in the east and south-east.

Forests cover approximately 9% of the land area of Ireland. Most of these forests are managed commercially for timber production and consist of plantations of exotic conifers. The remaining, non-commercial areas are made up of native and semi-natural woodlands which are generally protected as Special Areas of Conservation (SACs) or Natural Heritage Areas (NHAs). The commercial forests have been established as a result of national afforestation policies since the early 1900s when only 1% of Ireland was under forest. Most of these forests have been established on sites where conventional agricultural practice was either not possible or was economically marginal. The most recent afforestation efforts have also been the most ambitious and, as a result, just over half of the forest estate is under 25 years old (ITGA, 2000, 2001). Forestry has also evolved in this time from being almost exclusively a state-owned enterprise to a situation where virtually all afforestation is carried out by the private sector with a corresponding improvement in site type. The predominant species planted is Sitka spruce (*Picea sitchensis* (Bong.) Carr), which makes up about 60% of the forest estate. This species is a native of the Pacific North-West of America, as are some other conifers currently planted. Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua* Mill.) are the main European coniferous species utilised. Most broadleaves planted are either native or of European origin. Primarily because of its island status and geographical position, Ireland's forests are relatively free from pests and diseases and the effects of air pollution. About 2.5 million cubic metres of timber are supplied annually from Irish forests into a small but competitive processing sector. Overall, the Irish forest industry employs, directly and indirectly, approximately 16,000 people. A strategic plan for the development of the forestry sector in Ireland was published by the Irish government in 1996 (Forest Service, 1996). This envisaged an increase in forest cover to 18% of the land area by the year 2030. In 2000, the Forest Service produced a code of best forest practice which describes all forest operations and the appropriate manner in which they should be carried out to ensure the implementation of sustainable forest management (Forest Service, 2000a).

The growth of trees and forests is highly influenced by climate. Indigenous forest ecosystems evolve in response to changing biogeochemical conditions. Because these forests are adapted to local climates, changes in these are likely to impact future forest growth and timber outputs (Joyce and Nungesser, 2000). In many regions where native species are used in the establishment of plantations, great care is taken by foresters in the selection of seed sources to ensure suitability for specific micro-climatic conditions. In countries such as Ireland, where exotic species are widely used, foresters pay close attention to site suitability, focusing on soil type and the prevailing micro-climate, both of which are heavily influenced by overriding climatic conditions. Their decisions are also influenced by the potential economic environment into which they hope to sell products. Because of the longevity of trees and forests, questions have been asked as to whether there will be enough evolutionary response time for forest ecosystems to adapt to severe climatic change (Andrasko, 1990). In planning for the future, foresters must select species that will perform optimally over a full rotation. Currently, this embraces a period of 40 to 50 years but it is doubtful if this is an ecologically optimal solution and the possibility that rotations may be increased in duration in the future, must also be considered. It is, therefore, essential for foresters to know what the likely changes in climate over the period being considered will be and what potential impact these changes will have on trees and forests.

The commercial value of timber from trees and forests has meant that emphasis has always been placed on improving our understanding of their productive function. Historically, this has been done by focusing research and management on timber quality and production with less emphasis on other elements of the forest ecosystem. However, forest managers are increasingly responsible for the sustainable management of the forest ecosystem as a whole (Farrell *et al*., 2000). This is a considerably more complex task than fulfilling a single objective of sustainable timber production. Broadmeadow (2000) states that there are many uncertainties associated with all stages of the modelling of the potential impacts of environmental change on forests. Nevertheless, there have been attempts by some researchers to use computer models to predict future impacts. This chapter does not attempt to repeat such modelling but instead addresses important individual forest ecosystem parameters and discusses the potential effect of climate change on them. Potential effects are categorised as either primary (Section 5.3) or secondary (Section 5.4). A discussion, based on the relevant literature, of the potential interaction of different primary and secondary effects and their potential combined effects on Irish forestry is then presented (Section 5.5). Section 5.6 discusses potential implications for forest management practice in Ireland.

Most authors dealing with the subject of climate change and its potential effects on forestry emphasise strongly the limitations associated with their research. Trees are large organisms with considerable longevity and many different growth phases. There is also known to be considerable variation in response both between and within species. In addition to the difficulties of assessing responses at individual tree level, it is also difficult to apply results at a large scale due to the complexity and variability of forest ecosystems. Most research to date has been constrained by time, space and the ability to control some variables while isolating others. However, there are definite trends in the body of research carried out to date and, despite scepticism on the part of some researchers, such as Loehle (1996), there is broad agreement on many of the conclusions drawn so far.

5.2 Modelling Forest Growth

Forest planning, whether it is silvicultural[1] or economic, or at a local, regional or national level, is dependent on being able to forecast or model forest growth at forest stand level. Obviously, from a forest planning point of view, it would be useful to accurately model future changes to the forest ecosystem as a result of changing environmental and specifically climatic conditions. Currently, in Ireland, forest growth is modelled in one of two ways which are best described by García (1988) as ‘static’ and ‘dynamic’. Both of these approaches are described below in the context of their ability to cope with environmental change.

5.2.1 Static models

Static growth models attempt to predict changes over time in key production parameters, such as mean volume and mean diameter at breast height[2], based on reference to similar stands closely studied over extended periods. In other words, a ‘best fit’ model is sought based on current measurements of key parameters and then the growth of those parameters is assumed to match those tabulated from similar stands. Historically in Ireland, such tables, in the form of Forestry Commission Management Tables (Johnston and Bradley, 1963), have been used by foresters. Kilpatrick and Savill (1981) point out that there are no confidence limits or precision estimates associated with the Forestry Commission models. Because of their reliance on historic tabulated data, these models lack the ability to predict future

[1]Silvicultural planning can be described as forest planning to achieve an objective of enhancing a particular forest system, function or product.

[2]Breast Height is defined as 1.3 metres from the base of the tree.

changes in forest parameters in a rapidly changing environment. They are dependent on the maintenance of a *status quo* with regard to the macro-environment in which the forests grow and the management regime applied. They should, therefore, not be relied upon in forecasting the future productivity of Irish forests.

5.2.2 Dynamic models

For many reasons, including the ones outlined above, the Irish forest industry has produced dynamic growth models for three important commercial species, namely Sitka spruce, Douglas fir and Norway spruce (Broad *et al.*, 2000a, 2000b). Work is currently being carried out on the production of dynamic growth models for three other commonly grown species, namely Japanese larch, Scots pine and Lodgepole pine. Dynamic growth models, unlike static models as discussed above, account for changing management practice and environmental conditions over a forest rotation. Coillte, the Irish Forestry Board, currently uses these dynamic growth models for forecasting growth and yield of Sitka spruce, Norway spruce and Douglas fir (Lynch, personal communication, 2001). For practical and financial reasons, the Coillte models focus on a narrow range of timber production parameters (Top Height, Basal Area, Mean Volume, Mean Diameter at Breast Height) which are assessed at different production stages of the forest crop. The models do not directly use measurements of changes in the environment itself, nor do they measure or directly take account of changes to the forest ecosystem (e.g. available soil nitrogen, available moisture, soil pH, etc.) which greatly influence the productive potential of the timber crop. However, the effect of a changing environment is reflected in measurements of the timber production parameters over time. Unlike static models, dynamic models allow for current measurements of these parameters to form the baseline from which future growth is projected and there is no requirement to fit data into historic tables. In these ways, the rate and effect of environmental change is passively accounted for and these models represent a recognition of the need for a dynamic approach to growth modelling.

5.2.3 Process-based models

Unfortunately, from the point of view of this study, neither of the growth models currently used by Irish foresters attempts to model aspects of the forest ecosystem other than critical forest production parameters such as height, volume and diameter. There are many uncertainties associated with the modelling of a whole ecosystem and its vulnerability to climate change. However, in a period of significant environmental change, models based on ecosystem processes represent potentially the best means of predicting the future development of the ecosystem. Work is proceeding on these models in several countries, although they are still in the early stage of development. An initial attempt has been made in the application of a process-based model to forest growth in Ireland (Goodale *et al*., 1998). Currently no such developmental work is being conducted here.

5.3 Potential Primary Effects

Potential primary effects are defined as those which changing climatic elements, such as carbon dioxide (CO_2) enrichment, higher temperatures, stronger winds or lower rainfall, may have on tree or forest growth. Each climatic element is discussed separately below in the context of climate change projections.

5.3.1 Increased CO_2 levels

Atmospheric CO_2 is the carbon source for photosynthesis and plant growth is highly influenced by CO_2 levels in the atmosphere. Rising CO_2 concentrations, in addition to influencing other climatic factors, are, therefore, likely to have a direct effect on tree growth. CO_2 is limiting to the rate of photosynthesis in C_3 species (Breymeyer *et al*., 1996). (C_3 species are ones in which the first product of photosynthetic CO_2 assimilation is a three-carbon compound, phosphoglycerate (PGA) (Breymeyer *et al*., 1996).) This is thought to be particularly the case in a mature forest environment, where tree canopies are tightly bunched and air circulation is restricted (Daniel *et al*., 1979). Increased CO_2 concentrations would, therefore, be expected to stimulate tree growth, through what has become known as CO_2 fertilisation. This has been proven in experiments such as those on oak reported by Broadmeadow (2000) and across a range of woody plants by Ceulemans and Mousseau (1994). In a review of current knowledge of tree and forest functioning in an enriched CO_2 atmosphere, Saxe *et al*. (1998) report that recent data from a number of studies indicate the potential for a persistent enhancement of tree growth over several years. In one such study, DeLucia *et al*. (1999) increased the atmospheric concentration of CO_2 by 200 ml l^{-1} in a 13-year-old *Pinus taeda* L. plantation and found that after 2 years the growth rate of the trees had increased by about 26% relative to trees under ambient conditions.

However, Joyce and Nungesser (2000) and Saxe *et al*. (1998) both point out that most experimentation has been carried out using seedlings or juvenile trees. It may be too early, therefore, to say whether increased growth due to CO_2 fertilisation is sustained over a full rotation or in a mature forest environment. Indeed, the capacity of ecosystems for additional carbon uptake may be limited by availability of other nutrients and other biophysical factors (IPCC, 2000). Difficulties arise in some scenarios in attributing growth responses to single parameters. This is a point underlined by Andrasko (1990) who claims that, because very little work has been done *in situ* on forest or other natural communities over extended time frames, the net effect of CO_2 enrichment combined with forest decline from climate change and air pollution remains uncertain. Despite this, recent studies by Spiecker *et al*. (1996) found that growth rates in European forests have increased and this has been partly attributed to climate change and nitrogen deposition.

Most research conducted on the impact of elevated atmospheric CO_2 on water-use efficiency concludes that stomatal conductance from leaves will be reduced and that this will lead to diminished transpiration rates, thus leading to greater water-use efficiency (Saxe *et al*., 1998). The stomata of conifers tend to respond less to elevated atmospheric CO_2 than those of broadleaves (Jarvis, 1989, cited in Breymeyer *et al*., 1996). Despite this, Townsend (1993) reported a doubling of water-use efficiency in Sitka spruce seedlings when CO_2 concentrations were doubled. This may be offset by increased leaf area associated with CO_2 fertilisation (Saxe *et al*., 1998).

5.3.2 *Increased temperatures*

Apart from influencing other climatic factors such as rainfall, humidity and wind speed (Broadmeadow, 2000), a warmer climate will have a direct impact on tree and forest growth (Fig. 5.1). Virtually all chemical and biological processes in plants and soils speed up with warmer temperatures, and photosynthesis and respiration in trees are no exception (Saxe *et al*., 2001). The same authors conclude from a comprehensive literature review that, depending on N mineralisation and availability, increased temperatures will lead to an increase in net primary production of forests in temperate and boreal (northern) regions, including Ireland.

The site productivity of Irish forests is assessed using an index called Yield Class. This is an estimate of the maximum mean annual increment of stem volume per hectare per annum (Edwards and Christie, 1981). Yield Class was found in work reported by Worrell (1987) to be fairly closely correlated with both site temperature (estimated mean annual accumulated temperature above 5.6°C) and site windiness. Analysis based on measurements from 142 sample plots found that these two climatic variables accounted for 78% of the variation in Yield Class. A multiple regression model used by Worrell (1987) clearly indicates a rise in Yield Class with rising temperatures, all other variables being equal.

Bud phenology (i.e. the periodicity of leafing, flowering and fruiting) is closely connected to temperature (Saxe *et al*., 1998). It is expected that, on lowland sites, an increase in average winter temperatures will result in later bud flushing of certain species including Sitka spruce, Norway spruce, ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petrea* (Mattuschka) Lieblein). This is because these species require a certain number of chilling hours before bud flushing[3] can take place in the spring when conditions are correct (Cannell and Smith, 1983; Thompson, 1998). Later bud flushing in these species will result in a lower risk of damage from late spring frosts but may also mean a shorter growing season, potentially affecting biomass production.

Cannell and Smith (1983) argue that this effect would be lesser on upland sites where there would be more chilling hours through the winter than on lowland sites. In such situations, where sufficient chilling hours have occurred, earlier bud break may be expected with a consequent longer growing season as long as tender shoots are not

[3]Bud flushing is the process of buds opening and juvenile leaves emerging for the first time in spring.

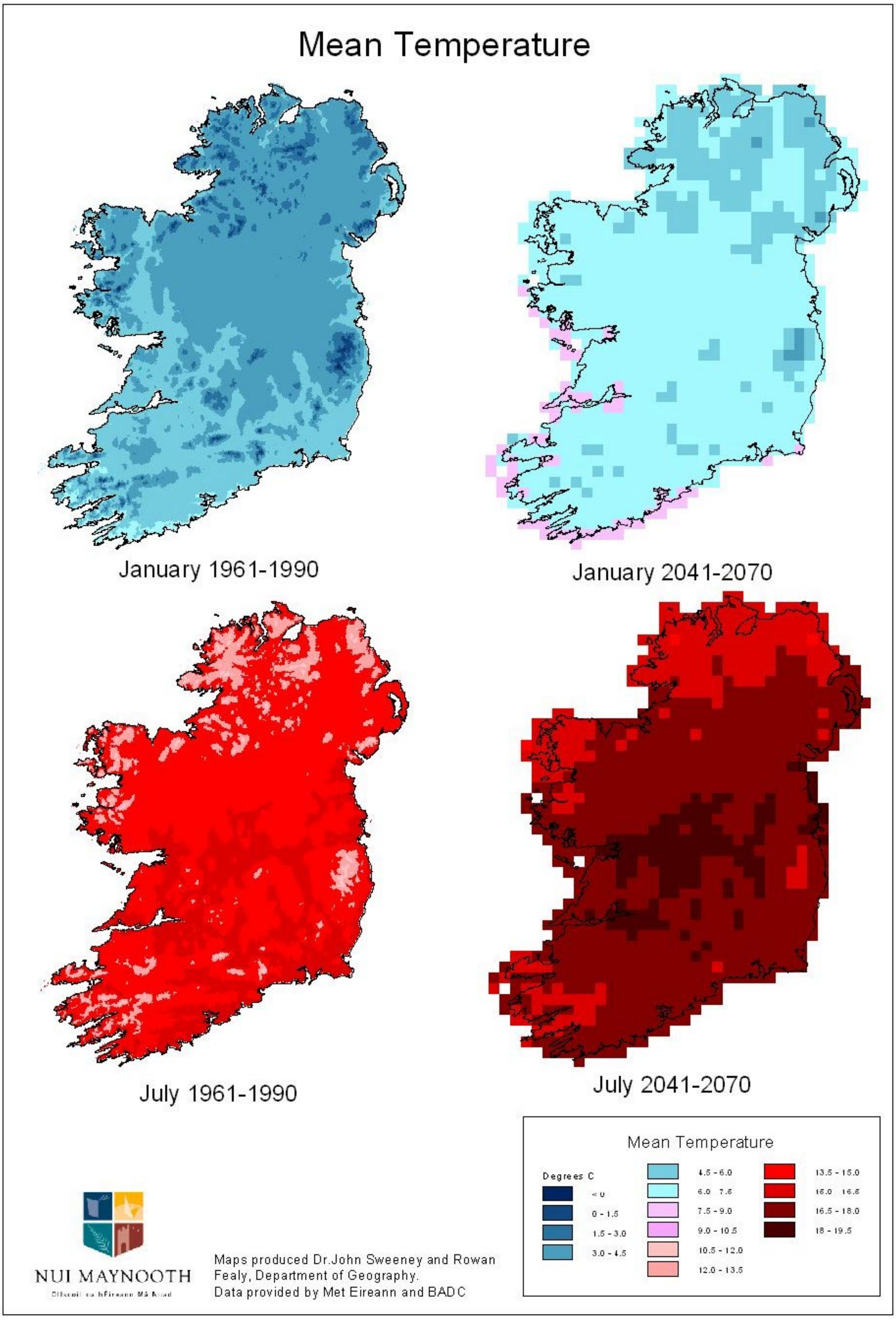

Figure 5.1. Mean temperatures 1961–1990 (baseline) and 2041–2070 (downscaled) (Sweeney and Fealy, 2002).

damaged by late frost. For most species, the dominant trigger for shoot and bud growth cessation in autumn is night length and not temperature (Saxe *et al*., 2001). Although shoot and bud growth may cease, it is possible that girth and volume growth may continue in warmer autumns.

Late spring frosts have caused considerable damage to early season growth of Irish forest crops, in particular Sitka spruce and ash planted on flat sites with low levels of air movement. Given that both winter and summer temperatures are expected to increase (Sweeney and Fealy, 2002), it is reasonable to assume that frosts will be less frequent, particularly early autumn and late spring frosts. It is, therefore, likely that, because of their elevated locations, most Irish forest crops will commence growth earlier in the spring than at present. Also, species such as southern beech (*Nothofagus* spp.) and Monterey pine (*Pinus radiata* D. Don), previously thought of as unviable because of, amongst other factors, potential frost damage, may be reconsidered as viable.

5.3.3 *Increased frequency of storms*

In the projections of future climate change made by the Intergovernmental Panel on Climate Change (IPCC, 2001b), increased frequency of strong wind and storm events are forecast for the North-East Atlantic and Western Europe. The location of Irish forests, generally on exposed, windy sites with poor drainage, renders an inherent vulnerability to wind damage. Irish forestry has recently suffered large losses to such events. In 1997, 1998 and 1999 Coillte, the Irish Forestry Board, reported about 0.5, 0.85 and 1.6 million m^3, respectively, of roundwood being blown down (Coillte, 1997, 1998, 1999). Britain suffers similarly, and it is estimated by Quaine *et al*. (1995) that, not counting the extreme storm events, windthrow accounts for approximately 15% of the annual production of Britain's forests. Up to 30% of the annual harvest in Ireland can comprise windthrown material (Forest Service, 2000a). Ní Dhubháin (1998) discusses the influence of wind on forestry in Ireland and suggests that for existing forests, planted on relatively exposed, ploughed sites and now reaching critical heights in relation to windblow, endemic windblow may increase. However, she suggests that younger forests, established on lower altitude, better-draining sites with improved cultivation and thinning techniques should be more wind firm than those currently at risk.

5.3.4 *Decreased rainfall*

Figure 5.2 presents baseline (1961–1990) and downscaled scenarios for 2041–2070 in relation to summer and winter precipitation for Ireland (Sweeney and Fealy, 2002). These show potentially wetter winters for many parts of the west and midlands with little change suggested for the east and south-east. It is in the summer, however, that the most significant changes are forecast with considerably less rainfall in all areas with the exception of the north-west.

Soil moisture deficits are rarely encountered in plantation forestry in Ireland (Keane, 1986). In general terms, reduced water availability, resulting from increases in potential evapotranspiration and reductions in summer rainfall, may lead to loss of vigour on some sites, particularly drier ones. However, this is very dependent on site type and species. A large proportion of commercial forests in Ireland are established on land considered marginal for agricultural use and almost by definition, these sites are associated with high water-holding capacities.

Periods of summer drought cause particular difficulties in the establishment of forests when roots have not yet fully developed and adjusted to their new environment. This has implications for current forest nursery practice and renewed research into the use of containerised stock or other methods of reducing planting shock may be worthwhile.

5.4 Potential Secondary Effects

Potential secondary effects are defined as those indirect effects which changing climatic elements may have on tree or forest growth as a result of their alteration of the forest ecosystem. A number of potential secondary effects are discussed in Section 5.4.1 the context of climate change projections and potential primary effects.

5.4.1 *Increased nutrient mineralisation*

A key component of vegetation functioning is the maintenance of a nutritional balance. Given this, it is likely that responses to increased CO_2 levels will be limited by nutrient availability (Rastetter *et al*., 1992;

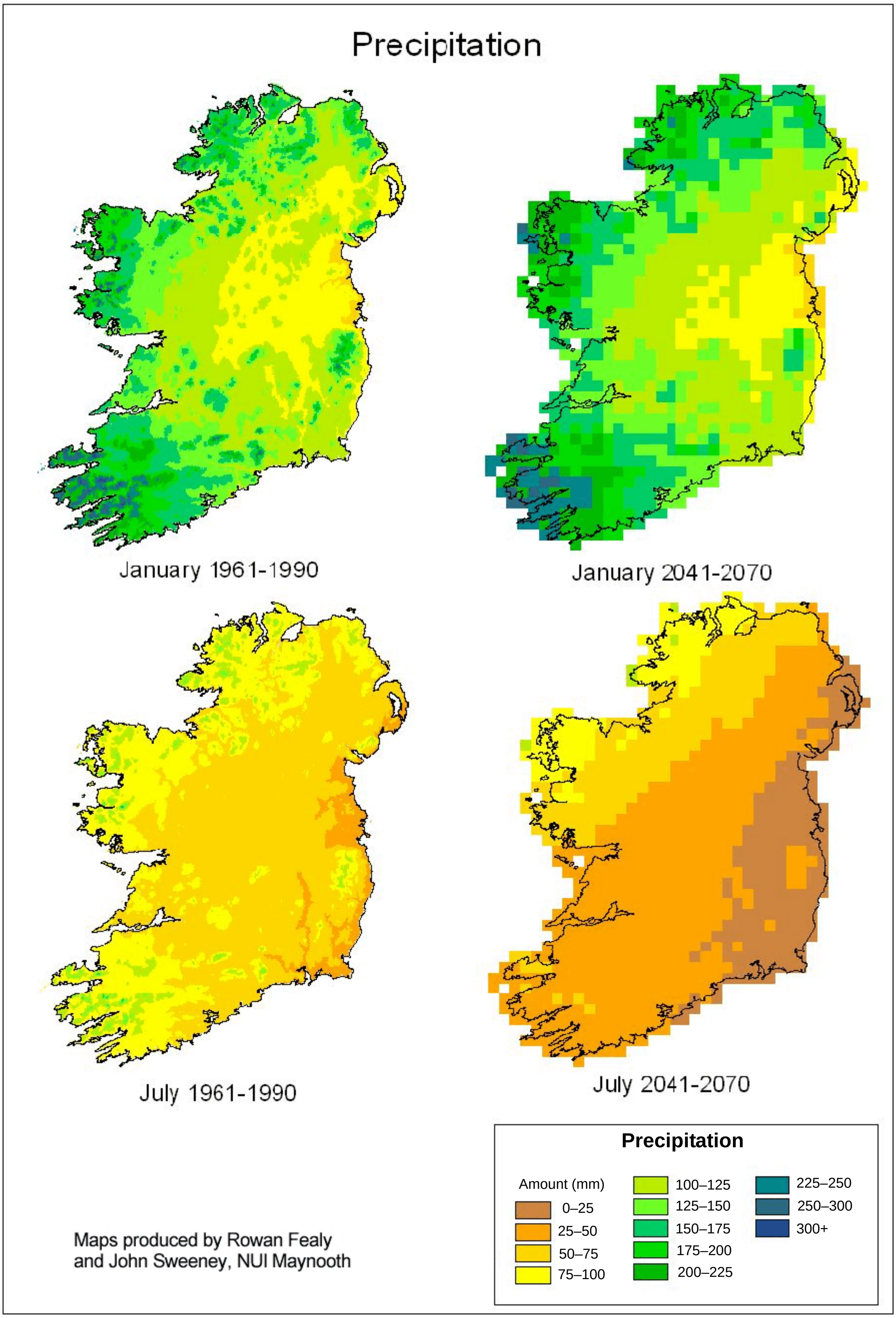

Figure 5.2. Precipitation 1961–1990 (baseline) and 2040–2069 (downscaled) (Sweeney and Fealy, 2002).

Shaver *et al*., 1992; Comins and McMurtrie, 1993). Nonetheless, the responses of vegetation are also linked to the ability of vegetation to acclimatise to increased CO_2 concentration by making greater efforts to acquire limiting soil nutrients or by decreasing nutrient concentrations in biomass.

Thornley and Cannell (1996) suggest that, with regard to tree and forest growth, the crucial processes in climate change are those which affect the nitrogen (N) cycle. Forest productivity is more strongly affected by N availability as, of all the nutrients required for growth and survival, it is the one required in most abundance (Saxe *et al*., 2001). In Ireland, N availability is more frequently affected by drainage or competing vegetation, and it is phosphorus (P) that is most commonly applied as a fertiliser, particularly in young forest crops.

Results from field and laboratory experiments show that elevated temperature will increase rates of organic matter decomposition and, therefore, nutrient availability (Saxe *et al*., 2001). However, work by Liski *et al*. (1999) suggests that old organic matter may be resistant to decay. Overall soil-warming effects on nutrient mineralisation may be no greater than the effects of continued nitrogen deposition, changes in vegetation and natural and anthropogenic disturbance.

5.4.2 Forest pests and diseases

Irish forests are recognised under the European Union Plant Health Directive 77/93/EEC as being among the healthiest in Europe, with relatively few serious forest pests and diseases (Forest Service, 2000a). This situation is maintained by Ireland's island status and by the enforcement of forest plant health regulations. However, the nature of our forest estate, which is primarily made up of exotic conifers planted in monoculture, means that there is an inherent risk of serious infestation.

Elevated CO_2 is expected to alter foliage content of C, mineral nutrients and secondary metabolites. This is expected to have the effect of modifying insect and tree interactions (Saxe *et al*., 1998). In general terms, although each species has its own optimal temperature range, insect populations increase with increasing temperature. Insect populations will also exploit situations where trees are stressed, e.g. as a result of drought, storm damage or flooding. There are a number of insects that currently afflict Irish forests or may potentially impact Irish forestry as a result of climate change. Some of the more important ones are outlined below.

Green spruce aphid (Elatobium abietinum)

The green spruce aphid is present in Ireland and acts by defoliating Sitka spruce, affecting all but the current year's growth. It rarely kills trees but can reduce productivity significantly as has been experienced in a number of locations in Ireland over the last decade. Temperatures of below –7°C are required to effect mortality of the green spruce aphid. Milder winters, particularly in drier areas, could result in large population increases and serious loss of growth on a regular basis.

Pine weevil (Hylobius abietis)

The pine weevil breeds on dead and decaying timber and attacks young trees at establishment phase by de-barking the stem. This is one of the more serious insect pests currently extant in Irish forestry, particularly on localised reforestation areas where breeding sites abound. A rise in average temperatures could result in greater pine weevil activity, particularly in combination with the effect of recent legislation which has banned the use of the chemical pesticide lindane.

Great spruce bark beetle (Dendroctonus micans)

This beetle is not currently present in Ireland but causes huge economic losses to Norway spruce across Europe. Ireland, with large areas of monocultural spruce may well become vulnerable to this species, particularly in areas such as the east and south-east where drought induced stress may become significant.

European pine sawfly (Neodiprian sertifer)

European pine sawfly attacks most species of pine by defoliating and thereby causing a considerable loss of increment. Serious outbreaks are dependent on a series of three consecutive dry summers over which populations peak. Population densities then decline abruptly, usually as a result of a virus outbreak. Projected climate change scenarios for Ireland would suggest that European pine sawfly will become an increasing threat to the productivity of pine forests here.

The potential effects of climate change on a sample of diseases that currently, or could potentially, afflict Irish forests are briefly described below.

Fomes (Heterobasidion annosum)

Fomes, a root and butt rot, is currently the most important disease affecting Irish forestry. The disease spreads through root contact and mycelia at a rate of approximately 1 m year^{-1} but most importantly through the landing of spores on freshly cut stumps. The optimum temperature for growth of this fungus has been found by Rishbeth (1951) to be 22.5°C. The same author also reports that fructifications are relatively resistant to both drought and moderate frost. This would suggest that Fomes may become more of a threat in a warmer and drier climate.

Phytopthora disease of alder

This fungus invades the stems and roots of alder trees causing them to die back by killing the bark. It has only recently been identified as present in Ireland and it is possible that its recent expansion is an indicator of environmental change. The effects of hot, dry summers (such as those recently experienced in the south of England) on the susceptibility of alders are currently being evaluated by the Forestry Commission in the UK (Brasier, 1999).

Honey fungus (Armillaria mellea)

Honey fungus is one of the most widespread of all root and butt rot disease fungi. Its mycelia and rhizomorphs grow optimally at between 20 and 25°C while fruit body formation is optimal at 25°C. Drought conditions have often been considered to render trees more liable to infection (Phillips and Burdekin, 1982). It would, therefore, seem reasonable to suggest that climate change as forecasted will provide more favourable conditions for the spread of honey fungus.

Mammals

Broadmeadow (2000) suggests that both deer and grey squirrel populations may respond positively to warmer winters in Britain. The unchecked population growth of both these mammals constitutes a significant threat to the Irish forest industry. Deer cause damage by stripping bark from young trees and browsing young and tender foliage. Grey squirrels also strip bark from young trees and the tops of older trees causing severe crown damage. Both can result in tree death or at least serious loss of productivity and timber degradation. Currently the damage they cause is limited to certain species and forest areas. However, the population and range of both deer and grey squirrels are increasing dramatically in Ireland (Rooney and Hayden, 2002). A further enhancement of their environment resulting from climate change could cause serious problems for the Irish forest industry.

Forest fires

Forest fires in Ireland are relatively infrequent compared with other countries. About 450 ha of forest are lost to fire each year in the period from February to September with the vast majority occurring in March, April and May. Weather, in the form of rainfall, humidity, wind and temperature controls the inflammability of competing vegetation, the tree crop and, on peat sites, the ground itself. In the high risk period of March to May, fire hazard conditions will exist on any day in which there has been less than 1 mm of precipitation in the 32 h prior to 14:00 h and on which the relative humidity at 14:00 h is less than 55% (Keane, 1986 quoting Duffy, 1985 – unpublished thesis).

Warmer and drier conditions, particularly in the spring and early summer can only serve to increase the risk of fire in Irish forestry. However, Keane (1993) validly points out that as most forest fires in Ireland actually start outside the forest it is more important to assess how climate change will affect other vegetation types before predicting whether or not forestry will be impacted.

5.5 Interaction of Different Effects

In the previous sections, an attempt has been made to review the potential impacts of isolated changes in climatic factors. However, it is clearly the interaction of these different factors and their potential combined effects on forest growth that is of real interest to forest managers and planners. Breymeyer *et al*. (1996) warn strongly that failure to take account of the interactions of individual climate factors with other environmental parameters can lead to serious errors in the prediction of their overall potential impact. There are a number of models which attempt to project the potential impact of climate change on forest ecosystems. As discussed earlier, this is a highly complex task and results are generally as much a function of model design as they are of model inputs. Despite this, huge progress has been made in modelling the potential impact of climate change on forests and a number of such studies are referenced below.

Thornley and Cannell's (1996) work on temperate forest responses to CO_2, temperature and nitrogen changes is perhaps the most interesting from an Irish forestry perspective. This work involved the simulation of effects on a managed conifer plantation in upland Britain, a scenario probably also quite typical of Irish forestry. It was found that rising temperatures, along with rising CO_2, may either increase or decrease forest productivity on such sites, depending on the supply of N and changes in water stress.

The particular model used analysed the potential impacts based on projected increases from 350 to 550 µmol mol^{-1} CO_2 and from 7.5 to 9.5°C (mean annual temperature). Goodale *et al*. (1998) drew similar conclusions stating that "*site specific conditions and management practices result in a range of forest productivity that is much greater than any likely to be induced by climate change or CO_2 enrichment*". Further evidence to suggest that soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere is provided by Oren *et al*. (2001). They point out that forests are usually relegated to sites of moderate fertility where tree growth is often limited by nutrient supply, in particular nitrogen.

Joyce and Nungesser (2000) suggest that forest productivity may increase under elevated CO_2, but that the local conditions of both moisture stress and nutrient availability will strongly temper any response. Thornley and Cannell (1996) suggest that because water-use efficiency is expected to improve in an elevated CO_2 environment, temperate forests may be protected from the predicted water stress resulting from increased temperatures.

Many of Ireland's commercial forests are located on poor-quality land that was drained specifically for the purpose of afforestation. Without the addition of fertiliser, many of these forests might never have been successfully established. On such sites it is, therefore, possible that limitations in the supply of N and P will temper any potential for increased biomass production due to CO_2 fertilisation or increased rates of photosynthesis. A further application of both N and P fertiliser may be possible but this has economic implications. However, much of the more recent, private sector, planting has been on better sites where one would not expect there to be limited nutrient availability. These newer forests, along with those older ones established on nutrient-rich sites, might be expected to increase their rate of production in a CO_2-enriched and warmer climate as long as water availability does not become limiting during the growth season.

Breymeyer *et al*. (1996), while acknowledging that nutrient limitation may negate the CO_2 fertilisation effect, maintain that C_3 plants will actually behave more efficiently in their use of nutrients in an elevated CO_2 environment. This agrees with the conclusions of Thornley and Cannell (1996) who state that, as a result of increased CO_2, N acquisition (where available) and N-use efficiency will increase. This will give rise to increased ecosystem productivity and carbon storage. Cannell *et al*. (1998) tested this theory by using both the ITE Edinburgh Forest Model and the Hybrid Model (Friend *et al*., 1997). Both of these models associated historical increases in Net Primary Productivity (NPP) and Yield Class with increased CO_2 levels, temperature and N deposition. Significantly, however, they also both predicted that the current rate of increase in productivity would continue until the end of the 21st century with an increase in Yield Class of about 5 m^3 ha^{-1} $year^{-1}$ and an increase in NPP of between 24 and 34% between 1990 and 2050.

Although increased CO_2 levels in the atmosphere are expected to increase water-use efficiency within trees, it is not necessarily correct to conclude that this will result in greater drought tolerance (Tschaplinski *et al*., 1995 as quoted in Saxe *et al*., 1998). The increased water-use efficiency may be offset by increased leaf production (Broadmeadow, 2000) and increased leaf area associated with increased N availability (Thornley and Cannell, 1996), both resulting from elevated CO_2.

Forecasted increases in wind speeds and the frequency of severe gales would suggest that Irish forestry will continue to suffer from wind damage and to a greater extent than in the past. However, as pointed out by Ní Dhubháin (1998), the increased afforestation of lower lying sheltered farm sites may mean that a higher percentage of Irish forests will be less vulnerable in the future. Shallow rooting and poor anchoring of trees as a result of impeded drainage and root alignment along plough ribbons are often the cause of windblow in Irish forest crops. In a decreased rainfall scenario, which may result in a lowering of the water table on some sites, it is conceivable that windblow risk will be reduced. However, wind damage is not limited to trees blowing over. Wind snap, whereby trees, whose roots are well anchored, break in very strong winds can be of even greater economic damage than windblow. This is because wind snap renders the stem unusable for structural timbers due to splitting and shattering whereas valuable sawlog material can be salvaged from trees that have simply blown over. The potential for wind snap would appear to be greater in the future assuming improved root anchorage and increased leaf area and thus canopy resistance to wind.

It is generally agreed that trees and forests exhibiting vigorous growth are less susceptible and quicker to recover from damage by pests and diseases. It is, therefore, difficult to predict what might happen to Irish forests in a situation where growth is stimulated by CO_2 fertilisation and increased temperatures yet climatic conditions favour a dramatic rise in the populations of damaging pests and diseases.

Different tree species have different optimal conditions for flowering and the production of seed. Generally these conditions are weather and climate related. For both broadleaves and conifers, conditions at the time of pollination determine the number of normally developed or ‘full’ seeds that are formed. Dry, sunny and windy weather at this time will result in greater numbers of full seeds than dull, wet and still weather (Gordon, 1992). Recent research summarised in Saxe *et al*. (2001) has shown that weather conditions at the time of pollination may also influence the progeny themselves.

5.6 Forest Management and Policy Implications

A mild and moist maritime climate is the one overriding factor that gives Ireland its competitive edge for forestry over other European countries. For this reason, any implications of climate change are of great importance to the Irish forestry sector. There are a number of industry-level models in existence, particularly in the USA (e.g. the Timber Assessment Market Model (TAMM, Adams and Haynes 1980, 1996) and the Forest and Agriculture Sector Optimization Model (FASOM, Adams *et al.*, 1996; Alig *et al*., 1997)) which attempt to model the effects of climatic change on the forest sector as a whole. These ‘forest sector models’ combine generic activities related to the use of wood such as forest growth and harvest, the manufacture and trade of pulp, paper and solid wood products, and the intermediate and final consumption of these products (Kallio *et al.*, 1987). As pointed out by Mills *et al*. (2000), these kind of models effectively “*operate at the interface of science and policy where the emphasis is on how models themselves improve the information available for decision makers*”. No such models are available for assessment of the potential impacts of climate change on the Irish forest industry. However, this section discusses some potential implications for foresters and policy makers.

5.6.1 Species and provenance selection

As outlined in the introduction, the Irish forestry industry is heavily reliant on the production of coniferous forest crops of exotic species. These species have been selected by foresters as suitable for growth in the prevailing Irish climate and on existing Irish site types. Coniferous crops are generally grown in Ireland over rotations of between 35 and 60 years. Unlike agricultural practice, there is no opportunity, without premature felling, for replacement of the selected species with a more suitable one until the prescribed rotation is complete. Therefore, foresters planting forests now must make species selection decisions in the context of potential climate change. Another opportunity will not present itself on the specific site for a further 35–60 years. From the point of view of matching species to climate and site, it is reasonable to think that a gradual climate change, although affecting growth in ways discussed earlier, can probably be accommodated without serious losses over what are, in forestry terms, relatively short rotations. However, a climate 'flip' as suggested by Fleming (1998) may have more serious consequences. Foresters will, based on their experience and information about future environmental change, make a decision on species or provenance choice for subsequent rotations.

As discussed earlier, all tree species are dependent on the basic physiological processes of photosynthesis and respiration that may be affected by climate change. However, different tree species have different requirements and adaptations in terms of the temporal, physical and chemical environment in which they grow. This is exhibited for example in the way that some species are tolerant of shade (beech) while others require direct sunlight (Scots pine), some species flush early in the spring (larch) while others flush later (ash). Therefore, climate change will potentially impact differently on different species and on different sites.

Sitka spruce is the predominant commercial species used in Irish forestry. Its natural distribution in the wet coastal forests of north-west America suggests that it has a high moisture requirement and Macdonald (1952) reports that, in Britain, it is rarely seen at its best in areas of less than 1000 mm of rainfall/year. This would suggest that, apart from in mountainous areas, conditions may become less favourable for the species along the east coast and in the south-east of Ireland, particularly if defoliating green spruce aphid (*Elatobium abietinum*) populations take advantage of crops exhibiting water stress (Lines, 1987). Apart from the frost tenderness of new growth, the performance of Sitka spruce appears to be relatively independent of temperature variations (MacDonald *et al*., 1957). There is, therefore, no apparent reason, apart from in the areas discussed above, to suggest that this species will not continue to be the mainstay of commercial forestry in Ireland.

Current Irish forest policy is to diversify the range of coniferous species planted. The main alternative commercial species to Sitka spruce are Norway spruce, Douglas fir and Japanese larch. Other diverse coniferous species such as Scots pine, lodgepole pine, European larch and Western hemlock are also planted. Norway spruce is a species associated with a continental climate and is thus more tolerant than Sitka spruce of drier summers on drier sites. Douglas fir comes from a huge natural range from coastal British Columbia in Canada to coastal California and inland as far as Colorado with pockets extending into Arizona and Mexico. Coastal provenances from Washington are currently used in Irish forestry but there is evidently good potential for other provenances of this species to be used if climate change occurs as forecasted. However, Douglas fir is intolerant of flooding and this may limit its use if wetter winters result in flooded forest sites. In contrast to Douglas fir, Japanese larch has a very small natural range and there are limited opportunities in provenance selection. It grows extremely vigorously in its early years, often resulting in poor stem form (Lines, 1987). Even more vigorous growth caused by warmer conditions and CO_2 fertilisation may exacerbate this problem and cause considerable loss in timber value. Western red cedar is a valuable timber species but little used in Irish forestry with approximately only 40 ha established per annum (Forest Service, 2001). This species thrives in wet and mild atmospheric conditions and on heavy soils with a high water-holding capacity. The inland part of its natural range is characterised by relatively dry summers (Lines, 1987). This species should be investigated further as one with considerable potential for use in a climate change scenario. Keane (1993) suggests some other species such as Eucalypts, *Nothofagus* and *Pinus radiata* that might also be considered for future use.

Thompson (1998) points out that genetic traits associated with adaptability to local conditions exist not just at species level but also at provenance, family and individual level. Saxe *et al* (1998), in a review of current knowledge on tree and forest functioning in an enriched CO_2 atmosphere, reference various studies that have shown different responses to CO_2 enrichment between species, hybrids of the same species and even different families within species. Bazzaz *et al*. (1995) suggest that future CO_2 levels would lead to increased intensity of natural selection. There is considerable genetic variation within coniferous species used in Ireland and seed sources, although of a specific provenance, are essentially 'wild' and unlike agricultural crops, with little selection for optimisation of traits for Irish climatic, site and market conditions. This is confirmed by COFORD (1994) who say that although there are tree-breeding programmes in place for most species, there is little genetically improved seed used in Irish forestry. It follows that, in a climate change scenario, there is good potential for continued use of existing species with increased selection for traits that will accommodate the predicted environmental changes.

Foresters who make decisions on what species and provenance to plant will now have to take potential impacts of climate change into account. They will need assistance in the form of research results and availability of different species, provenances and varieties. In New Zealand, where, like Ireland, a forest industry has developed around the growing of exotic conifers, new varieties can be produced from their plant breeding programme in 12–14 years (Grace *et al*., 1991). This, they believe, will allow them to keep pace with climate change as it occurs.

5.6.2 Forest locations

The over-riding principle applied by foresters in establishing new forests is to appropriately match species to site. (The general term 'site' incorporates soil type, aspect, climate, altitude and some other factors.) It has already been discussed that the quality of site types available to Irish foresters has improved in recent years and this has facilitated a much greater diversification in terms of the species selected for planting. Species selection has always assumed that the site will not alter significantly during the course of the rotation. However, this can no longer be assumed to be the case. The Irish Forest Service has recently created a GIS-based Forest Inventory and Planning System (FIPS) which is currently being developed to include forest soils data for the whole of Ireland. It is suggested that forecast climate change scenarios be added to the FIPS in order that foresters can take full account of all site-related factors in the future planning and management of new and existing forests.

In the past, forestry has been located on land that has not been economically viable for agricultural use. This is still the case although to a lesser extent, particularly with the availability of generous grants and premiums for forestry. The potential impact of climate change on Irish agriculture is, therefore, of critical importance to Irish forestry as it may have a large bearing on where and how much forestry is established in the future. However, it is likely that forestry will continue to be established on wet land, marginal for economic agricultural activity. There is no current reason to suggest that these sites will ever become unsuitable for forestry. However, as discussed earlier, the importance of matching species to site has never been more important.

5.6.3 Forest establishment and management

Current forest establishment practice in Ireland involves cultivation and drainage, protection in the form of fencing, planting and vegetation control. Other operations such as fertilising, control of browsing mammals and the ploughing of fire breaks can be locally important (Forest Service, 2000a). Tree planting is carried out in the dormant, winter season although the use of cold stored plants means that the planting season can be extended into late spring. In a potentially milder climate, the timing of a number of these operations may become more critical. On some sites, the use of machinery in cultivation and drainage is currently restricted by wet winter conditions. In a scenario such as the one forecast, where winters become generally wetter, it may become necessary to complete all drainage and cultivation work in the summer or autumn prior to planting rather than in conjunction with planting as is currently widely practised. Competing vegetation will probably benefit from an extended growing season and increased growth rates. The control of competing vegetation may, therefore, require earlier and more frequent interventions. Similarly, depending on species, the dormancy period may be affected with a resulting effect on optimal planting dates. Post planting care may also become more critical, particularly in areas experiencing warmer, drier summers which are often the cause of tree mortality in newly planted areas. The use of container grown transplants, used in some countries to extend the growing season and reduce planting shock, may be worth investigating in this regard. Fire management is likely to become increasingly relevant with warmer and drier summers forecast. It is probable that extra management resources will be required in order to mitigate against the risk of economic loss due to fire.

5.6.4 Harvesting and transport

The principal forms of forest harvesting undertaken in Irish forests are thinning and clearfelling (Forest Service, 2000a). These are carried out using large machinery which may, as part of a harvesting plan, be seasonally restricted, for example as a result of wet weather or waterlogged sites. For this reason, certain sites are considered in the industry as ‘summer sites’, referring to the fact that they are best harvested during drier summer weather. If Irish forestry is to experience wetter winters and drier summers as a result of climate change, there may be increased pressure to carry out harvesting on a greater number of sites in the drier summer period. This may cause logistical problems for the Irish forest industry in the supply of timber to the processing sector and the continuity of work for harvesting contractors.

5.6.5 Silvicultural systems

Conventional practice within the Irish forest industry is to operate a silvicultural system using even-aged crops of generally not more than two species grown over an optimal financial rotation, followed by clearfelling and replanting. There are many alternative silvicultural systems to clearfelling, and the prospect of climate change provides an appropriate opportunity to raise the relative merits of these alternatives systems vis-à-vis their potential ability to cope with changing conditions.

The clearfelling system offers the forester the opportunity to initiate a completely new crop with a new species and management regime that matches the prevailing site and climatic conditions. Alternative systems do not afford this opportunity to the same extent. However, the bare establishment site is a relatively harsh environment for young trees, exposed to wind, drought, and attack from pests and vigorous competing vegetation. Group and continuous cover silvicultural systems offer the newly planted or naturally regenerated tree a more protected environment in which to establish. These alternative silvicultural systems also appear to be less susceptible to wind damage, leaving fewer exposed edges than clearfelling and providing a diverse stand height structure that, in addition to providing mutual crown support, effectively filters wind rather than behaving as a resistive barrier. There are virtually no species of insect that trouble a tree from sapling through to maturity. This may be used as another strong argument for greater use of silvicultural systems that involve mixed-age classes. From a purely economic viewpoint, the economies of scale associated with clearfelling cannot be matched by alternative silvicultural systems. However, it is still perhaps too soon to economically assess the sustainability of production from clearfelling and alternative systems.

Much of the European and American literature on the potential impact of climate change on forests is taken up with discussions of the ability of forests to migrate with changing environmental conditions. The concern is that the rate of forest migration will not be able to keep pace with the rate of climate change and that, as a result, there may be large areas of forests stranded outside of their ecological niche causing severe stress and decline. In Ireland, where plantation forests make up about 90% of the total area of woodland, this is of lesser concern in that these areas can be gradually replanted with more suitable species, provenances or varieties if required. However, Ireland’s native and semi-natural woodlands have a very important heritage value and research is required into their potential response to climate change.

5.6.6 Forest protection and health

There are two main resistive forces to windthrow of trees: root anchorage and contact or support between crowns of adjacent trees. Current practice in Ireland as outlined in the Forest Service’s (2000a) *“Code of Best Forest Practice – Ireland”* represents an improvement on past practice with regard to both of these key forces. Root anchorage is expected to improve significantly on sites cultivated using either mounding or ripping and improved drainage. The opening of new gaps in the canopy and the creation of edges vulnerable to wind will be reduced with earlier and more selective thinning and with improved forest and felling design plans.

Current government policy with regard to forest protection and health is defined in the Strategic Plan for the Development of the Forestry Sector in Ireland (Forest Service, 1996). The policy statement is “*to maintain a healthy forest environment by ensuring good management, identifying risks and maintaining a sustained commitment to measures which prevent the entry and establishment of destructive forest pests and diseases*.” Predicted downscaled climate change scenarios for Ireland (Sweeney and Fealy, 2002) show warmer and drier summers for the period 2041–2070, particularly in the south-east and east of the country. Forests in these areas are likely to suffer from increased frequency and severity of insect and disease damage as a result of drought-induced stress. These warmer, drier conditions will also make Irish forestry more vulnerable than at present to the introduction of pests such as the great spruce bark beetle (*Dendroctonus micans*) and current policies on preventing entry will require regular review. Most shipped trade with Europe comes through ports in the south-east and east and this adds to Ireland's vulnerability.

Measures currently in place to limit the spread of Fomes (*Heterobasidion annosum*) include a legal requirement to treat all freshly cut stumps with urea which renders them inhospitable to colonisation. It is unlikely that any further measures would be cost effective in controlling the spread of this or other diseases.

Forecast climate change scenarios would suggest a more favourable habitat for already threatening mammals such as deer and grey squirrel. Regional management plans will be necessary for the control of these species as they are not practically managed on a site-by-site basis.

5.6.7 Carbon sequestration

The ability of forests to sequester atmospheric CO_2 is well documented (e.g. Valentini *et al*., 2000). In the context of the Kyoto Protocol, countries will be able to use part of their forest sink to offset their emissions of greenhouse gas emissions. Given the fact that most of our forests are young and that the forest estate is rapidly increasing, Ireland is particularly well placed to take advantage of this. The National Climate Change Strategy (Department of Environment and Local Government, 2000) foresees forestry as playing a significant role in helping Ireland meet its obligations under the Kyoto Protocol.

The ability of forests to function as carbon sinks in a changed climate remains uncertain. While the combined effects of stimulated photosynthesis and reduced respiration result in increased rates of carbon sequestration, there is evidence that soil warming may increase C losses from soil by accelerating microbial respiration and dissolved organic carbon leaching (MacDonald *et al*., 1999). In a study of the impacts of terrestrial ecosystem warming in tundra, grassland and forest, Rustad *et al*. (2001) found that soil warming increased soil respiration, nitrogen mineralisation and plant productivity. In contrast to these findings, Liski *et al*. (1999) found that the amount of carbon in Finnish soils of both high- and low-productivity forest types actually increased with temperature. Given the scientific uncertainty which exists, it is clear that, in order to understand the possible effects of climate change on the carbon cycle in Irish forests, studies of the importance of specific factors such as moisture, temperature, soil type and land-use history at different spatial and temporal scales, will be required. Any future changes in the carbon balance of Irish forests will have implications for national strategies to reduce greenhouse gas emissions.

As discussed above, forestry may help in mitigating climate change through carbon sequestration. The use of woody biomass as a renewable energy resource, may also become an important tool in the Irish Government's Climate Change Strategy. The production of woody biomass is already an important component of other European countries' renewable energy sectors. It is likely that the Irish forestry sector will be charged with the responsibility of creating and managing such a resource in the future.

5.6.8 Research and development

It is evident that climate change as forecast both internationally by the IPCC and nationally through research such as that of Sweeney and Fealy (2002) will impact on Irish forestry. The many different sub-sectors within Irish forestry will all potentially be impacted to varying degrees. Specific research is required into these sub-sectors in order that proper planning and mitigation of any potential impacts can be put in place if necessary.

Irish forest research is administered by the National Council for Forest Research and Development (COFORD). COFORD currently funds research into the climate change related areas of carbon sequestration and the use of woody biomass for renewable energy. Other research areas identified by COFORD as being of strategic importance such as forest genetics and tree breeding, forest health and vitality, silviculture, nursery research and development are all potentially affected by climate change. It is important that all such research takes account of potential changes in the Irish climate.

5.7 Concluding Remarks

A number of specific areas require further research. These are summarised as follows:

- Recent advances have been made with the introduction of dynamic yield models. These should be regarded as a stepping stone to a more holistic forest ecosystem or process-based model. Through simulating ecosystem processes, these models should ultimately predict the development of the ecosystem over time and in response to changing environmental conditions. The output of the model will then encompass forest production but also the wider issue of sustainability of the forest ecosystem.
- Long-term research is required into the potential impact of climate change on organic matter turnover and N mineralisation.
- There is a need to continue to assess different provenances and species in long-term research trials. It is recommended that particular attention be paid to alternative provenances of Douglas fir and western red cedar.
- The national tree-breeding programme should be reassessed in the light of current knowledge on potential climate change and with a view to the selection of traits that will accommodate and capitalise on these changes.
- The potential for the production and transplanting of containerised nursery stock should be reassessed.
- Climate change scenarios should be included in the Forest Inventory and Planning System operated by the Forest Service in the Department of Communications, Marine and Natural Resources.

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6 Assessment of the Impacts of Climate Change on Biodiversity in Ireland

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6.1 Introduction

The aims of this section of the report are to: (i) review the impacts of climate change on Irish species and habitats, (ii) investigate the vulnerability of selected Irish species and habitats to changes in temperature and rainfall predicted for 2055 and 2075, and (iii) identify key areas that future work should focus on.

Biodiversity or biological diversity describes the variety of life at any point on the earth's surface. There are several key elements of biodiversity which can be organised into three groups: ecological, genetic and organism diversity (Kevin *et al*., 1998). This section of the study focuses on species as elements in organism diversity and habitats as elements in ecological diversity and the environmental processes affecting them. Particular attention is given to species and habitats of nature conservation value, i.e. those listed in the EU Habitats Directive (92/43/EEC).

The Irish Government has an obligation under several global and European conventions and directives to protect its biological diversity and safeguard the loss of species and habitats against threats, including climate change. The most important international conventions and directives are the Ramsar Convention (1971) on wetlands of international importance especially as waterfowl habitat, the Rio Convention (on Biological Diversity, 1992), the EU Habitats Directive (Council Directive on the conservation of natural habitats and of wild fauna and flora 92/43/EEC) and the EU Birds Directive (Council Directive on the conservation of wild birds 79/409/EEC). In addition, biodiversity is protected at the national level under the Heritage Act (1995), the Wildlife Act (1976, amended 2000), the Whale Fisheries Act (1937) and various flora protection orders (1999). Ireland also ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and signed the Kyoto protocol in 1998, indicating its support for international measures to reduce greenhouse gas emissions by setting legally binding emission reduction targets. There are also several other pieces of legislation protecting various aspects of biodiversity in Ireland.

6.2 Climate Change Impacts

Climate plays a pivotal role in determining the geographic distribution and ecology of species (Brown and Lomolino, 1998) as the climatic tolerances of most species are largely fixed (Hill *et al*., 1999). This is particularly true of plants, invertebrates, amphibians, reptiles and freshwater fish. In addition, many birds are indirectly affected by climate through their dependence on features of the vegetation (Malcolm and Pitelka, 2000).

Ecologists have developed the concept of a 'climate envelope' which refers to the range of climatic conditions over which species or vegetation types occur (Box, 1981; Emanuel *et al*., 1985). This approach assumes that the geographic range of a particular species or vegetation type is defined by the current climatic conditions over that range. For example, the vegetation of Ireland has a distinctive and highly oceanic character as a result of its location on the north-western extremity of Europe. The potential natural vegetation of Ireland under present climatic conditions would largely be forest, except for the mires, mountain tops and some coastal areas (Cross, 1998). However, the current distribution of any species is the result of many factors operating alongside climate, including soil conditions, hydrology, inter-specific competition, population isolation, habitat availability and dispersal ability (Hossell *et al*., 2000). As a result, organisms often occur in only a fraction of their climatically suitable range. Such complexities must be considered in forecasting changes in the distributions of species or vegetation types.

Climate also affects the biological functioning of species and habitats. In particular, climate determines the total amount of plant growth per unit area per year – the net primary product (NPP). The amount of carbon stored by a habitat as a result of NPP is also dependent on climate. In Ireland, the carbon storage potential of natural and semi-natural habitats, such as peatlands, woodlands and grasslands, is very important because it represents one possible method of mitigating the effects of increasing atmospheric carbon dioxide (CO_2) concentrations.

Future climate scenarios, described in Chapter 2, indicate that Ireland will experience warmer and drier summer months with a longer growing season, and evidence of a longer growing season in Ireland have already been detected (Sweeney *et al.*, 2002). These are the primary impacts of climate change considered in this review. The impacts of secondary climatic variables (including clouds and water vapour) and the frequency of extreme events on biodiversity have not been considered due to the lack of information. While little work has been done on the effects of extreme events on biodiversity (Hossell, 2001) it is anticipated that these will have significant impacts on species survival and distribution. Impacts of sea level rise on biodiversity were also not addressed.

Relatively little experimental work has been done in the Republic of Ireland on the potential impacts of climate change on species and habitats of conservation importance. Most research has been in relation to agricultural crops and single species of agricultural grasses (Jones, 1999) and has focused on the direct effects of increasing atmospheric CO_2 concentrations (Donnelly *et al.*, 1999; Finnan, *et al.*, 2002). Recently an EU 5th Framework Programme project (MEGARICH) has investigated the direct effects of elevated CO_2 on a semi-natural grassland community. This was the first whole-ecosystem study undertaken in Ireland to investigate the impacts of elevated CO_2 on biodiversity (Byrne and Jones, 2002). Other studies on climate change impacts include experimental and modelling work on the effects of elevated CO_2 on *Gunnera tinctoria* (Giant Rhubarb) (Osborne, personal communication). In addition, a number of projects have investigated carbon balance and carbon storage potential in intact peat, cutaway bog and commercial forestry (Byrne *et al*., 2000; Byrne and Perks, 2000) while other work has assessed the implementation of, and impediments to, strategies to protect peat bogs in Ireland against the adverse impacts of climate change (Grant, 2001).

6.3 Climate Change Impacts on Species

6.3.1 Introduction

Based on all the available evidence from both experiments and models, a change in climate of the magnitude predicted in Chapter 2 is expected to have significant effects on the distribution of species. As in Britain, the impacts of climate change in Ireland on species are likely to be influenced by its island nature (Hossell, 2001). An island setting means that the potential for species extinction is greater and survival of species is more precarious than on continents (MacArthur and Wilson, 1967). To survive climate change, many species will need to shift their distribution and/or alter their behaviour (Hossell, 2001). Palaeoecological evidence indicates that species have shifted their distributions in the past in response to changing climates (Brown and Lomolino, 1998). However, estimates of the future rate of climate change suggest that it may occur some ten times faster than the warming at the end of the recent glacial maximum (Malcolm and Pitelka, 2000). It is therefore likely that some species (particularly plants and some sedentary insect species) will be unable to move fast enough to remain within their climate envelope and may become extinct as climatic conditions become increasingly unsuitable. Evolutionary responses to environmental change on this timescale are rare, although small genetic adjustments, e.g. in timing of hatching, are possible for short-lived organisms such as insects and migrating birds (Hill *et al*., 1999). However, evidence from Quaternary examples suggests that few vertebrate species will be able to evolve rapidly enough to adapt to the predicted climate change through natural selection (Hossell *et al*., 2000). Also, long-lived species, such as trees, are unlikely to be able to evolve fast enough in response to rapid climate change (Bugmann, 1997).

6.3.2 Some projected distribution changes of Irish species

The general consensus among experts is that the most threatened species in Ireland are likely to be Arctic and

Boreal relicts and mountain species. For example, it has been suggested that temperature-sensitive salmonids in Ireland such as *Salvelinus alpinus* (Arctic Char) may be detrimentally affected. Increasing temperatures are expected to disrupt their life history and development cues leading to a decline in species numbers through competition from other fish species, loss of reproductive success and loss of niche space. The related *Osmerus eperlanus* (Smelt) and other arctic fish relicts such as *Coregonus autumnalis* (Pollan) may be similarly threatened. Likewise, species which are at the southern end of their distribution range in Europe (Boreo-temperate or Boreo-alpine) may become less widely distributed or extinct due to increasing temperatures, e.g. *Mertensia maritima* (Oysterplant), *Catinella arenaria* (Sandbowl Snail), *Pelophila borealis* (Beetle), *Diaptomus laticeps* (Copepod) and *D. laciniatus* (Copepod). Other cold-hardy species may become less widely distributed or extinct, e.g. species adapted to cool mountain conditions such as *Vaccinium vitis-idaea* (Cowberry) and *Dysticus lapponicus* (an upland Water Beetle). Species whose life cycle has a critical water-dependent stage, e.g. the fern *Dryopteris affinis*, may also be negatively affected by warmer, drier conditions as may many wetland species and oceanic bryophytes.

In contrast, species which are at the northern (or north-western) edge of their distribution range in Europe (Boreo-temperate) may move northwards and possibly extend their range, e.g. *Otanthus maritimus* (Cottonweed) (extinct in Britain and restricted to two sites in Co. Wexford in Ireland), *Hadena glauca* (Glaucous Shears Moth), *Bufo calamita* (Natterjack Toad) and *Rhinolophus hipposideros* (Lesser Horseshoe Bat). Deep-rooted stress-tolerant species, e.g. calcareous forbs, are predicted to benefit from warmer, drier conditions in south-eastern Britain (DOE, 1996). This may also be the case in Ireland, and they may extend their range, although this depends on the existence of a suitable habitat. Warming is also expected to benefit insects, especially butterflies, provided the changes are not too extreme or too rapid. Also predicted in Britain, and likely for Ireland as well, is that agricultural insect pests and predatory insect species will increase in abundance (Davis *et al*., 1998).

As is the case in Britain, species movement into Ireland (invasion) is restricted by the sea (Hossell *et al*., 2000) and the species pool is unlikely to change significantly over the next century. The high mobility of many insects may however assist their invasion from Britain or continental Europe although it remains unclear as to the critical determining factors associated with the arrival and survival of butterfly species such as *Issoria lathonia* (Queen of Spain Fritillary), *Pontia daplidice* (Bath White), *Colias hyale* (Pale Clouded Yellow), *Nymphalis antiopa* (Camberwell Beauty) and *Polygonia c-album* (Comma). There may also be increased numbers of bird migrants appearing in the country such as *Egretta garzetta* (Little Egret) and *Larus melanocephalus* (Mediterranean Gull). Both species have been reported in Ireland in recent years.

Introduced species will increase their range if they are favoured by climate change. These include invasive plant species such as *Crocosmia crocosmiflora* (Montbretia), *Epilobium nerterioides* (New Zealand Willowherb), *Gunnera tinctoria* (Giant Rhubarb), *Rhododendron ponticum* (Rhododendron) and *Spartina townsendii* (Townsend's Cordgrass), as well as the potential agricultural pest *Tandonia budapestensis* (Budapest Slug), the dragonfly colonist *Aeshna mixta* (Migrant Hawker), the reptile *Anguis fragilis* (Slow Worm) and the mammal *Clethrionomys glareolus* (Bank Vole).

6.3.3 Some projected developmental and behavioural changes of species

Current evidence in Ireland suggests that developmental processes of many ***plant*** species are altering in response to climate change (Sweeney *et al*., 2002). Bud burst of trees is occurring earlier in spring and alterations in other processes, such as leaf fall, are also expected. Another biological process expected to alter in response to climate change is decomposition. Increasing temperatures may lead to higher decomposition rates of plant material and hence to increases in the rate at which CO_2 is being added to the atmosphere (Malcolm and Pitelka, 2000). However, plant productivity is also expected to increase in response to increasing CO_2 and temperature so that increased CO_2 uptake may counteract the effects of decomposition. Increases in productivity are likely to affect the competitive interactions between species.

Weeds, for example, may be favoured at the expense of less aggressive species (Hossell *et al*., 2000).

Invertebrates are an extremely diverse group and even closely related species may respond very differently to changing climate (Hossell, 2001). In general terms, invertebrates are expected to benefit from climate change as higher temperatures should increase the likelihood of extra generations being produced and this may lead to population growth. In addition, warmer winters may affect hibernation and increase survival rates of many invertebrates. Developmental processes of insects are likely to alter in response to climate change. In Britain, it has been shown that an increase of 3°C could advance butterfly appearance date by up to 3 weeks (Sparks and Yates, 1997).

Research suggests that ***amphibian*** reproductive cycles in temperate countries will shorten in response to climate warming (Beebee, 1995) and this could lead to early emergence of amphibian species in Ireland. As a result, competitive relationships between frogs and newts may alter.

Birds are most likely to be indirectly affected by climate change through the availability of food and habitat. For example, an increased growing season for plants may increase insect availability as food for birds. A longer growing season may also induce earlier breeding with larger clutches (Hossell, 2001). Higher spring temperatures may also lead to the earlier arrival of spring migrant species (Sparks, 1999). However, migrational changes are extremely difficult to predict due to complex interactions that depend on alterations in departure sites, staging posts and final destinations. Warmer winters may also result in larger numbers of overwintering birds with reduced mortality but increased competition between species.

Climate impacts on ***mammals*** (other than bats) are likely to be few (Hill *et al*., 1999). Warmer temperatures may have a negative effect on the birth weights of *Cervus elaphus* (Red Deer). Bats are highly temperature dependent, which means that changes in the timing and length of the growing season will impact on their life cycle. A review by Hossell (2001) in Britain indicates that there may be increased winter survival of bats.

Table 6.1 summarises some of the more important projected impacts of climate change (increasing temperatures and a longer growing season) on species in Ireland.

6.4 Climate Change Impacts on Habitats

6.4.1 Introduction

Changes in species distribution and/or their functioning, as a result of climate change, are likely to significantly alter the habitats they constitute. For example, the degradation or eventual loss of existing habitats in many areas is expected due to a shift in habitat conditions, i.e. changes in species composition, structure and morphology. Habitats may reappear elsewhere but only when the requisite biotic (living) elements are able to track the abiotic (physical) elements. If suitable biotic elements fail to migrate, then the new habitat areas may be of lower quality for many species (Malcolm and Pitelka, 2000). In Britain, Hossell *et al*. (2000) have estimated that a 1°C rise in temperature across the country may significantly alter the species composition in approximately half the statutory protected areas, allowing the expansion of southern habitats into more northerly areas, and the expansion of lower altitude habitats to higher altitudes. Similar habitat shifts may be expected in Ireland. However, movement of habitats may be restricted by non-climatic elements such as geology, soil conditions and human activities (Hossell, 2001). Indeed human activities such as land-use change, air and water pollution, construction, and water abstraction have already contributed greatly to habitat destruction and fragmentation (Malcolm and Pitelka, 2000; Hossell, 2001; Montgomery, 2002) and it is likely that climate change will exacerbate these impacts on habitats.

There are seven broad categories of natural and semi-natural habitats in Ireland. Table 6.2 links the habitats of nature conservation importance within these broad habitat categories. These habitats were designated under Annex 1 of the EU Habitats Directive (92/43/EEC).

The potential impacts of climate change on these habitats are reviewed in the following sections.

Table 6.1. Summary of possible impacts of climate change on species in Ireland.

Distributional changes

- Decline (and in some cases extinction) of Arctic and Boreal relicts, cold-hardy species, water-dependent species, wetland and oceanic species.
- Extension of Boreo-temperate species and other species that favour increased temperatures, e.g. deep-rooted calcareous forbs, butterflies, insect predators and pests.
- Increases in migrant species – mainly insects and vagrant birds.
- Changes in distribution of introduced or invasive species.

Behavioural changes

- Changes in the phenological processes of plants (seed germination, bud burst and leaf emergence).
- Changes in plant decomposition and productivity.
- Alterations in competitive interactions between plants.
- Increased numbers of generations of many insects which may lead to population growth.
- Greater winter survival rates of invertebrates.
- Changes in phenological processes of insects, e.g. early appearance of butterflies.
- Earlier breeding of amphibians.
- Possible changes in the competitive relationships between frogs and newts.
- Changes in timing of migration, hatching, development and spawning of freshwater fish with negative and positive implications for particular species.
- Increased competition between species for niche space, e.g. *Salvelinus alpinus* (Arctic Char) and other species.
- Changes in bird migrational patterns.
- Earlier breeding of birds and larger and more numerous clutch sizes.
- Greater numbers of overwintering birds, with reduced mortality but greater competition between species.
- Changes in the life cycle of bats.
- Greater winter survival rates of bats.
- Reduction in birth weight of *Cervus elaphus* (Red Deer).

6.4.2 Coastal habitats

In Britain and Ireland, the MONARCH project (MOdelling NAtural Resource responses to climate CHange) predicted that species composition of salt marshes and sand dunes will change in response to increasing temperatures (Harrison *et al*., 2001), and that this will affect the habitat characteristics. For example, on salt marshes *Bylsmus rufus* (Saltmarsh Flat Sedge) is predicted to disappear entirely from Ireland whereas *Atriplex portulacoides* (Sea Purslane) could expand around the coast. In another study by Long (1990), it was suggested that elevated temperature might influence competitive interactions between *Spartina anglica* (Common Cordgrass) and *Puccinellia maritima* (Common Saltmarsh Grass). This may affect the potential for *S. anglica* to invade the *P. maritima* dominated vegetation of the lower salt marsh zone and to persist in middle and upper salt marsh zones. Thus, the nature and character of salt marshes may change in the future.

Sand dunes are expected to suffer from increased summer droughts, although this is likely to have limited effects on the drought-tolerant species of embryonic, marram and fixed dune systems. In contrast, wet and semi-aquatic dune slacks are likely to dry out and some species may be negatively affected, e.g. *Equisetum variegatum* (Variegated Horsetail) and *Bufo calamita* (Natterjack Toad). As a result, some dune species may migrate northwards to more suitable climate space. In Britain, it is expected that many coastal birds may winter further to the north and east in response to warmer winters (Harrison *et al*., 2001) and this may also be true for Ireland.

Table 6.2. Habitats of nature conservation importance in Ireland designated under Annex 1 of the EU Habitats Directive (92/43/EEC). Each habitat is defined by a code (in brackets).

Coastal habitats	**Rocky habitats and caves**
Annual vegetation of drift lines (1210)	Siliceous screes (8110)
Perennial vegetation of stony banks (1220)	Calcareous and calcshist screes (8120)
Vegetated sea cliffs (1230)	Chasmophytic vegetation of calcareous slopes (8210)
Coastal salt marsh (1310, 1320, 1330, 1410 and 1420)	Chasmophytic vegetation of siliceous rocky slopes (8220)
Embryonic shifting dunes (2110)	*Limestone pavements (8240)
Marram dunes (2120)	
*Fixed dunes (2130, 2140, 2150)	**Native woodlands**
Coastal dune slacks (2170, 2190)	Old oak woodlands (91AO)
*Machair (21AO)	*Bog woodlands (91DO)
	*Alluvial forests (91EO)
Semi-natural grasslands	**Taxus baccata* woods (91JO)
Calaminarian grasslands (6130)	
*Lowland calcareous grasslands (6210)	**Freshwater habitats**
*Species-rich *Nardus* grasslands (6230)	Lowland oligotrophic lakes (3110)
Molinia meadows on chalk and clay (6410)	Upland oligotrophic lakes (3130)
Eutrophic tall herb communities (6430)	Hard oligo-mesotrophic waters (3140)
Lowland hay meadows (6510)	Natural eutrophic lakes (3150)
	Dystrophic lakes (3160)
Heaths and scrub	*Turloughs (3180)
Wet heaths (4010)	Floating river vegetation (3260)
Dry heaths (4030)	*Chenopodietum rubri* of rivers (3270)
Montane heaths (4060)	
Juniperus communis formations (5130)	
Peatlands	
*Active raised bogs (7110)	
Degraded raised bogs (7120)	
*Active blanket bogs (7130)	
Transition mires (7140)	
Depressions on peat substrates of the Rhynchosporion (7150)	
*Calcareous fens and petrifying springs (7210, 7220)	
Alkaline fens (7230)	

* Priority habitats, in a European context.

It is unlikely that higher temperatures will affect drought-resistant vegetation of drift lines and stony banks, but the priority machair habitat, a seasonally flooded dune grassland system of north-western Ireland (Conaghan, 2001), may suffer degradation through desiccation. Coastal habitats will also be vulnerable to sea level rise.

6.4.3 Semi-natural grasslands

Of the six grassland types listed in Table 6.2, lowland calcareous grasslands are probably of highest conservation priority in Ireland followed by species-rich *Nardus* grassland, which is generally more characteristic of Continental Europe. Calcareous grasslands may undergo a change in species composition due to increased drought (Brown *et al*., 1998) with a decline in perennial grasses and other drought-sensitive species. In contrast, deep-rooted, drought-tolerant forbs, including ruderal weeds, may favour warmer, drier conditions. Species composition changes are likely to alter competitive interactions between species and there may also be invasion by new species (Harrison *et al*., 2001; Hossell, 2001). Drought in these grasslands may have the effect of increasing their nutrient status through increased nitrogen mineralisation and as a result insect populations may increase (Harrison *et al*., 2001).

Little work has been done on the remaining grassland types. In Britain, it is thought that productivity of lowland hay meadows may increase with a longer growing season and increased atmospheric CO_2 concentrations and that grassland production may extend to higher altitudes (Hossell *et al*., 2000). However, in Ireland, soils may dry out due to higher evapotranspiration and lower summer precipitation, and grassland productivity under these conditions may be reduced. Wetland species of *Molinia* meadows and eutrophic tall herb communities are very likely to be negatively affected by increasing temperatures and drier soil conditions and, thus, changes in species composition may result. Alterations in soil moisture content are also likely to affect soil microbial activity. It is important to appreciate that the fate of all grasslands is closely linked with how they are managed so that any changes to grazing, cutting or fertilising regimes may have as great an influence, if not more, than climate change. Lowland hay meadows and *Molinia* meadows are particularly at risk from more intensive management.

6.4.4 Heaths and scrub

The MONARCH project predicted that warmer and drier conditions will reduce the extent of wet heath, in favour of dry heath or acid grassland (Harrison *et al*., 2001). It is also hypothesised that both wet and dry heaths might be replaced by acid grasslands in warmer and drier conditions due to increased nitrogen availability (through greater decomposition) and a longer growing season (Hossell *et al*., 2000). In addition, both types of heath may migrate up-slope to higher altitudes (Hill *et al*., 1999). Despite projected distributional changes, there may be little net change in the extent of either type of heath, although new habitat areas may be of lower quality for many species. Hossell *et al*. (2000) also indicate that changes in the competitive balance between species may occur so that, for example, bracken invasion may be reduced, as heather species appear to be favoured over bracken by warmer temperatures. Increasing temperatures may also increase insect herbivory of heaths, which, together with increased nitrogen, is likely to further benefit competitive grasses and cause further degradation of both wet and dry heaths (Hossell, 2001). Both wet and dry heaths may also be at greater risk from fire due to increasing temperatures and soil dryness (Hossell, 2001).

Of all habitats reviewed by the MONARCH project, montane heaths were suggested to be the most sensitive to climate change (Harrison *et al*., 2001). It was predicted that *Salix herbacea* (Dwarf Willow), a constituent species of montane heaths, would disappear by the year 2050. Other species such as *Carex bigelowii* (Stiff Sedge) may be similarly affected; however, more research is needed on this and other species. Hossell *et al*. (2000) also cited this habitat as being at great risk. This is because many montane species are at the lower altitude/ southern latitude edge of their distribution range and the potential for them to migrate up-slope or northwards is limited (Hill *et al*., 1999). Currently in Ireland, high rainfall and humidity mean that montane heath is kept very wet even if the soils are free-draining or rocky (Fossitt, 2000). However, a prolonged increase in temperature, accompanied by drying of the soils may prove extremely detrimental for this habitat. Furthermore, it is unclear whether montane heaths are as threatened in Ireland as they are in Britain and more work is needed to clarify this.

6.4.5 Peatlands

Ireland has a considerable variety of peatlands, three of which are of international importance (raised bogs, lowland and upland blanket bogs, and ‘rich’ calcareous fens). In fact, Ireland holds a significant proportion of the world’s total area of oceanic raised bog and blanket bog. Peatland systems are fed by rainwater (bogs) or by groundwater (fens) and in their natural state they contain a high percentage of water, typically 95–98% (Foss, 1998). Any process, such as climate change, which interferes with the hydrological balance of peatlands is likely to be highly detrimental. Predicted rising temperatures in Ireland, accompanied by a likely decrease in summer rainfall, will increase the moisture deficit of peatlands both in amount and in duration (McWilliams, 1991). Drying of soil increases the possibility of wind erosion, especially on degraded sites, whilst oxidation prevents peat formation (Grant, 2001). For example, the IPCC (2001) predict that a 1–2°C rise in temperature will lead to an estimated 25% reduction in peat formation. Upland blanket bogs may be more at risk as they are largely confined to cool, wet areas of the country (Conaghan, 2001) and may respond more negatively to increases in temperature than other peatland systems. However, higher temperatures may also increase *Sphagnum* growth and counteract higher decomposition rates (Hossell *et al*., 2000) although this effect may be restricted by available nutrients.

Drying of peatland surfaces is likely to lead to species composition changes (Grant, 2001; Harrison *et al*., 2001). Many specialised plant and animal communities of these systems may be affected. For example, even a slight lowering of the water table in raised bogs causes a decline of the pool and hollow habitat and a decrease in the differentiation of the bog vegetation pattern (Schouten *et al*., 1992). There may also be an increase in dwarf shrubs and graminoid species, which will put many peatland species that have poor competitive ability at risk (Hossell, 2001). The MONARCH project (Harrison *et al*., 2001) predicted changes in four species, which may affect future composition of peatlands: *Eriophorum vaginatum* (Hare's-tail Cotton Grass), *Rhynchospora alba* (White-beak Sedge), *Sphagnum papillosum* (Sphagnum Moss) and *Coenonympha tullia* (Large Heath Butterfly). Migration of species from peatlands may be limited by fragmentation of the bog (Grant, 2001), while migration of species from fen habitats (particularly valley fens) may be severely hampered by the lack of suitable migration routes (Hossell, 2001).

Loss of peatlands as a result of climate change will lead to a loss of stored carbon. Peatlands hold the bulk of Ireland's carbon store. The effectiveness of peatlands to function as a carbon sink depends on a range of factors including age, trophic and hydrological status and the climatic regime. When the hydrological balance of a peatland is disturbed by climate change (or through anthropogenic processes such as drainage or peat harvesting) as much as 8 t of CO_2 per hectare per year are emitted from the degraded system (Byrne *et al*., 2000).

Climate change may also affect the release of pollutants from peat. In Britain, drought was found to increase the leaching of metals stored in peat, causing damage to species and habitats (Tipping, 2000). Also, McWilliams (1991) suggested that an increase in oxidation of sulphides to sulphates might contribute to acid episodes in streams and rivers running off upland bog catchments.

6.4.6 Rocky habitats and caves

Limestone pavement in Ireland is prioritised under the EU Habitats Directive (92/43/EEC, 1992). The most extensive area of limestone pavement is in the Burren, Co. Clare, and although it covers a mere *ca* 0.5% of Ireland's land surface it contains 81% of the 900 native plant species (Cabot, 1999). The MONARCH (Harrison *et al*., 2001) study estimated the impacts of climate change on limestone pavement in the Burren based on predictions of an increase in summer temperatures, a decrease in summer rainfall and an increase in winter rainfall. It suggested that these conditions would lead to an increase in limestone dissolution rates resulting in increased dissolved loads in the waters of the area and, thus, an increased potential for re-precipitation of these dissolved ions at other points within the environment (e.g. cave systems or around tufa-depositing springs). However, further work is needed to clarify the effects of climate change on this sensitive habitat (Harrison *et al*., 2001).

There is a lack of information on the impacts of climate change on the remaining habitat types in this section. Freeze–thaw action may be reduced with warmer temperatures, which may affect many screes that depend on frost heave to keep them open (Hill *et al*., 1999). Also, arctic alpine species may be lost from rocky slopes. However, it is likely that species migration from all rocky habitat types will be limited due to the dependence of these habitats on the underlying geology (Hossell, 2001).

6.4.7 Native woodlands

Three woodland habitats of international importance occur in Ireland (Table 6.2) but all are relatively uncommon in the country (Dwyer, 2000) and *Taxus baccata* woods are classified as rare (Fossitt, 2000). Deciduous forest was once widespread in Ireland (Mitchell, 1982), especially during the warm part of the current interglacial (4000–8000 BP). Such past conditions imply that current global warming may encourage the expansion of broadleaved woodlands (Cannell, 1990). A review of the research in Britain (Hossell, 2001) concluded that the response by trees to increased warming is likely to be slow. It is suggested that the main response by trees will be through migration but that the speed of migration may not be sufficient (due to slow reproductive and dispersal rates) to remain in equilibrium with their optimum climatic conditions. However, the MONARCH project (Harrison *et al*., 2001) did predict that *Quercus robur* (Pedunculate Oak) will continue to find suitable climate space in Britain in the future, and it was suggested that this is also likely to be true for Ireland. Moreover, in Scotland it has been predicted that increases in temperature will result in more vigorous growth and regeneration of broadleaved woodland, especially oak, as well as alluvial forests (Hill *et al*., 1999).

One response of trees to increased temperature and a longer growing season, which is already observable in Ireland, is earlier bud burst (Sweeney *et al*., 2002). However, any tree species that depend on day length to trigger leaf fall and dormancy may be unable to extend their growing season into the warmer autumn. Such changes could therefore have implications for competition between species and therefore for the future composition of woodlands. The ground flora of woodlands may suffer seriously from summer droughts due to rising temperatures (Harrison *et al*., 2001) and bryophyte species, which are particularly reliant on moist humid conditions (e.g. in Killarney, Co. Kerry), may be reduced. Such changes in ground flora are likely to be more rapid than for trees (Hossell, 2001).

Other impacts proposed for Britain (Hossell *et al*., 2000) that are also likely to occur in Ireland include the invasion of bog woodlands into surrounding bogs where the surface has been degraded. In fact, if conditions become unsuitable for the growth of bogs, they may be replaced by bog woodland (Hill *et al*., 1999). In addition, *Rhododendron ponticum* (Rhododendron) may spread and continue to threaten oak woodlands while other introduced species, such as *Castanea sativa* (Sweet Chestnut) may also be favoured by warmer conditions.

6.4.8 Freshwater habitats

It is likely that freshwater habitats in Ireland will be affected by a combination of summer drought and higher water temperatures. Such conditions can be expected to lead to a decline in surface water resources during the present century. However, the MONARCH project (Harrison *et al*., 2001) makes somewhat different predictions. Using a PPT-PET model (precipitation minus potential evapotranspiration), the authors predict an increase in water availability, of up to 60 mm, during the months December to February, although during the months from June to August it is also predicted that most of Ireland will experience reduced surface water levels. It is also likely that changes in the extent of water bodies will have substantial effects on water quality and hydrological regimes, which will in turn have implications for the flora and fauna of these habitats (Eyre *et al*., 1993).

6.5 Vulnerability of Key Species and Habitats

6.5.1 Introduction

Here we review how vulnerable species and habitats respond to temperature and rainfall changes predicted for Ireland during the current century. Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change (IPCC, 2001). Vulnerability is a function of both sensitivity to change in climate and the capacity to adapt to the change. Consequently, a highly vulnerable species or habitat is one that is very sensitive to a moderate change in climate and for which the ability to adapt is severely limited. This analysis is based on the premise that species and habitat distributions are largely a function of climate (Brown and Lomolino, 1998; Hill *et al*., 1999; Malcolm and Pitelka, 2000), particularly temperature and rainfall. Using the 'climate envelope' approach which is now widely adopted by ecologists

(Box, 1981; Emanuel *et al*., 1985), current species and habitat distributions in Ireland were established and the climate conditions (or zones) where they most often occurred were identified. It was assumed that the climate zone(s) in which a species or habitat was most often found, was its preferred climate range. A statistical test, the Chi-square association, was used to identify significant associations between species and habitats and their preferred climate zone(s). Future changes in area and location of each climate zone were assessed and it was hypothesised that such changes would affect the species and habitats with which they were significantly associated. A vulnerability table was drawn up and a vulnerability rank was given to each species and habitat based on their likely response to the predicted changes in temperature and rainfall. The vulnerability rank also took into account whether climate zones disappeared or their areas contracted or expanded in the future. If suitable climate zones continued to exist in the country but in a different location, the potential of species and habitats to move was considered. Factors such as dispersal ability, and soil type and hydrology of the new climate zone areas were taken into account.

6.5.2 Species and habitat selection

A selection of 54 species and 24 habitats of nature conservation concern were chosen for this study using the EU Habitats Directive (92/43/EEC). In some cases, the Directive species were excluded and additional species were chosen on the advice of experts. Additional species generally included 'issue' species. These are species particularly distinctive to Ireland and species that may become extinct or invasive in the future. Distribution data, on a 10 or 20 km square grid basis, were obtained from several sources. Species atlases were used for plants, butterflies, molluscs and birds (Perring and Walters, 1982; Lack, 1986; Hill *et al*., 1991, 1994; Kerney, 1999**;** Asher *et al.*, 2001). Distribution data for several invertebrate groups, including Coleoptera and Heteroptera, were obtained courtesy of the Ulster Museum and information on the Odonata group was obtained from Dúchas, The Heritage Service. Distribution data for *Salvelinus alpinus* (Arctic Char) were supplied by Shannon Regional Fisheries Board. Other freshwater fish distributions were obtained from the NGO special areas of conservation shadow list (Dwyer, 2000). Amphibian and reptile data were obtained from Korky and Webb (1999) and McGuire and Marnell (2000). Habitat data were obtained from Dúchas, The Heritage Service (Conaghan, 2001) and Dwyer (2000).

6.5.3 Climate zones

A climate zones map of Ireland was constructed using the baseline maps of temperature and precipitation (1961–1990) described in Chapter 2. The climate zones were specified using three categories of mean annual air temperature and four categories of total annual rainfall. Eight climate zones for the period 1961–1990 were identified on the baseline map at an output resolution of a 1 × 1 km square grid (Fig. 6.1a). Two predictive climate zone maps (Figs 6.1b and 6.1c) were produced in the same manner for the period 2055 (2041–2070) and 2075 (2061–2090) at an output resolution of a 10 × 10 km square grid. Four new climate zones were identified on the predictive maps. These were due to an additional temperature category (10.7–12.2°C) combined with all four baseline rainfall categories.

6.5.4 Changes in climate zone areas

The area of all climate zones is predicted to change by 2055 and 2075 relative to the baseline. In 2055, Zones 1 and 2 will disappear while Zones 3–7 are predicted to contract (Zones 3 and 4 greatly) and Zone 8 will expand. In addition, four new climate zones are predicted to appear (9–12). In 2075, Zones 3 and 5 will also disappear, while Zones 4, 6 and 7 will contract (Zone 4 will virtually disappear). Also, by 2075, Zone 8 is predicted to contract relative to 2055 but it will still occupy a larger area relative to the baseline. Three of the new climate zones (10, 11 and 12) are predicted to expand by 2075 and one zone (9) will contract somewhat relative to 2055. Table 6.3 summarises this information on changes in climate zone areas.

6.5.5 Changes in location of climate zones

In addition to any changes in area of the climate zones described above there is a clear shift northwards of the zones. For example, Zone 8 (salmon colour) remained largely unchanged in area but it occurs in progressively more northerly locations in 2055 and 2075 while Zone 7 (cream) halves in area by 2075 and also shifts northwards

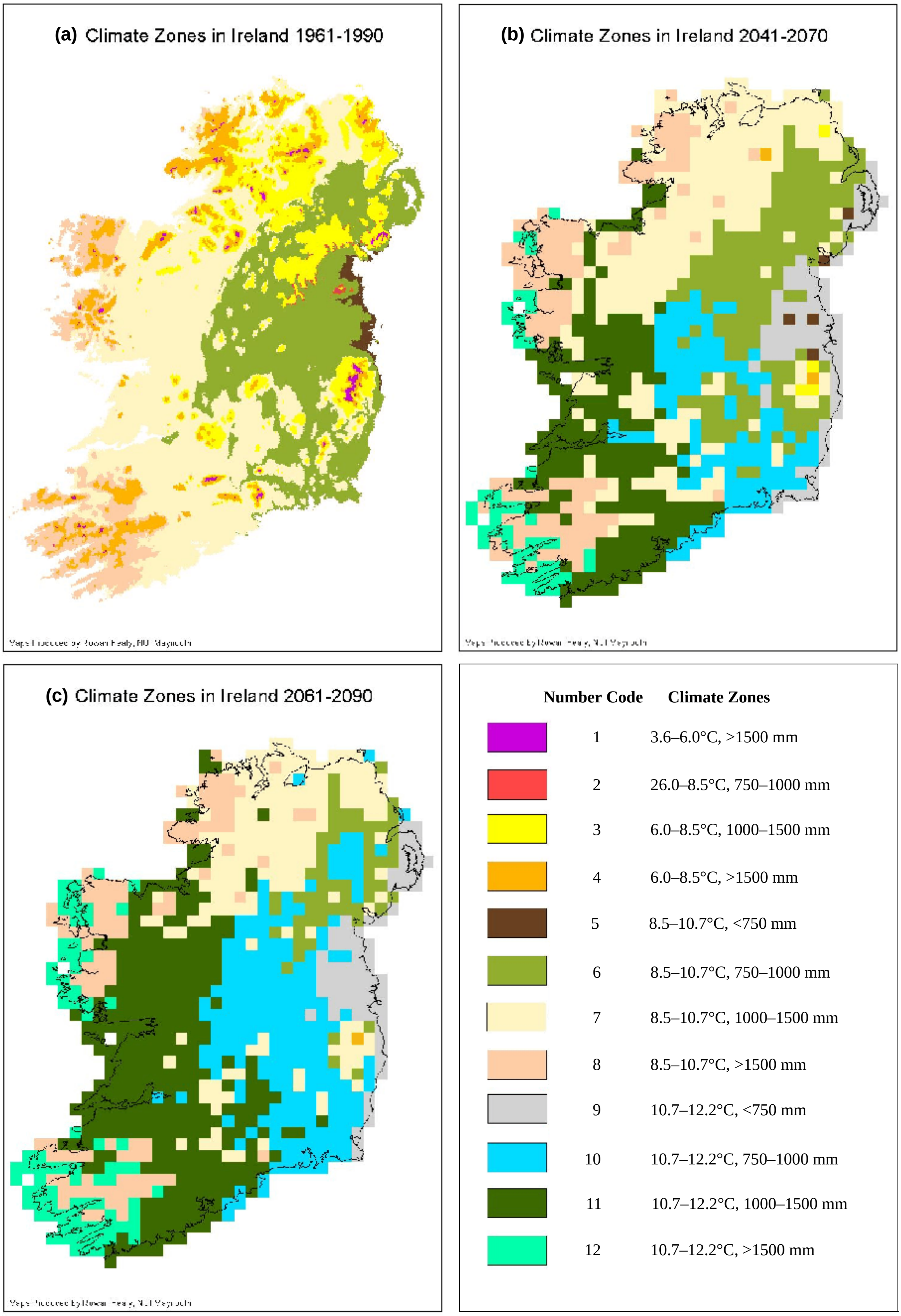

Figure 6.1. (a) Baseline map of climate zones in Ireland, 1961–1990, (b) predictive map of climate zones in Ireland, 2041–2070, and (c) predictive map of climate zones in Ireland, 2061–2090.

Table 6.3. Area (% of total) of the climate zones in the baseline map and the two predictive maps of 2055 and 2075. Climate zones not present in a particular map had an area of zero. Changes in climate zone area from the baseline are summarised by '+', '–' and '– –' which specifies an increase in climate area, a decrease in climate area, or the effective disappearance of climate area, respectively.

Climate Zones	Baseline	2055	Change from baseline	2075	Change from baseline
1 (pink)	0.60	0.00	– –	0.00	– –
2 (red)	0.27	0.00	– –	0.00	– –
3 (yellow)	13.21	0.48	– –	0.00	– –
4 (orange)	8.86	0.24	– –	0.12	– –
5 (brown)	0.95	0.53	–	0.00	– –
6 (mid green)	24.93	19.89	–	7.10	–
7 (cream)	42.67	28.04	–	19.60	–
8 (salmon)	8.50	12.15	+	10.54	+
9 (grey)	0.00	5.94	+	5.20	+
10 (blue)	0.00	12.47	+	22.77	+
11 (dark green)	0.00	18.23	+	29.86	+
12 (sea green)	0.00	2.04	+	4.81	+

(Fig. 6.1a and 6.1b). As warming proceeds, all the new climate zones appear in the south and, by 2075, they occupy more than 60% of the land surface.

6.5.6 Species and habitat vulnerability

In order to carry out a vulnerability analysis the number of occurrences of each species/habitat in a 10,000 km^2 area was determined. Following this, the Chi-square statistic was used to identify the climate zone with which the species/habitats were significantly associated. For each species and habitat, changes in temperature, rainfall and climate area were determined based on the changes predicted for the climate zone with which they were significantly associated. Using this information vulnerability tables were drawn up based on four fundamental questions:

- What is the likely response of particular species/ habitats to the new temperature and rainfall conditions predicted to develop over their current climate range?
- Do the climate zones with which species/habitats significantly associate disappear, contract or expand, i.e. is it physically possible for the species/habitat to migrate?
- Do species/habitats have the potential to migrate (northwards) with their preferred climate zone(s), i.e. what is the actual dispersal potential of the species/ habitats, given that a suitable climate area may exist further north?
- When a climate zone moves and a species/habitat has the potential to migrate, do suitable soil nutrient and hydrological conditions exist in the new climate areas, which would allow for re-colonisation?

The literature was reviewed and any published data were used to answer these questions. Where the ecology of the species or habitat was known an attempt was made to score a vulnerability rank. In many situations, no such data were available (particularly for species). Vulnerability tables are based on predictions for climate change up to 2075 and have been drawn up for species (Tables 6.4–6.6) and habitats (Table 6.7).

6.6 Conclusions

In reviewing the impacts of predicted climate change on Irish species and habitats, it has become clear that there are substantial deficiencies in our knowledge of both the precise climatic conditions that will impact on the biosphere in the future and the response of species and habitats to these conditions.

For future studies, we will need clearer predictions of possible changes in climate variables and, in particular, information is required on diurnal variations in

Table 6.4. Vulnerability of plant species to climate change by 2055 and 2075. Temperature changes at current locations are indicated by '+' and '++' which specifies an increase of one or two temperature categories, respectively. Rainfall changes are indicated by '–' which specifies a decrease of one rainfall category. Changes in climate area are indicated by '+', '–' and '– –' which specifies an increase in climate area, a decrease in climate area, or the total disappearance of climate area, respectively. A zero '0' indicates no change. The likely response by the species to these changes is shown, together with a vulnerability rank. Introduced or invasive species are denoted with an 'i'.

Plant species	Year	Changes in temperature	Changes in rainfall	Changes in climate area	Likely response to changes in temperature and rainfall	Vulnerability rank
Arctostaphylos uva-ursi	2055	+	0	–	Negative	Medium?
(Bearberry)	2075	+	0	–		
Arbutus unedo	2055	+	0	–	Positive	Low?
(Strawberry Tree)	2075	+	0	–		
Crambe maritima	2055	+	0	–	None	Medium?
(Seakale)	2075	+	0	– –		
Crocosmia crocosmiflora (i)	2055	0	0	+	Positive in 2075	Favoured?
(Montbretia)	2075	+	0	+		
Daboecia cantabrica	2055	+	0	–	Negative	Medium?
(St. Dabeoc's Heath)	2075	+	0	–		
Epilobium nerterioides (i)	2055	+	0	–	Negative	Medium?
(New Zealand Willowherb)	2075	+	0	–		
Hymenophyllum wilsonii	2055	+	0	–	Negative	Medium?
(Wilson's Filmy Fern)	2075	+	0	–		
Mertensia maritima	2055	+	0	–	Negative	Medium–high?
(Oysterplant)	2075	+	0	– –		
Najas flexilis	2055	+	0	– –	None	Medium?
(Slender Naid)	2075	+	0	– –		
Petalophyllum ralfsii	2055	0	0	+	Negative in 2075	Low?
(Liverwort)	2075	+	0	+		
Puccinellia fasciculata	2055	+	0	–	Negative	Medium–high?
(Borrer's Saltmarsh Grass)	2075	+	0	– –		
Rhododendron ponticum (i)	2055	+	0	–	Positive	Low?
(Rhododendron)	2075	+	0	–		
Saxifraga hirculis	2055	0	0	+	None	Favoured
(Marsh Saxifrage)	2075	+	0	+		
Spartina townsendii (i)	2055	+	0	–	Positive	Low–medium?
(Townsend's Cordgrass)	2075	+	0	– –		
Trichomanes speciosum	2055	+	0	–	Negative	Medium?
(Killarney Fern)	2075	+	0	–		
Trifolium striatum	2055	+	0	–	None	Medium?
(Soft Clover)	2075	+	0	– –		
Vaccinium vitis-idaea	2055	+	0	– –	Negative	Medium–high?
(Cowberry)	2075	+	0	– –		

Table 6.5. Vulnerability of invertebrate species to climate change by 2055 and 2075. Temperature at current locations changes are indicated by '+' and '++' which specifies an increase of one or two temperature categories, respectively. Rainfall changes are indicated by '–' which specifies a decrease of one rainfall category. Changes in climate area are indicated by '+', '–' and '– –' which specifies an increase in climate area, a decrease in climate area, or the total disappearance of climate area, respectively. A zero '0' indicates no change. The likely response by the species to these changes is shown, together with a vulnerability rank. Introduced or invasive species are denoted with an 'i'.

Invertebrate species	Year	Changes in temperature	Changes in rainfall	Changes in climate area	Likely response to changes in temperature and rainfall	Vulnerability rank
Coleoptera						
Dytiscus lapponicus	2055	+	0	– –	Negative	Medium–high?
(A Water Beetle)	2075	+	0	– –		
Heteroptera						
Corixa panzeri	2055	+	0	–	Negative	Medium?
(A Water Boatman)	2075	+	0	–		
Sigara fallenoidea	2055	+	0	–	Negative	Medium?
(A Water Boatman)	2075	+	0	–		
Lepidoptera						
Coenonympha tullia	2055	+	0	–	Positive	Low
(Large Heath)	2075	+	0	–		
Cupido minimus	2055	+	0	–	Positive	Low
(Small Blue)	2075	+	0	–		
Thecla betulae	2055	+	0	–	Positive	Low
(Brown Hairstreak)	2075	+	0	–		
Odonata						
Aeshna mixtaI (i)	2055	+	0	–	Positive	Low?
(Migrant Hawker)	2075	+	0	–		
Coenagrion lunulatum	2055	+	0	–	Negative	Medium?
(Irish Damselfly)	2075	+	0	–		
Sympetrum danae	2055	+	0	–	Positive	Low?
(Black Darter)	2075	+	0	–		
Mollusca						
Leiostyla anglica	2055	+	0	–	Negative	Medium–high?
(English Chrysalis Snail)	2075	+	0	– –		
Geomalacus maculosus	2055	0	0	+	None	Favoured
(Kerry Slug)	2075	+	0	+		
Semilimax pyrenaicus	2055	+	0	–	Negative	Medium–high?
(Pyrenean Glass Snail)	2075	+	0	– –		
Spermodea lamellata	2055	+	0	–	Negative	Medium?
(Plated Snail)	2075	+	0	–		
Tandonia budapestensis	2055	+	0	–	Negative	Medium–high?
(Budapest Slug) (i)	2075	+	0	– –		
Vertigo angustior	2055	0	0	+	Negative	Low
(Narrow-mouthed whorl Snail)	2075	+	0	+		

Table 6.6. Vulnerability of fish, amphibia, mammal and bird species to climate change by 2055 and 2075. Temperature changes at current locations are indicated by '+' and '++' which specifies an increase of one or two temperature categories, respectively. Rainfall changes are indicated by '–' which specifies a decrease of one rainfall category. Changes in climate area are indicated by '+', '–' and '– –' which specifies an increase in climate area, a decrease in climate area, or the total disappearance of climate area, respectively. A zero '0' indicates no change. The likely response by the species to these changes is shown, together with a vulnerability rank.

Species	Year	Changes in temperature	Changes in rainfall	Changes in climate area	Likely response to changes in temperature and rainfall	Vulnerability rank
Fish						
Salvelinus alpinus	2055	+	0	–	Negative	Medium
(Arctic Char)	2075	+	0	–		
Salmo salar	2055	+	0	–	Negative	Medium–high
(Atlantic Salmon)	2075	+	0	– –		
Amphibia						
Bufo calamita	2055	+	0	–	Positive and negative	Low–medium
(Natterjack Toad)	2075	+	0	–		
Mammals						
Clethrionomys glareolus	2055	+	0	–	None	Low–medium?
(Bank Vole)	2075	+	0	–		
Martes martes	2055	+	0	–	None	Low–medium?
(Pine Martin)	2075	+	0	–		
Rhinolophus hipposideros	2055	+	0	–	Positive	Low?
(Lesser Horseshoe Bat)	2075	+	0	–		
Cervus elaphus	2055	+	0	–	Negative	Medium
(Red Deer)	2075	+	0	–		
Birds						
Carduelis flavirostris	2055	0	0	+	None	Favoured?
(Twite)	2075	+	0	+		
Vanellus vanellus	2055	+	0	–	Negative	Medium
(Lapwing)	2075	+	0	–		
Numenius arquata	2055	+	0	–	None	Low–medium?
(Curlew)	2075	+	0	–		
Tyto alba	2055	+	0	–	Positive	Low?
(Barn Owl)	2075	+	0	–		
Buteo buteo	2055	+	0	–	None	Medium?
(Buzzard)	2075	+	0	– –		

Table 6.7. Vulnerability of habitats to climate change by 2055 and 2075. Temperature changes at current locations are indicated by '+' and '++' which specifies an increase of one or two temperature categories, respectively. Rainfall changes are indicated by '–' which specifies a decrease of one rainfall category. Changes in climate area are indicated by '+', '–' and '– –' which specifies an increase in climate area, a decrease in climate area, or the total disappearance of climate area, respectively. A zero '0' indicates no change. The likely response by the species to these changes is shown, together with a vulnerability rank.

Habitat	Year	Changes in temperature	Changes in rainfall	Changes in climate area	Likely response to changes in temperature and rainfall	Vulnerability rank
Salt marsh	2055	0	0	+	Negative and positive	Low
	2075	+	0	+		
Machair	2055	0	0	+	Possibly negative in 2075	Low?
	2075	+	0	+		
Perennial vegetation of stony banks	2055	0	0	+	Possibly none	Favoured?
	2075	+	0	+		
Vegetated sea cliffs	2055	0	0	+	Unknown	Unknown
	2075	+	0	+		
Marram dunes	2055	0	0	+	Possibly none	Favoured?
	2075	+	0	+		
Fixed dunes	2055	0	0	+	Possibly none	Favoured?
	2075	+	0	+		
Sand dunes	2055	+	0	–	Possibly negative	Medium–high?
	2075	+	0	– –		
Lowland calcareous grasslands	2055	+	0	–	Positive and negative	Medium–high
	2075	+	0	– –		
Calaminarian grasslands	2055	++	–	– –	Negative	High
	2075	++	–	– –		
Lowland haymeadow	2055	0	0	+	Positive and negative	Low
	2075	+	0	+		
Wet heath	2055	+	0	–	Positive and negative	Medium
	2075	+	0	–		
Montane heath	2055	+	0	– –	Negative	Medium–high
	2075	+	0	– –		
Dry heath	2055	0	0	+	Positive and negative	Low
	2075	+	0	+		
Active raised bog	2055	+	0	–	Negative	Medium–high
	2075	+	0	– –		
Degraded raised bog	2055	+	0	–	Negative	Medium–high
	2075	+	0	– –		
Active blanket bog	2055	+	0	–	Negative	Medium
	2075	+	0	–		
Calcareous fens and	2055	+	0	–	Negative	Medium–high
petrified springs	2075	+	0	– –		

Table 6.7. ***contd***

Habitat	Year	Changes in temperature	Changes in rainfall	Changes in climate area	Likely response to changes in temperature and rainfall	Vulnerability rank
Alkaline fen	2055	+	0	–	Negative	Medium–high
	2075	+	0	– –		
Siliceous scree	2055	+	0	– –	Unknown	Unknown
	2075	+	0	– –		
Limestone pavement	2055	+	0	–	Unknown	Unknown
	2075	+	0	– –		
Old oak woodland	2055	+	0	–	Positive and negative	Medium
	2075	+	0	–		
Bog woodland	2055	+	0	–	Positive and negative	Medium–high
	2075	+	0	– –		
Turloughs	2055	+	0	–	Negative	Medium–high
	2075	+	0	– –		
Upland oligotrophic lakes	2055	++	–	– –	Negative	High
	2075	++	–	– –		

temperature, including increases in night-time temperatures, likely changes in precipitation-related variables, including clouds and water vapour and trends in extreme events, such as changes in the frequency of intense precipitation and late frosts. These may be met by a strengthening of the climate monitoring network across the country and the use of downscaled predictive models.

In addition, on the biological side, we require more baseline monitoring for all groups of species and habitats. The vulnerability study clearly highlighted the need for more baseline information on species and habitat distributions. It also indicated that very little information currently exists in Ireland on the possible responses that species and habitats might make to changes in climate variables. Here we have collected information mainly from British studies or from the expert opinion of individual researchers in the field. Lack of published information has made it difficult to come to conclusive views with regard to species and habitat vulnerability to climate change variables. According to the vulnerability study, species and habitats requiring the most attention in the future are those that ranked medium-high or high in the vulnerability index. In summary, this consists of three plant, four invertebrate and one freshwater fish species and sand dunes, lowland calcareous grassland, calaminarian grassland, montane heath, active raised bog, degraded raised bog, calcareous fens and petrifying springs, alkaline fens, bog woodland, turloughs and upland oligotrophic lakes. Of these, additional effort should be paid to those species and habitats that are under extreme anthropogenic pressure such as sand dunes and active raised bog.

Another area of uncertainty is the direct impact of increasing concentrations of carbon dioxide in the atmosphere on Irish species and habitats. To quantify these responses it will be necessary to carry out long-term experiments as well as modelling studies which will look at whole-system functioning and which will address the interactions of other climate variables with elevated carbon dioxide.

In conclusion, the vulnerability assessment was of necessity a preliminary study and more work is needed to refine its approach. One possible way forward may be to link with the MONARCH 2 project in Britain to ensure full coverage of the Britain and Ireland geographical area. This will allow the collection of more baseline data which, alongside increased modelling activity, will give greater predictive power to assessments of future species and habitat distributions under a changed climate.

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7 Climate Change and the Irish Marine Environment

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7.0 Introduction

Predictions for changes in Ireland due to anthropogenically induced climate change, through the increase in concentration of greenhouse gases, have to date been mainly focused on the terrestrial environment. These predictions do not consider the possible changes in the marine environment and possible impacts of major shifts in ocean circulation patterns.

The scenarios being examined are detailed below. Consideration needs to be given to the timescale over which these scenarios occur, as this will greatly affect the rate at which species and communities will change. The scenarios used are broadly consistent with those developed in Chapter 2 of this report and also approximate to those published by the Climatic Research Unit, University of East Anglia (Hulme and Jenkins, 1998).

- Temperature – the predictions in land temperature show an increase ranging from +0.5 to +1.2°C in 2020 to +1.0 to +2.8 °C in 2080.
- Precipitation – predicted average rainfalls are difficult to predict although a conservative assumption would be a change between +10% in winter and –10% in the summer.
- Sea level – an increase in sea levels similar to the global mean prediction of 0.49 ± 0.08 m emanating from the IPCC Third Assessment Report (IPCC, 2001).
- An increase in the number of extreme events (higher wind speeds, more storms, hotter summers).

7.1 Scope of the Project

It is 10 years since the last review of the effect of climate change on Ireland's marine environment was completed. The review was, however, not able to cite any publications that dealt with changes in marine life in Ireland due to climate change. The present study aims to update existing published knowledge on climate change on the marine environment, in particular marine biodiversity, including marine birds and exotic species, and to examine trends in Irish fisheries and aquaculture with respect to sea temperature change and likely economic repercussions.

This study will add to the information gathered in the first report on climate change (Aqua-Fact International Services Ltd., 1991) and will document the relevant publications since then. It is important to note that predicting changes in marine benthic habitats is difficult in Ireland due to the lack of data on species and habitat distributions, environmental requirements and how ecosystems function. In addition, no long-term datasets are available on species and habitats with which to examine patterns of marine environmental change over time.

7.2 Implications for Marine Biodiversity

7.2.1 Biogeography

The distribution or biogeography of marine species is determined by many factors, and at many different scales. Large-scale environmental variations, e.g. changes in water characteristics, including temperature and primary productivity, can determine broad distribution patterns of species and habitats and localised conditions can allow and prevent the development of specific assemblages of species. Key physical parameters determining the distribution of marine species would be:

- Substratum
- Wave exposure
- Tidal stream currents
- Water temperature
- Depth/immersion (depth in sea or height up the shore)
- Salinity
- Water quality.

Secondly, a range of biological factors will modify community composition and determine the distribution of species, e.g.

- Source of nourishment
- Predation pressure
- Competition for space and food
- A viable source of larvae for isolated populations
- Absence of pathogens.

A third range of anthropogenic influences also affects the distribution of species causing changes in localised conditions and results in a reduction in habitat or optimum conditions for growth.

Each of these factors combines and interacts with one another to produce a range of conditions suitable for colonisation by different marine species. Any alteration in any of these factors due to anthropogenic input or through larger changes in climate can lead to changes in conditions. Species can then find that (a) new possibilities for colonisation occur or (b) conditions for growth and reproduction are less favourable. This chapter examines the likely changes that may occur as a result of climate change.

Ireland lies between two major biogeographic provinces (Fig. 7.1), the Boreal (cold temperate) region to the north and the Lusitanian (warm temperate) region to the south. The biogeography is greatly influenced by the North Atlantic Drift bringing relatively warm waters across the Atlantic. As a result, the west coast of Ireland supports species that would be described as typical of more southern waters (Boreal–Lusitanian). These include the sea urchin (*Paracentrotus lividus*), the gastropod (*Monodonta lineata*) and the soft corals (*Eunicella verrucosa* and *Parerythropodium coralloides*). However, several species that would be more typical of northern waters, also occur along the west coast, e.g. the red seaweeds (*Ptilota plumosa* and *Odonthalia dentata*).

The Irish Sea, however, is generally much cooler than the open Atlantic coasts and supports a more Boreal suite of species.

7.2.1.1 Change in water and air temperature

Water temperature is one of the most important physical characteristics determining the distribution of marine organisms both at local level and at a larger scale. However, it is difficult to extrapolate predictions for increases in land temperatures to determine the likely changes in sea temperatures. Increased radiance will undoubtedly increase sea temperatures in shallow coastal areas such as enclosed bays, lagoons and estuaries; however, the impact is likely to be limited to the surface waters. Sub-surface temperature changes are harder to predict as they are controlled by larger oceanographic circulation patterns that may or may not be affected by increased radiance.

Associated with an elevated air temperature is an increase in likely desiccation for intertidal species.

Intertidal habitats and species

There is an absence of direct evidence for long-term changes in the Irish marine fauna and flora (primarily because of a paucity of long-term studies) and thus a link with climatic factors. Studies in Dublin Bay (Wilson, 2003) have highlighted changes in the bivalve fauna (the cockle, *Cerastoderma edule*, and tellin, *Angulus tenuis*) over the past 20–30 years. Initial data from Dublin Bay suggested a long decline in the cockle (*C. edule*) populations (Wilson 1993), in common with similar, if not so marked declines in other prominent bivalves such as *Angulus tenuis* (Wilson 1997). Currently, the cockle populations, if not recovered are at least holding their own while there has been a 10-fold increase in *A. tenuis* densities over the last few years (Wilson, 2003).

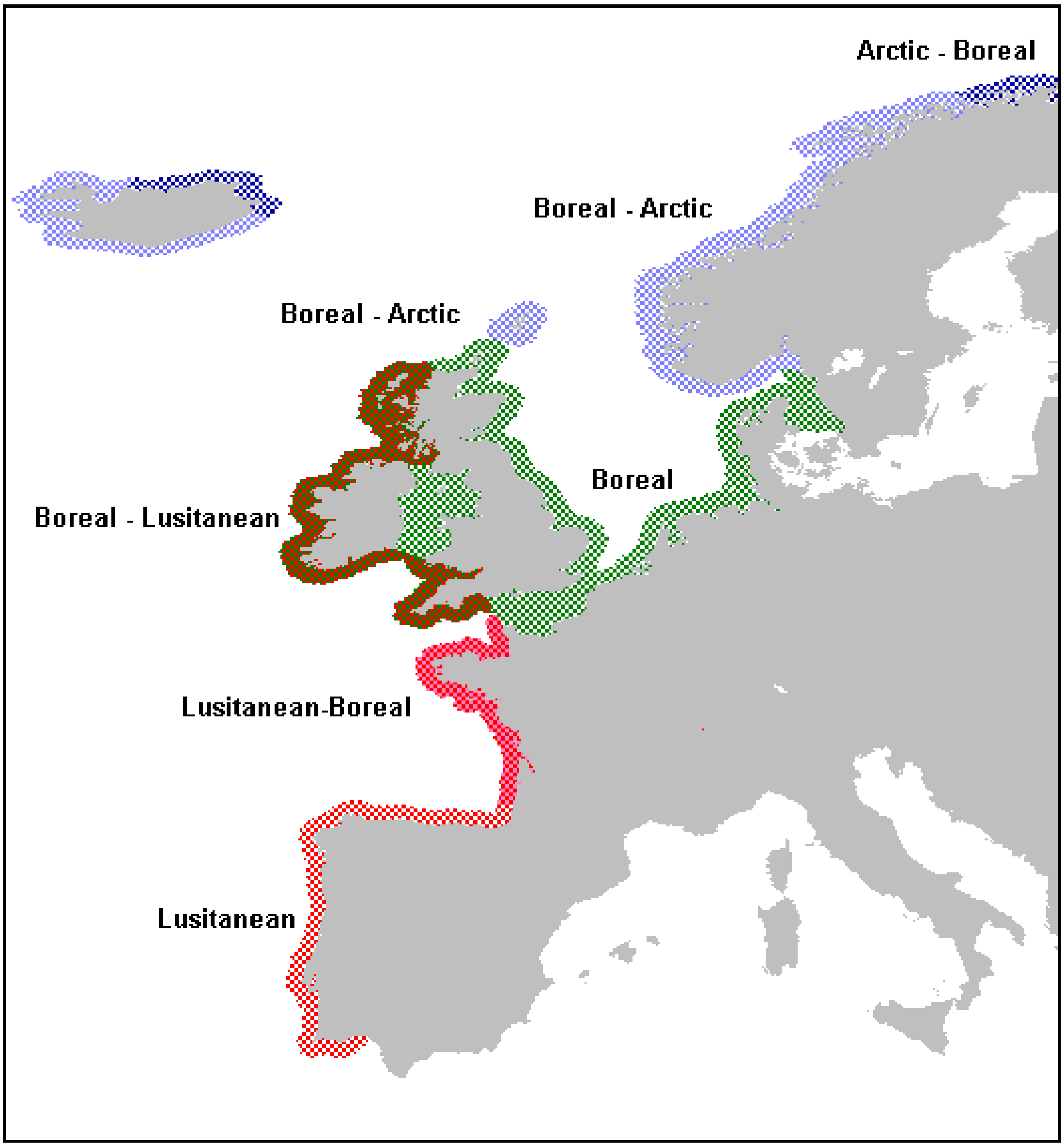

Figure 7.1. Marine biogeographic regions. Redrawn from Hiscock (1996).

However, although a detailed study by Wilson (1997) failed to find any conclusive link between climate and either growth or settlement of *A. tenuis*, similar fluctuations from the Wadden Sea (Dekker and Beukema 1999) considered that this may be evidence of a warming in climate thus enabling the bivalve *Abra tenuis*, which prefers the warmer conditions, to become established in North-Atlantic coastal waters. Wilson (1997) noted that the pattern of predation, and the resultant life strategy, of *Abra tenuis* alters from the consumption of whole individuals by crabs and predatory gastropods in the south of its range to the cropping of the siphons (but long-term survival of individuals) by juvenile flatfish in the north of its range. Were the latter to be displaced following a rise in sea temperature, then not only would the ecological balance be altered, but also direct economic losses would ensue. Thus, changes in individual species abundance may result in fundamental changes to the coastal ecosystem.

Other intertidal species will be affected by increases in radiance and the likely consequences of increased air temperature and species exposed at low water subject to the increased desiccation effects of the sun. The zonation of intertidal marine algae to survive desiccation is one of the key factors determining their zonation down rocky shores (Barnes and Hughes 1982). The settlement of larvae of sedentary intertidal species is also limited by desiccation, for example juvenile barnacles settling high on the upper shore may not survive before the next tidal immersion (Barnes and Hughes, 1982). Similarly, the upward limit of mussels is determined by their ability to withstand desiccation. The loss or change in distribution or composition of species on a rocky shore will ultimately have an effect on those species that utilise them as a habitat or food source. More complex effects have also been noted in certain intertidal species.

- Kelp species have been identified as being sensitive to rapid short-term increases in temperature, although they can generally adapt if the change is slow. For example, *Laminaria digitata*, a brown kelp commonly occurring on the lower extremes of rocky shores around Ireland, shows only slightly sub-optimal growth over a range of temperatures, from 0 to 20°C, with optimum growth at 10°C (Bolton and Luning, 1982). It is unlikely to be sensitive to a long-term, chronic change in temperature within this range, e.g. a 2°C change in temperature for a year, but may be particularly sensitive to rapid changes in temperature outside of its tolerance range, for example, during an exceptionally warm summer in Norway, Sundene (1964) reported the destruction of plants exposed to temperatures of 22–23°C. Despite this, it is unlikely that climatic change will cause mass mortality of this species; however, there may be local losses if temperatures increase above these levels.

- The barnacle *Semibalanus balanoides* is a boreal species adapted for cool environments and is commonly recorded on many Irish rocky shores. Studies have shown that reproduction is inhibited by temperatures greater than 10°C (Barnes, 1989) and cirrial beating rate reaches a maximum at 18°C in the UK (Southward, 1955) and 21°C at Woods Hole, USA, where summers are warmer (unpublished data, Crisp and Southward) and that high internal temperatures (of approximately 44°C) can cause 50% mortality if experienced for more than 45 min (Southward, 1958). Therefore, *S. balanoides* is likely to exhibit some sensitivity to temperature change and the distribution in Ireland may change due to perhaps increased temperatures.

- The sub-littoral fringe seaweed *Alaria esculenta* is common on the wave-exposed shore around Ireland. Sundene (1962) noted that its germlings can tolerate up to 16°C, above which growth is inhibited, and that it is only found on shores where the August mean seawater surface temperature is 16°C or lower (except in areas of extreme wave exposure). Munda and Luning (1977) reported that temperatures of 16–17°C for a few weeks were lethal to *A. esculenta* sporophytes; they could survive for a several days at that temperature but a longer duration was lethal. Temperature was, therefore, considered to be the main factor controlling its distribution in Europe (Sundene, 1962; Widdowson, 1971; Munda and Luning, 1977; Luning, 1990). Birkett *et al*. (1998) further suggest that kelp are stenothermal (intolerant of temperature change) and that the lethal limits of kelp would be between 1 and 2°C above or below the normal temperature tolerances and that any change in temperature is likely to affect its distribution, the southern distribution being determined by the position of the mean surface temperature isotherm in Europe and, therefore, by climatic change.

Sub-tidal habitats and species

An increase in sea and air temperatures may also have a small effect on sub-tidal habitats and species, with significant changes occurring in shallow enclosed areas where the sea temperature is subject to fluctuations due to the sun. Although little detailed work has been carried out on the likely impacts of climate change on sub-tidal benthic species the potential impacts on a number of common organisms occurring around Ireland have been examined. In many cases, changes may be subtle shifts in distribution.

- The starfish *Henricia oculata* has quite a restricted global distribution. However, it is common around the Irish coast (Picton and Costello, 1998). Any long-term temperature changes may cause a population to die or relocate. Rapid, acute temperature increase will probably also cause death. Although the adults are mobile, it is unlikely that they will move large distances (MarLIN, 2003).

- The common starfish *Asterias rubens* is widespread around Britain and Ireland, suggesting that the species is tolerant of a range of temperatures and may become locally adapted to the temperature regimes present. A number of observations, however, have been made of *A. rubens* when exposed to changes in temperature. At unusually high temperatures, *A. rubens* will shed its arms before dying (Schäfer, 1972). Lawrence (1995) recorded numbers of *A. rubens* dead in rock pools during prolonged periods of hot calm weather. During cold winters and hot summers the feeding activity of *A. rubens* declines (Anger *et al.*, 1977).

- The barnacle *Balanus crenatus* is a boreal species common around the Irish coast (Picton and Costello, 1998). It is thought to be sensitive to increases in water temperature. In comparative studies in areas of higher water temperature, *Balanus crenatus* was replaced by the sub-tropical barnacle *Balanus amphitrite*. However, after the water temperature cooled, *Balanus crenatus* returned (Naylor, 1965). Increases in sea temperature may result in this pattern occurring in Ireland.

- Minchin (1993) identified that the cuttlefish *Sepia officinalis* bones, found all around the Irish coast, were more common in the south-west of Ireland. Large and small bones were identified, possibly indicating two year classes and possibly a spawning population in the south-west. Any increase in sea temperature may result in an extension of their range and increase in numbers.

The extension of biogeographic range may not be the only consequence of increased sea temperatures.

- The starfish *Marthasterias glacialis* is a common species all around Ireland (Picton and Costello 1998). Minchin (1987) examined its spawning patterns in Mulroy Bay, Co. Donegal, and determined that it requires specific spawning conditions – the afternoons of warm sunny days. Any increase in the occurrence of these conditions through climate change may result in an increase in spawning activity and thus an increase in recruitment potential. Minchin (1992) also examined the reproductive behaviour of invertebrate species in Lough Hyne, Co. Cork, and identified multi-species spawning events, increased larval settlement and recruitment associated with periods of increased sea temperature. This suggests that increased sea temperatures through climate change may result in more favourable conditions for the recruitment of some species in Irish waters. Of particular note is the purple sea urchin *Paracentrotus lividus*, which has been commercially exploited and depleted in some areas of Ireland. Increases in spawning and recruitment due to increased water temperature may result in a range extension and a commercially exploitable population.

The implications of climate change on the marine environment in Europe were examined in the MONARCH project (Harrison *et al*., 2001). Five marine habitats of high nature conservation value (maerl beds (calcareous free-living algae) *Serpula vermicularis* reefs, *Sabellaria alveolata* (honeycomb worm) reefs, *Sabellaria spinulosa* (Ross worm) reefs and *Modiolus modiolus* (horse mussel) beds) were examined and the likely impacts considered. All five habitats occur in Irish waters. A range of direct and indirect effects was considered (Table 7.1).

Maerl beds in Ireland are extensive along the south-west and west coasts (De Grave *et al.*, 2000), where they form dense beds supporting a diverse range of plants and

Table 7.1. Possible impacts on the marine environment considered by the MONARCH project.

Direct effects	Indirect effects
Sea-level rise	Change in thermohaline circulation*
Sea surface temperature change	Alteration in nutrient supply*
Increase UV-B penetration*	Changes in wave climate*
	Changes in storminess*

*Insufficient evidence to predict likely scenarios.

animals, in relatively shallow wave-sheltered conditions. Four species (*Lithothamnion corallioides*, *Phymatolithon calcareum*, *Lithothamnion glaciale* and *Lithophyllum fasciculatum*) have been recorded in Ireland (Picton and Costello, 1998). Viles (2001) suggests that the more northern species *L. glaciale* may retreat northwards with increasing water temperatures and the southern species *L. coralloides* may extend its range further north (Birkett *et al*., 1998). It is not possible to say whether the fauna and flora associated with these species will change or that the replacement of one species of maerl with another will result in a loss in biodiversity.

Viles (2001) also considered the impact of increased sea surface temperatures on the reef-building polychaete worms *Sabellaria alveolata*, *Sabellaria spinulosa* and *Serpula vermicularis* to be negligible, although he considered that *S. alveolata* may benefit slightly as it is sensitive to cold winters particularly when occurring on the lower shore. The impact on *Modiolus modiolus* beds of a sea surface temperature rise may be more significant. *M. modiolus* reaches its southern limit in Britain and Ireland and, therefore, may be particularly vulnerable to temperature increases.

Fish species

A number of non-commercial fish species may have their range extended with the advent of increased sea temperatures.

- Mullet (*Chelon labrosus)* are present on all Irish coasts during the summer months; however, during the winter period they are only recorded in the south-west of Ireland (Minchin, 1993). It is thought that they spawn in deep water (Hickling, 1970) and may spawn in alternate years. In Lough Hyne, they appear during July where they remain until October–November. Changes in the summer temperature in Lough Hyne have been shown to influence the growth rate of mullet. The size of juvenile ‘O group’ fish in August has been correlated with air temperatures from May to August. Kennedy and Fitzmaurice (1969) have also shown that mullet growth is slow and variable and influenced significantly by sea and air temperatures. Mullet feed actively above sea temperatures of 10°C but cease below 8°C. An increase in sea temperature could result in the occurrence of mullet on more Irish coastal areas in winter and promote the survival and growth and spawning of individuals at a younger age.

- Bass (*Dicentrarchus labrus*) spawn on the south-west to south-east coasts of Ireland (Kennedy and Fitzmaurice, 1972) and spend much of their life in inshore waters (Minchin 1993). Kennedy and Fitzmaurice (1972) indicate that growth and year class strength is positively correlated with greater sea temperatures. Although bass occur around the entire Irish coast they are less abundant in the north. Increases in sea temperature may result in bass becoming more frequent throughout Ireland’s coastal waters.

There are a number of more southerly species that may also benefit from increased sea temperatures and become more frequent visitors to Irish waters.

- Larvae of the garfish *Belone belone* are recorded off the south coast during warm summers (Minchin, 1984).

- Larvae of the red mullet *Mullus surmuletus* are only recorded from the warmer southern Irish sea and south coast (Minchin, 1987).

- Red gurnard *Aspitrigla cuculus*, although recorded around all the Irish coasts, only have their youngest year classes occurring off the south coast and may become more abundant.

- The trigger fish *Balistes carolinensis* comes from the eastern Atlantic and from the North Sea south to the Mediterranean (Lythgoe and Lythgoe, 1991); however, it is being increasingly recorded in Irish waters (Went, 1978; Quigley, 1985; Quigley *et al*., 1993a, 1993b). A biogeographical review of this species has also shown it to be increasing in the North and South Atlantic for reasons unclear although global climate or oceanographic changes are suggested, particularly an increase in sea temperature. This species may become more abundant although it is unlikely to form a breeding population in Irish waters as trigger fish are reported to become dormant below 15°C and die below 12°C which suggests that they are unlikely to survive year round in Irish waters.

- Migrations of the long fin tuna *Thunnus alalunga* are associated with the 17°C isotherm (Minchin, 1993) and this band of water extends along the Irish south-west and west coasts extending northwards in the summer months. The extension of the long fin tuna migrations varies according to this extension and increases in sea temperature could result in a range extension of tuna northwards. Other fish species associated with tuna such as the Atlantic bonito *Sarda sarda* and skipjack tuna *Katsuwonus pelamis* may undergo similar range extensions.
- The occurrence of eagle ray *Myliobatis aquila* and gilt-head sea bream *Sparus aurata* are both considered to have potentially harmful implications for shellfish culture and benthic marine biodiversity. One record of eagle ray occurs from Co. Antrim (Vickers, 1959) and may become more common in Irish waters (Minchin, 1993).

Marine mammals

The impacts of climate change are considered to have a serious threat on cetaceans at a global level (Burns, 2000). The main threats are associated with a potential reduction in the primary production in the oceans resulting in a loss or failure of the zooplankton, the main food source for baleen whales. This may occur if increased sea and air temperatures result in a substantial increase in the melting of sea ice. Likewise, the reduction in primary productivity could have a ‘knock-on’ effect up the food chain resulting in the reduction of large prey items for toothed whales and dolphins.

The consequences of this are, however, outside of the scope of the proposed scenarios. Smaller increases in temperature may have local impacts on the primary productivity of Irish waters and thus a local impact on potential food for cetaceans. Such impacts are, however, difficult to predict.

Plankton

Plankton plays a critical role in the development of marine ecological systems. Phytoplankton is responsible for nearly all the primary production in the sea and any significant changes in plankton development could potentially have significant impacts further up the food chain. Having limited mobility, they are reliant on water movement to determine their distribution and the correct environmental conditions for development. Seasonal patterns in phytoplankton distribution are generally known to occur during the winter months due to the development of light-limiting conditions, as high wave energy causes mixing to occur to a greater depth than in the spring. As the air temperature increases, vertical stability in the water column occurs, allowing phytoplankton to bloom. Nutrient depletion in the upper layers of the water column in the summer limits plankton development until the autumn, when a breakdown of the thermocline allows a small bloom of phytoplankton limited by decreasing irradiance levels.

Sea surface temperature, therefore, plays a significant role in the timing and development of phytoplankton communities and, therefore, the development of other marine communities. Temperature changes may also result in regional changes in the species composition of phytoplankton and zooplankton species, affecting the availability and suitability of prey for higher trophic level species, including those of commercial importance.

Algal blooms, whether harmful or not, have been associated with increased water temperatures. The prevalence and intensity of such blooms appears to have increased (Pybus and McGrath, 1992). Increased water temperature and decreased vertical mixing of the water column can contribute to the growth of the algae and, in the case of toxic species, changes in the level of toxicity can occur with changes in nutrients (Hallegraff, 1993; Boesch *et al*., 2000). With increaseing sea temperatures, it is likely that there will be an increase in bloom events.

Although long-term plankton datasets do occur (Colebrook *et al.*, 1991), precise information linking it with other marine communities, makes it very difficult to predict precisely the significant impacts on the marine environment in Ireland through changes in plankton communities due to climate change.

7.2.1.2 Change in sea level

Changes in sea level will mostly affect intertidal species through the loss or alteration of habitat. The likely alteration in the extent of habitats will probably be insignificant on hard substratum shores, where there will be a small extension of zonation patterns up the shore. Soft substratum shores, however, are generally low lying and an increase in sea-level rise will have a greater effect extending habitats further up the shore. New habitats may be formed at the top of the shoreline and a change of species composition may also occur. Increased sediment loads in the water column may result in a reduction of light penetration or in the smothering of existing habitats resulting in the loss of species and the creation of new habitats for other species to colonise.

Low-lying coastal areas, such as estuaries and coastal lagoons, are likely to be most vulnerable and significantly affected by sea-level rise. Coastal lagoons that have a specific salinity regime maintained by a coastal barrier may be particularly vulnerable to small sea-level rises. If the coastal barrier is breached, allowing salt water incursion, then significant changes in habitat and consequently species composition may occur. Changes in sea-level rise are, however, likely to be long term, and adaptation to new conditions will be made.

Estuarine systems will be subject to coastal squeeze, with urbanisation infringing from the landward side and sea-level rise from the sea. Large areas of intertidal habitat (mudflats, saltmarsh and sand flats) may be lost with little possibility of compensatory habitats being created. Many estuarine habitats are of high nature conservation value particularly for migratory birds. The loss of estuarine habitats through sea-level rise is likely to be significant.

7.2.1.3 Change in precipitation level

A change in precipitation may affect the marine environment in two main ways.

1. The direct effects of increased rainwater falling on shores may have an effect on the species growing there; however, this is likely to be minimal although in coastal lagoon systems, where salinity is an important factor, rainfall may have more significant effects. Such systems can have a very fine salinity balance determined by the input of freshwater from rainfall, runoff and incursion of marine waters. Significant changes in rainfall may result in this balance being altered resulting in more saline or freshwater conditions.
2. More likely effects may occur from the increased runoff from rivers and streams through estuaries. Increased or decreased runoff could lead to elevated or reduced riverine inputs. Such changes may lead to changes in salinity gradients within estuarine ecosystems. Higher rainfall may also lead to higher sediment loads in rivers and also to higher loads of contaminants. Past changes in regional freshwater runoff have tended to be short term but have had a significant adverse biological effect on the communities (Countant, 1987), although recoverability was possible. Predicted changes, however, will be long term and significant impacts may occur. Increased runoff is likely to deliver increased amounts of nutrients such as nitrogen and phosphorous to estuaries, while simultaneously increasing the stratification between freshwater runoff and marine waters. Both nutrient additions and increased stratification would increase the potential for blooms of algae that deplete the water of oxygen, increasing stresses on benthos, fish and shellfish. Decreased runoff is likely to reduce flushing, decrease the size of estuarine nursery zones, and allow predators and pathogens of shellfish to penetrate further into the estuary.

7.2.1.4 Change in ocean circulation patterns

The oceans occupy over 71% of the surface of the planet. Evaporation and CO_2 balance at the ocean surface is very temperature dependent. Climate change may alter ocean circulation patterns, vertical mixing and sea-ice cover, and these in turn will affect nutrient availability, biological productivity, structure and functioning of marine ecosystems, and heat and carbon storage capacity. Such changes could be significant with major changes occurring in the marine environmental conditions in Irish waters; however, further considerations are outside the scope of the climate change scenarios and are not easily predicted.

7.2.1.5 Change in occurrence of storm events

The distribution of habitats and species around Ireland is determined to a certain degree by exposure to wave action, primarily at a regional and local scale. High wave exposure sediment shores are generally constructed of coarser more mobile material supporting more transitory species than wave-sheltered more stable shores which can support diverse communities. Rocky shores are generally more stable than sediment shores and, although the habitats present will not change, the suite of species present will alter, depending on wave exposure.

Generally, it is not the maximum wave action that is experienced but the average wave exposure that is the determining factor in species distribution. Storm events or periods of extreme weather occur on all coasts and may have short-term impacts on the species and communities occurring there. Such events are usually short lived and, when prevailing conditions return, species will recolonise the habitats. If storm events are longer and the average wave exposure at a site is significantly increased, then species may not be able to resettle or re-establish themselves and the community species composition shifts.

Another important factor is the direction from which sites are exposed to wave action. The prevailing wind in much of Ireland is from the south-west (Met Éireann, 2002). Habitats and communities have developed in these prevailing conditions. If increased storm events and high winds are to occur it is possible that they will come from the same direction as the prevailing weather. However, if the coast is exposed to storm events from 'unusual' directions exposing previously wave-sheltered locations more significant changes in the distribution of habitats and species may occur.

It is unlikely that an increased occurrence of storm events will significantly change the distribution of marine species in Ireland unless the events are so regular as to change the average wave exposure at a site. Otherwise, changes may be localised with the loss of wave-sheltered species at some sites being replaced by more wave-tolerant species.

Many coastal lagoons require periodic breaching by seawater to maintain their brackish state. Such lagoon systems may, however, be subject to significant changes if storm events cause breaches to coastal barriers, allowing larger amounts of saltwater into the system and unbalancing the salinity regime. Increases in the periodicity of this could have a significant impact on the conditions within the lagoon resulting in a change of species composition. Lagoons also occur within low-lying areas of Ireland which may be vulnerable to sea-level rise.

A number of sub-tidal species which are common and of conservation interest around Ireland are sensitive to wave exposure.

- Sea grasses (*Zostera* spp.) grow in wave-sheltered environments, with gentle long shore currents and tidal fluxes. Where populations are found in moderately strong currents they are smaller, patchy and vulnerable to storm damage and 'blow outs'. Increased wave exposure may increase sediment erosion creating small patchy populations and recently established populations and seedlings may be highly sensitive to increased wave action since they have not developed an extensive rhizome system. Losses of sea grass beds may occur due to increased storm events in areas previously not exposed to high wave action.

- Kelps *Laminaria hyperborea* and *Laminaria saccharina* are unable to survive where wave action is extreme because they have a large frond area which is liable to snap off the stipe. *L. saccharina* is particularly sensitive. Wave action reduces the upper limit of populations to several metres below low water. Older and larger plants are most sensitive to wave action. As wave exposure increases, *L. hyperborea* and *L. saccharina* are out-competed by *Laminaria digitata* or *Alaria esculenta*. An increase in the level of wave exposure may cause plants to be torn off the substratum or the substratum with the plants attached may be mobilised. Recovery, however, is likely to be high because the species rapidly colonises cleared areas of the substratum. Kain (1975) recorded that *L. saccharina* was abundant 6 months after the substratum was cleared.

A number of common intertidal species are also sensitive to increased wave action.

- The brown algae *Fucus serratus* occurs on coasts with moderate wave exposure or less. Above this level of wave action, individual plants can break fronds or be completely removed from the substratum. *F. serratus* is more sensitive to wave exposure than *Fucus vesiculosus*. However, if *F. serratus* is removed, other species may come to dominate and re-establishment of the seaweed may depend on the ability to out-compete other species and depend on the resumption of suitable environmental conditions.

- *Ascophyllum nodosum* cannot resist very heavy wave action and exposure to wave action is an important factor controlling the distribution of the species. The number of plants reduce from wave-sheltered to wave-exposed conditions and individual plants become increasingly short and stumpy (Baardseth, 1970). Any increase in wave exposure can cause plants to be torn off the substratum and replaced by *Fucus vesiculosus*. Sensitivity to wave exposure is therefore high.

- Spiral wrack *Fucus spiralis* and channel wrack *Pelvetia canaliculata* live on sheltered to moderately exposed shores and increases in wave exposure could result in plants and germlings being torn off the substratum or mobilisation of the substratum with the plants attached. In areas of high wave exposure, *P. canaliculata* only grows in crevices. However, as with most algae, *F. spiralis* has been observed to readily colonise cleared areas (Holt *et al*., 1997), so, if wave-sheltered conditions return recovery rates are high.

It is difficult to make specific predictions, as there are no clear scenarios as to changes in storminess. However, it is not expected that a significant loss of species will occur. Losses may be short term with colonisation occurring following the return to prevailing conditions.

7.2.2 Marine birds

7.2.2.1 Introduction

The objective of this section is to give a brief overview of the existing environment for birds feeding and breeding in Irish marine and coastal habitats, and possible scenarios which arise in the future through current predictions on climate change.

Marine and coastal birds are divided into a number of categories for the purposes of this report, based on vulnerability to climate change. There is overlap between categories for some sites.

1. Cliff and ‘high’ island nesting seabird species, which are in general not vulnerable to rising sea levels but which may be affected by changes in prey abundance, or climatic changes which reduce the availability of prey.

2. Shore and ‘low’ island nesting species, which are vulnerable to rising sea levels and storm surges, and which may also be affected by changes in prey abundance. This category includes tern colonies, with little terns being particularly vulnerable. Shore nesting waders are also vulnerable. A decrease in summer rainfall may enhance breeding success.

3. Coastal wintering species – wildfowl and waders on estuaries, bays and rocky/shingle coasts. Vulnerable to rising sea levels and storm surges which may result in habitat change and loss affecting both feeding and roosting areas. Changes in prey abundance may also occur.

4. Marine wintering species which generally feed offshore, coming close to shore during severe weather – principally species using the Irish Sea, e.g. little gulls. Increased storm activity may impact on energetics and reduce breeding success, which could also be affected by changes in prey species.

Some of these groups and others, such as breeding wildfowl and waders, may also be affected by habitat change arising from sea-level rise and storms in coastal habitats on the landward side of current shorelines. These include machair, and low-lying fresh water and brackish wetlands which are currently separated from the sea by shingle ridges. Examples of such areas are Lough Donnell in Co. Clare, Lady’s Island Lake and Tacumshin in Co. Wexford, and Kilcoole marshes in Co. Wicklow.

On a larger scale (Western Palaearctic, North Atlantic), there may be shifts in the range occupied by individual bird species using marine and coastal areas. There is some evidence that this is already occurring.

7.2.2.2 Key sites for seabirds and waterfowl in coastal areas

In general, seabirds and waterfowl occur in significant concentrations at specific sites during at least part of the year, facilitating the collection of population data from which site-specific, all-Ireland and international populations and trends can be derived. Seabirds breed in colonies, while wintering waterfowl concentrations reach their highest numbers in coastal and inland wetland habitats. Approximately 60% of the Irish wintering waterfowl use coastal habitats. Of these, some 80% are concentrated in bays, estuaries, lagoons and polder lands. The remaining 20% are more dispersed on shingle and rocky shorelines (Marine Institute, 1999). While there is a long history of knowledge of individual sites, detailed quantitative data are more recent. Improvements in census methodologies in recent years mean that data from the 1970s, for example, are not always comparable with current data. This creates some difficulty in the analysis of population trends.

It is not intended to list current Irish populations of seabirds and wintering waterfowl in this report, or to discuss population trends, since major reports on these are currently in preparation (see Sections 7.2.2.3 and 7.2.2.4 below).

The most recent listing of Important Bird Areas (IBAs) in Europe is given in Heath and Evans (1999). (Compilation of the review of IBAs in Ireland was completed in 1997, and is based on information from the All-Ireland Tern Survey (completed 1995), the first 2 years of I-WeBS (Delany, 1996; 1997), and seabird listings from the previous IBA review (Grimmett and Jones, 1989)). This is a site-based listing, including all internationally important sites/site complexes, as well as a small number of sites for Annex 1 listed species (Birds Directive 79/409/EEC) (Council of the European Communities, 1979) which may not reach the international threshold but are important in protecting the range of that species in Ireland. (The threshold for international importance is 1% of the world population of a species or sub-species.)

Irish coastal IBAs are shown in Figs 7.2–7.4 under the following categories:

Figure 7.2 Category 1, important seabird breeding colonies on cliffs and 'high' islands

Category 2, important seabird breeding colonies on shores and 'low' islands (0–10 m above mean sea level), where some of the species present typically nest close to sea level and are vulnerable to changes in sea level and storm surges

Figure 7.3 Category 3, wintering waterfowl on 'high' islands, mainly barnacle geese

Category 4, wintering waterfowl of estuaries and low coasts where habitat loss or change is a risk

Figure 7.4 Category 5, freshwater and brackish lagoons separated from the sea by sand dunes or shingle ridges and polder lands, where habitat loss or change is a risk.

Coastal IBAs listed for the presence of concentrations of the terrestrial bird species chough and corncrake have been excluded from consideration in this section.

Most of the IBAs listed have been classified as Special Protection Areas under the EC Birds Directive 79/409/EEC (Council of the European Communities, 1979). The remaining sites are required to be classified by the European Commission, under ongoing infringement proceedings against Ireland under the Birds Directive in which inadequacies in the implementation of the Habitats Directive are cited. These Directives require, *inter alia*, that existing bird populations are maintained at a favourable conservation status, that their existing geographic ranges are maintained, and that measures are taken by Member States to ensure that protected sites do not deteriorate in ways that have an adverse impact on the bird populations using them.

7.2.2.3 Seabirds

There are six families of seabirds that have a long history of breeding in Ireland:

Petrels – Procellariidae: fulmar, Manx shearwater, storm petrel and Leach's petrel

Adapted for long-distance flight and all species forage over very large areas of sea, surface feeders on plankton or scraps of offal.

Cormorants – Phalacrocoracidae: cormorant and shag

Feed by diving from the sea surface, swim underwater.

Gannets – Sulidae: gannet

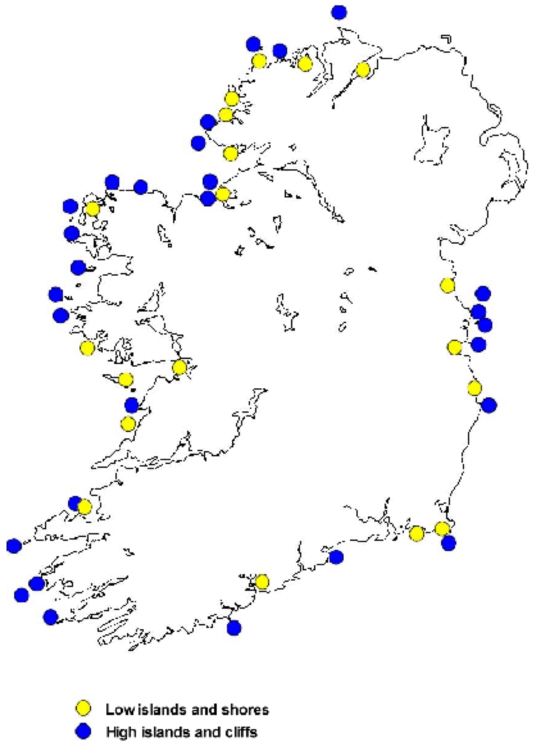

Figure 7.2. Important Bird Areas listed for breeding seabirds.

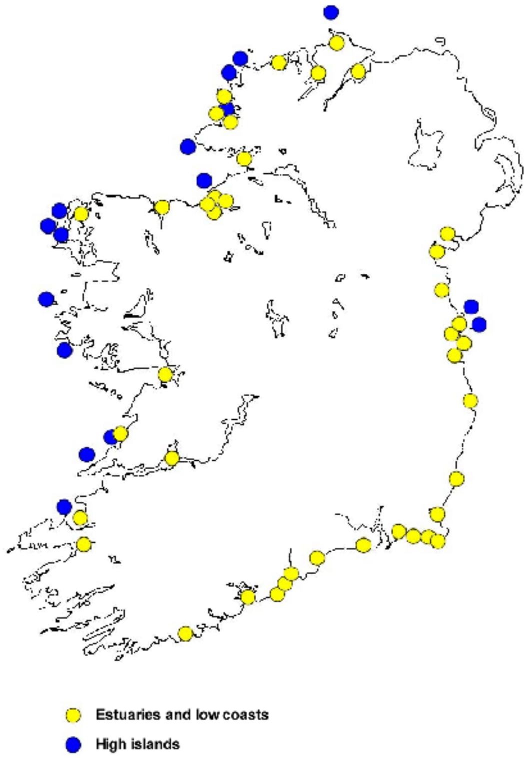

Figure 7.3. Important Bird Areas listed for wintering waterfowl.

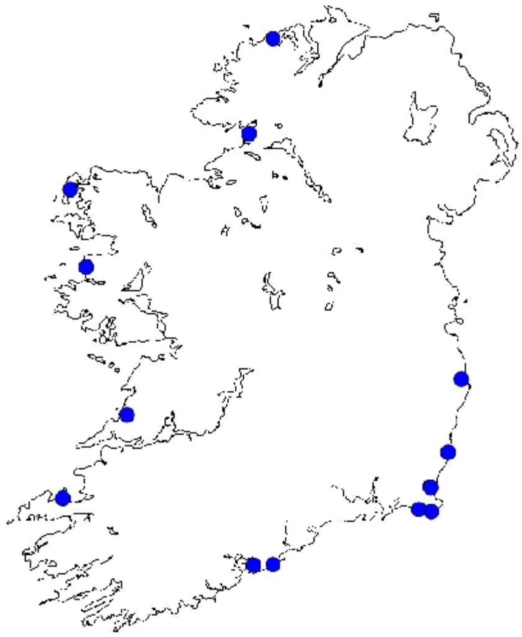

Figure 7.4. Lagoons, lakes and polder lands listed as Important Bird Areas which are separated from the sea by sand dunes and shingle ridges.

Plunge dives for food, often from a height.

Gulls – Laridae: herring gull, common gull, black-headed gull, lesser black-backed gull, great black-backed gull and kittiwake

Mediterranean gulls are a recent addition to the list of Irish breeding seabirds. The core range of this species is the Ukraine, and the population has expanded both within and northwards from this area since the 1980s. The first recorded breeding attempt in Ireland was in 1995.

Gulls are opportunistic feeders using terrestrial, intertidal and marine habitats. Black-headed and common gulls are estuarine and inland feeders, the three larger species mainly in inshore waters and rocky coasts. Kittiwake feed further out to sea than the other gull species, where they take food from the surface and shallow depths. Little gulls are surface feeders; wintering concentrations on the Arklow Bank off the Wicklow coast may be feeding on northern krill *Meganyctiphanes norvegica* (Coveney and Phalan, 2001).

Terns – Sternidae: sandwich tern, roseate tern, common tern, arctic tern and little tern

Feed by hovering and plunge dive for fish and crustaceans.

Auks – Alcidae: Guillemot, razorbill, black guillemot and puffin

Wings adapted for high speed propulsion under water, diving from the water surface.

A seventh family, skuas (Stercorariidae), occur as vagrants in Irish coastal waters, and have recently established a breeding presence. A pair of great skua was confirmed as breeding in Ireland for the first time in 2001 (Newton, 2001). Paradoxically, this species has a northern breeding distribution, and its arrival as a breeding species in Ireland represents a southward expansion of its range. Great skuas are predators of kittiwake and storm petrel.

Little egrets are another recent addition to the list of breeding species. This tree-nesting heron species is not exclusively coastal, but all four current Irish breeding sites are close to estuarine habitats. Little egrets have been resident in Ireland since 1990, and first bred in 1997. Their range has been expanding in Western Europe during the last 50 years, particularly along the Atlantic coast of France. Key factors in range expansion have been identified as complete protection in France since 1962, and a succession of mild winters since the 1970s (Smiddy, 2002).

Nest site vulnerability

The distribution of seabirds breeding on cliffs and high islands is determined by the distribution of preferred nesting habitats at individual sites, and does not necessarily vary in relation to height above sea level. Storm petrels show the greatest vertical range; they nest among boulders on storm beaches, and also on the ground under heathers (e.g. on Inishtooskert), and in dry-stone field boundary walls. Puffins need soil for nest burrows and are generally located on cliff tops, although wide ledges on cliff faces can accumulate sufficient soil for nesting. Fulmars also nest on soil rather than rock. Razorbills prefer clean rock ledges, while kittiwakes favour very narrow ledges. Cormorants nest on steep cliff slopes, but also on flat reefs and skerries which are vulnerable to rising sea levels. Shags generally nest at relatively low levels and could be vulnerable at some sites. The vertical distribution of breeding seabird species, therefore, varies between individual sites. In general, immature birds nest at lower levels on cliffs than do adults of the same species. Immature birds may, therefore, be subject to reduced breeding success.

Gulls and terns nest on lower shores and islands and some tern species are particularly vulnerable. Little terns at the North Wicklow Coastal Marshes IBA sometimes nest on the shingle beach within the range of spring high tides, and nests at risk of submergence are moved by wardens working on the Little Tern Protection Scheme at this site. Most coastal tern colonies are at least partly at risk in a rising sea-level scenario. The internationally important tern colony at Lady's Island Lake was established after Tern Island in Wexford Harbour was washed away by sea during the early 1970s. Low-lying IBAs listed for breeding seabirds which are vulnerable to rising sea levels and storm surges are listed in Table 7.2.

Seabirds such as terns nesting on low shores have always had to contend with natural changes to colony sites. In a

Table 7.2. Important breeding seabird colonies on shores and 'low' islands (0–10 m above mean sea level), or where some of the species present typically nest close to sea level. These sites are vulnerable to sea-level rise and storm surges.

Site name	County	IBA No.	Altitude (m)	Main species	Other categories
Lough Swilly	Donegal	005	0–5	Sandwich tern	4
Greer's Island	Donegal	008	0–5	Arctic tern, sandwich tern, black-headed gull	4
Inishbofin, Inishdooey and Inishbeg	Donegal	013	0–38 ? colony	Arctic tern	3
Inishkeeragh and Illancrone	Donegal	018	0–6	Little tern, common tern, arctic tern, sandwich tern	4
Roaninish	Donegal	019	0–10	Great black-backed gull, herring gull	4
Inishduff	Donegal	026	0–5	Shag, great black-backed gull	–
Ardboline and Horse islands	Sligo	032	0–10	Cormorant	4
Broadhaven, Blacksod, Tullaghan and parts of Mullet peninsula	Mayo	041	0–30	Sandwich tern	4, 5
Inishglora and Inishkeeragh	Mayo	042	0–22 ? colonies	Arctic tern, little tern	1, 3
Connemara islands	Galway	054	0–63 ? colonies	Little tern, sandwich tern, common tern, arctic tern	3
Inner Galway Bay**	Galway	057	0–5	Sandwich tern, cormorant	3
Aran Islands (part)	Galway	061	0–79 ? colonies	Arctic tern, little tern, cormorant, shag, fulmar, black guillemot	–
Magharee Islands	Kerry	070	0–22 ? colonies	Arctic tern, little tern, great black-backed gull, lesser black-backed gull, cormorant, shag	1, 4
Cork Harbour	Cork	088	0–5	Common tern	4, 5
Keeragh Islands	Wexford	097	0–9	Cormorant, arctic tern	–
Lady's Island Lake	Wexford	101	0–10	Sandwich tern, roseate tern, arctic tern, common tern	4, 5
North Wicklow coastal marshes	Wicklow	105	0–10	Little tern	4, 5
Dublin Bay	Dublin	109	0–10	Common tern, arctic tern	4
Boyne estuary	Louth/Meath	119	0–10	Little tern	4

Note: Sites where the exact height of the breeding seabird colonies are not known are indicated: ? colonies.

climate change scenario of rising sea levels, colony turnover rate may increase, and the availability of alternative sites may diminish. Low offshore shingle banks and islands may owe some of their attraction as breeding sites to an absence of mammalian predators such as foxes, hedgehogs and rats. Selection of alternative sites on larger islands or on the mainland could result in reduced breeding success due to predation, and may require increased levels of human intervention to protect colonies.

Food resources for seabirds

Current population and breeding success trends in seabird numbers are related in some instances to fisheries management. A detailed discussion of fluctuations in seabird populations in relation to fishery management and exploitation is given in Lloyd *et al.* (1991). Changes in fish stocks and fisheries management are an important determinant of seabird populations and breeding success. Commercial sand eel fisheries in the UK have adversely impacted on breeding seabird colonies. There is no commercial sand eel fishery in Irish waters, and, in consequence, there is very little information on stocks. Kittiwake populations in south-east Ireland declined significantly between the mid-1970s and the mid-1980s, apparently in relation to declining stocks of herring during the same period (McGrath and Walsh, 1985). There has been a slight recovery in the numbers of breeding pairs since 1993, with an increase in breeding success (McGrath and Walsh, 1996).

A study of the Celtic Sea herring fishery in 1994/95 estimated that 800 t of fish, mainly herring, are discarded during the winter fishing period. Seabirds using this food resource were gannet, kittiwake, and herring, lesser and great black-backed gulls (Berrow, 1998). Fulmars, gannets and the larger gulls feed on offal discarded from fishing vessels. It should be noted that discards of under-sized fish might be a useful concentrated food resource for seabirds, but not necessarily a sustainable one.

Predictions of climate change-induced changes in fish species and stocks in Irish waters are tentative currently. Sand eels could be displaced northwards, and could be replaced as a seabird food resource by pilchard and anchovy. Sprat are an important food species for roseate terns in the Irish Sea. Changes in the distribution and abundance of plankton could affect petrels.

Other factors, such as feeding at tipheads, are associated with botulism-induced mortality in herring gulls. This appears to be a major factor in the virtual collapse of herring gull numbers particularly in east coast colonies. Increased temperatures may increase the seasonal duration of risk from botulism, while improved management of tipheads may reduce their accessibility to feeding birds in the future.

Current trends in seabird numbers

Seabird 2000, a major re-survey of breeding seabird colonies in Ireland and the UK, is almost complete. Publication of the results and analysis in book form is anticipated in early 2004 (S. Newton, personal communication). This will provide an update and overview of seabird counts carried out under the Seabird Colony Register that was established in 1984. The first major synthesis of the results of the Seabird Colony Register was published in Lloyd *et al*. (1991).

7.2.2.4 Wintering waterfowl

Wintering waterfowl (swans, geese, ducks and waders) occurring in Ireland breed in north-east Canada, Greenland, Iceland and northern Europe. For some species, Ireland is their end destination (swans, geese, duck and many waders). Other species occur in Ireland in spring and autumn on passage to wintering grounds located further south, in Southern Europe and Africa (mainly waders, e.g. whimbrel). In the context of Western Europe, most wintering waterfowl occur on the warm side of the 5°C January isotherm.

Habitat requirements for wintering waterfowl

Wintering waterfowl depend on the availability of food resources and safe, undisturbed roosting locations. Swans and geese are herbivorous, and feed on coastal grasslands and marshes, including saltmarsh and brackish and freshwater marshes in coastal wetland complexes (e.g. greylag geese feeding on freshwater marsh, and Brent geese feeding on improved agricultural grassland, both in the North Wicklow Coastal Marshes). Eelgrass (*Zostera*) and green algae (*Enteromorpha* and *Ulva* spp.) are important food resources for Brent geese and wigeon. These food species are vulnerable to habitat loss through increased wave action and exposure. Most duck species eat both animal and plant material; seeds are an important food resource in coastal marsh habitats.

Waders feed on littoral muds, sands, gravels, mixed substrates, and mussel and oyster beds. Different species are selective as regards feeding habitat; black-tailed godwit feed mainly on littoral muds, while bar-tailed godwit prefer muddy sands and sands. Redshank feed on all three of these, but tend to occur in higher densities in the muddier habitats. Turnstone feed on stony shores and among *Fucus*, and also on mussel beds and oyster beds, and occur dispersed along coastlines as well as in IBAs. The prey species taken by waders vary, with some groups mainly surface feeding, e.g. plovers. Longer billed species probe in the sediment, and bill length influences the availability of different invertebrate prey species. Foot stirring and trampling can be used to dislodge invertebrates from the upper sediment layer, or to induce invertebrates to rise within the sediment column.

In sites where saltmarsh is present, it is used principally for high tide roosting by waders; duck feed extensively in saltmarsh habitats at high tide. Both groups move to more elevated habitats during spring high tides when saltmarshes are submerged, such as sand dune habitats (dune slacks), supra-littoral rock, shingle or sand bars, or adjoining agricultural land. Man-made structures can also be used as high tide roosts where these are undisturbed, Dun Laoghaire Pier and the railway embankment in south Dublin Bay being examples.

Climate change and wintering waterfowl

Climate change has the potential to affect waterfowl through habitat change on both wintering and breeding grounds. Habitat change on tundra breeding grounds could impact on overall population levels. There is evidence that this is already happening in Greenland white-fronted geese, as the most northerly part of their breeding range in north-west Greenland is becoming colder in summer as predicted by climate change modelling (Fox, 2002). The total population of this species, which winters in Ireland and Scotland, has been in decline since the mid-1990s. Declining numbers were first noted in the flocks which winter furthest south in Ireland; this race of geese shows 'leap-frog' migration, in that the birds which winter furthest south breed in the most northerly parts of the breeding range where climate change impacts are more pronounced.

An eastward shift in the position of the 5°C January isotherm in Western Europe seems likely to impact on the winter distribution of waterfowl. Northern European breeding species may stop short of migrating to Britain and Ireland in the long term, if habitat suitability increases within mainland Europe. Within Britain, there is evidence that regional changes in waterfowl populations are already occurring (Austin *et al.*, 2000). Analysis of wader count data between 1969 and 1996 in different regions in Britain suggests that warmer winters are making it less essential for birds to travel on to the milder south-west of Britain, a change which is independent of site-specific changes in the different regions. Ringed plover, knot, sanderling, dunlin, black-tailed godwit, bar-tailed godwit and redshank have declined in south-west England and Wales during the time period considered. During the same period, all of these species have increased in south and south-east England, with the exception of sanderling. Wader populations in north-east Scotland, east England, north Wales and north-east England have also increased. A similar analysis is planned for Irish waterfowl data, and is expected to be complete in late 2003 (Colhoun, personal communication). It is unclear at present whether the dataset will support a sub-division of Ireland into regions, given the shortage of annual records for many sites until the I-WeBS programme commenced in 1994.

While warmer winters may mean that a larger proportion of wintering waterfowl populations will overwinter in mainland Europe, a complicating factor is that rising sea levels will reduce the size of coastal wetlands and, hence, habitat availability unless a policy of managed retreat is widely implemented. Currently, the UK is leading the field in this regard.

Habitat change arising within Ireland is likely to occur as a result of climate change. With rising sea levels, and an increased frequency and/or intensity of storm surges, saltmarsh, sand dune and shingle ridge habitats are expected to be increasingly vulnerable to erosion (Monarch, 2001). There may be regional variations in vulnerability, as sea-level rise is likely to be most marked along the southern coast of Ireland (see Chapter 8).

Climate change impacts on coastal habitats are likely to be seen here first. However, storm surges could be more pronounced along the Atlantic seaboard because of the greater fetch over which wave height increases.

Currently 41 estuaries and low coasts are listed as IBAs for wintering waterfowl; 24 of these are at least partly sheltered by sand dunes and shingle ridges (Table 7.3). Erosion of these habitats could cause significant habitat change in the littoral and supra-littoral habitats currently protected by them. These 24 sites, distributed around the Irish coast, could be regarded as particularly vulnerable.

The ability for coastal habitats to migrate inland depends on existing topography, land use, and also on coastal management. Where the hinterland slopes upward steeply from the shore (e.g. Cork Harbour), or where the shoreline is largely constructed embankment and sea walls (e.g. Dublin Bay), the potential for habitats to migrate inland is limited. This could impact on waterfowl roosting as well as feeding areas, by reducing or eliminating roosting areas, or making them more liable to human disturbance. Sites where roosting areas are lost may become much less used as feeding areas, or birds continuing to use them for feeding may have reduced breeding success because of the high energy cost of extended flight time spent commuting to roost sites elsewhere. A policy of managed retreat could result in habitat gains where extensive (and possibly formerly reclaimed) low-lying land adjoins the shore. Implementation of this policy would mean that habitat losses in sites where managed retreat is not an option could be at least partly compensated for elsewhere in Ireland.

Estuary morphology is an important determinant of intertidal sediment type. Relatively long, narrow estuaries have more mud, while relatively wide, short estuaries have more sand (Yates *et al*., 1996). Tidal range is also a factor; estuaries with low tidal ranges tend to be muddier than those with high tidal ranges, presumably because of differences in tidal velocities which would increase with tidal range. Climate change impacts could, therefore, be expected to be specific to broad classes of estuarine morphology. There is a general expectation that littoral habitats will become sandier (Monarch, 2001). The extent to which this occurs may be moderated by estuary morphology, and by changes in sediment type and volume discharged into estuaries. The latter could be influenced by climate change induced increases in winter rainfall, which could alter erosion patterns in river catchments.

Changes in substrate type in coastal IBAs listed for wintering waterfowl may favour certain species. An increase in sandy substrates would tend to benefit oystercatcher and possibly sanderling, but would have negative impacts for species which prefer muddy habitats such as dunlin, black-tailed godwit and redshank (Monarch, 2001). Light bellied Brent geese would also be adversely impacted by an increase in sandy substrates, which would support reduced biomass of *Zostera* and green algae, the most important autumn and spring food plants. Ireland holds almost all of the Canadian Arctic breeding population of light-bellied Brent geese. Changes are also likely to occur in the food resources available to plants, invertebrates and fish, with follow-on consequences for wintering waterfowl, although these are difficult to predict with any certainty.

Current trends in waterfowl populations

An analysis of trends in waterfowl populations in Ireland is in progress, and is expected to be completed towards the end of 2003. The I-WeBS programme commenced in 1994, and co-ordinates waterfowl surveys during the winter months. Previous surveys were carried out over three consecutive winters in the 1970s and 1980s. The ongoing I-WeBS programme provides a good baseline against which to measure future change.

7.2.3 Exotic species

Climate is fundamentally important for the stability and maintenance of populations. Alterations in climate will exclude or encourage those species on the fringe of their natural distributions. Future changes are likely to create new opportunities for non-native species and, with the large number of transmissions by vectors, further appearances are not only likely, but certain. Normally, once a species becomes established it remains unnoticed until there is some impact. However, the expansion of some non-native species distributions are being traced elsewhere in Europe; by monitoring likely regions for their establishment in Ireland, an early appearance may become known. Increases in mean temperatures are also

Table 7.3. Important Bird Areas listed for wintering waterfowl, which are low lying and vulnerable to sea level change and storm surge impacts of climate change

Site name	County	IBA No.	Altitude (m)	Main species	Other categories
Trawbreaga Bay* #	Donegal	003	0–10	Barnacle goose, Brent goose	–
Lough Foyle*	Donegal	004	0–10	Bewick's and whooper swans, Greenland white-fronted goose, Brent goose, wigeon, bar-tailed godwit, curlew	–
Lough Swilly	Donegal	005	0–5	Bewick's and whooper swans, Greenland white-fronted goose, greylag goose, dunlin, curlew, redshank	2
River Foyle	Donegal	006	0–5	Whooper swan, Greenland white-fronted goose	–
Dunfanaghy New Lake*	Donegal	011	0–10	Greenland white-fronted goose, barnacle goose	–
Inishkeeragh and Illancrone	Donegal	018	0–6	Barnacle goose	2
Roaninish	Donegal	019	0–10	Formerly used by barnacle goose	2
Sheskinmore Lough	Donegal	020	0–20	Barnacle goose	–
Donegal Bay	Donegal	030	0–20	Great northern diver, common scoter, long-tailed duck, red-breasted merganser	–
Ardboline and Horse islands	Sligo	032	0–10	Barnacle goose	2
Drumcliff Bay and Ballintemple*	Sligo	033	0–10	Barnacle goose, Greenland white-fronted goose	–
Cummeen Strand*	Sligo	034	0–15	Brent goose, bar-tailed godwit	–
Ballysadare Bay*	Sligo	035	0–27	Brent goose, bar-tailed godwit	–
Killala Bay*	Sligo/Mayo	038	0–26	Brent goose, knot bar-tailed godwit	–
Broadhaven, Blacksod, Tullaghan and parts of Mullet peninsula* #	Mayo	041	0–30	Whooper swan, Brent goose, barnacle goose, bar-tailed godwit	2, 5
Inner Galway Bay*	Galway	057	0–5	Brent goose, bar-tailed godwit, black-throated diver	2
Mid-Clare coast including Mutton and Mattle Islands	Clare	065	0–30	Turnstone	1,3, 5
Shannon and Fergus estuary	Clare/Kerry/ Limerick	068	0–10	Whooper swan, Brent goose, scaup, golden plover, knot, dunlin, black-tailed godwit, bar-tailed godwit, curlew, redshank	–
Tralee Bay and Barrow Harbour*	Kerry	069	0–10	Great northern diver, Brent goose, Scaup, dunlin, bar-tailed godwit	–
Castlemaine Harbour*	Kerry	074	0–10	Brent goose, knot, bar-tailed godwit, common scoter, red-throated diver	–
Inner Clonakilty Bay*	Cork	083	0–10	Black-tailed godwit, curlew	–
Cork Harbour	Cork	088	0–5	Dunlin, black-tailed godwit, bar-tailed godwit, curlew, redshank, great crested grebe	2

Table 7.3. ***Contd***

Site name	County	IBA No.	Altitude (m)	Main species	Other categories
Ballycotton, Ballynamona and Shanagarry*	Cork	089	0–5	Bewick’s swan	5
Ballymacoda	Cork	090	0–5	Dunlin, black-tailed godwit, bar-tailed godwit, curlew	–
Blackwater Estuary	Cork/Water-ford	091	0–5	Black-tailed godwit, curlew	–
Dungarvan Harbour*	Waterford	094	0–10	Brent goose, knot, dunlin, black-tailed godwit, bar-tailed godwit	–
Tramore Backstrand*	Waterford	095	0-20	Red-throated diver, Brent goose, bar-tailed godwit	–
Bannow Bay*	Wexford	096	0–10	Brent goose, dunlin, bar-tailed godwit	–
The Cull/Killag*	Wexford	098	0–14	Bewick’s swan, Brent goose, black-tailed godwit, curlew	–
Tacumshin Lake*	Wexford	100	0–20	Mute Swan, Bewick’s swan, scaup, curlew	5
Lady’s Island Lake	Wexford	101	0–10	Mute swan	2, 5
Wexford Harbour and Slobs*	Wexford	102	0–10	Whooper swan, Greenland white-fronted goose, Brent goose, scaup, grey plover, knot, dunlin, black-tailed godwit, bar-tailed godwit, curlew	5
Cahore Marshes	Wexford	103	0–10	Bewick’s swan, Greenland white-fronted goose, golden plover	5
North Wicklow Coastal marshes	Wicklow	105	0–10	Bewick’s swan, Brent goose, greylag goose	2, 5
Dublin Bay*	Dublin	109	0–10	Brent goose, black-tailed godwit, Bar-tailed godwit, redshank	2
Baldoyle Bay*	Dublin	112	0–5	Brent goose, bar-tailed godwit	–
Malahide/Broadmeadow Estuary*	Dublin	113	0–5		
Rogerstown Estuary	Dublin	115	0–5	Brent goose, knot	–
Nanny estuary and shoreline*	Meath	118	0–5	Knot	–
Dundalk Bay	Louth	121	0–10	Greylag goose, Brent goose, knot, dunlin, bar-tailed godwit, curlew, redshank	–
Carlingford Lough	Louth/Down	122	0–10	Brent goose, scaup	–

Note: sites including sand dune systems/shingle ridges are indicatedby an asterisk (*). Sites which include machair are indicated by a hash sign (#).

likely to provide opportunities for northward natural expansions in Europe.

Exotics are also referred to as introduced, alien, non-native or non-indigenous organisms and may range from disease agents, microorganisms to vertebrates representing all phyla. The general knowledge of exotic species within marine ecosystems is poor; many remain unnoticed either because of their small size, small numbers, lack of study or highly localised distributions. Very often species may not be clearly identified as being exotic because it is not always possible to be certain whether a species is introduced. These species are termed cryptogenic (hidden-origin) (Carlton, 1996a). This component of the biota has arisen because of the extensive trade that spread (the mainly hull fouling) organisms before the awareness of their impact stimulated surveillance. Some, such as the mussels *Mytilus edulis* and *M. galloprovincialis*, were probably distributed to many parts of the world by shipping (Carlton, 1999) and continue to significantly contribute to the fouling of ships (Gollasch, 1996, 2002; Minchin and Gollasch, 2003).

Species continue to be described in Britain and Ireland and Costello *et al*. (1996) have shown that some taxonomic groups, such as the Copepoda, have many species that have, in all probability, yet to be described. There are few accounts of extinctions of marine organisms in the literature (Carlton, 1999) and so exotics will add to the species present in an assemblage and, as they expand their ranges, will become a more important component. This account does not consider vagrants, those species that occasionally arrive in Ireland by natural means, perhaps appearing in small numbers in most years or only rarely, and will be at the fringe of their natural range and so by definition are not exotic.

Exotics are of economic importance either because they produce new employment opportunities through their production (Minchin and Rosenthal, 2002) or because they may have negative impacts on ecosystems with consequences for fisheries, aquaculture and human health (Carlton and Geller, 1993; Harbison and Volovik, 1994; Gollasch and Leppakoski, 1999; Ruiz *et al*., 2000). Those that become abundant and cause changes to working practices, or the environment, are referred to as invasive. It is this component that is the best known. Invasive species are unlikely to be eradicated but if managed at an early stage this may be possible; for example, the elimination of the polychaete *Terebrasabella heterouncinata* infesting the shells of the South African abalone *Haliotis midae* once it had moved to California, USA (Culver and Kuris, 2000) and the elimination of a potentially invasive bivalve *Mytilopsis sallei* from a docks in Darwin (Willan *et al*., 2000). It is normal once a harmful exotic becomes established to manage their numbers and reduce their further spread, thus reducing their impact.

There is a general pattern of an increase in invasion frequency in areas that are well studied (Cohen and Carlton, 1998). These increases, and the generally unexplained disease, mortality and toxic events over the last few decades, are causes for concern (Carlton, 1992). Alterations of climate may, in part, be responsible.

7.2.3.1 Climate and exotic species

For marine distributions, extreme meteorological events may be as important as gradual climate changes. Such events may either enable the establishment of new populations or the reduction of an existing population to below its maintenance level. Extremes or sudden changes in temperature, salinity and turbidity may favour some exotic species. Changes to sea level, in combination with storm events, are likely to result in alterations to low-lying areas and, with the addition of sea breaks in the form of sedimentary barriers, concomitant changes to water temperature, circulation, retention and sediment redistribution are likely to modify native species assemblages and could provide niches for exotics.

Modelling scenarios indicate that there will be more hot days, fewer cold and frost days, higher maximum and minimum temperatures, reduced diurnal ranges of temperature, more intense precipitation and a sea-level rise which will vary around the Irish coast (Pugh, 1982). South coast areas, from 1842 to recent times, show a greater apparent sea-level rise. These changes are likely to have impacts on estuaries (Jones, 1994), areas where many exotic species are found.

Mean temperature projected increases, given the same temperature distribution pattern, will result in the present south coast temperatures appearing in the northern part of the country. On the north coast, mean daily July maximum coastal air temperatures may increase from 17°C to 20°C. However, shallow bays, lagoons and shallow regions of lakes, estuaries and partly enclosed inlets are most likely to respond to mean daily temperatures and periods of high insolation, especially should there be reduced wind speeds. For this reason, sea temperatures in Cork Harbour, for example, may attain temperatures >20°C. Because of the high specific heat of water, deeper waterbodies will not be expected to respond as rapidly, unless there is water stratification. Stratification occurs during the summer on all coasts except for highly localised areas with tidally and wind induced water mixing. This mixing may be periodic (Edwards *et al*., 1996). In estuaries, stratification occurs with freshwater runoff.

It is, therefore, likely that shallow inshore, brackish and freshwater areas will be subjected to significant increases of summer temperature. Currently, several exotics in Ireland are known to be established in such areas. These refuge areas are likely to change in frequency in accordance with climate changes and redistribution of sediments. Thus, some coastal waterbodies currently suited for colonisation by specific exotics may become less suitable and new ones may form. The number of these areas is likely to be small because the main refuge areas of docks, estuaries and partially enclosed inlets are expected to continue to succour their exotic compliment and could become areas for further colonisation.

To predict future expansions of exotic species is difficult and is one of the more elusive aspects of invasion biology. This is because a large component of the world's biota comprises potentially exotic species and many of these are not described. The taxonomic skills to undertake large-scale studies require long-term support and are not readily available. The parameters that determine the ranges of exotics are generally not known. However, some reasonable predictions of future establishing species to Ireland may be deduced from their range expansions in Continental Europe and/or Britain. For some, the physiological tolerance of species, where known, will provide some reasoned basis for the extent of future range. Many of those species that do become established will inevitably carry with them some of their associated biota, which includes pests, parasites and diseases.

Temperature increases may enable spawning events, or more frequent spawnings with perhaps better conditions for larval development and shorter larval planktonic phases that may aid in maintaining or expanding population size. Lower river flow rates, following dryer summers, are likely to result in higher estuarine salinities and reduced turbidity, but these may be contrasted with lower salinities and higher turbidity with the expected greater water runoff in winter. Consequently, exotics confined to estuarine regions may need to be more tolerant of turbidity, wide ranges in salinity and higher sea temperatures.

The majority of known exotic species arriving in Ireland will have already been established elsewhere in Europe; these will be transmitted by aquaculture, shipping and natural drift. Changes in climate elsewhere in Europe may provide the 'stepping stones' that will ultimately provide a species with an opportunity to become established in Ireland.

7.2.3.2 From where will they arrive?

To ascribe future movements of exotics to climate change alone would be unwise. There is a complicated set of variables as well as changes in climate that determine the opportunities for an exotic species to become established. These include the transmission by wind and current vectors, the mode of life of the species, anthropogenic activities, or combinations of these. The majority of species arriving in Ireland will have been as a result of secondary spread following their expansion from Britain or the European continent. The means of spread to the primary site and by secondary movements often involve different transmission methods.

Some exotics will expand independently of climate changes while others are likely to expand or have their opportunities enhanced with changing conditions (Table 7.4). Those currently established on southern coasts may expand northwards. Some species, given their previous history of expansion, will continue to expand their range in Ireland (Fig. 7.5) and elsewhere in Europe.

Table 7.4. Exotic (cryptogenic in parentheses) species present in Ireland that are likely to spread. Those in bold font are likely to increase their range with increases of temperature.

Species	Taxon	Vectors	Present known locations	Impact	References
(*Alexandrium tamarense*)	Dinoflagellate	Ballast, oysters	Cork Harbour	Paralytic shellfish toxin events	Minchin and Sheehan (1998)
Sargassum muticum	Brown alga	Natural spread, oysters	Strangford Lough	Fouling of inshore shallow zone	Davidson (1999)
Cryptonemia hibernica	Red alga	Hulls	Cork, Oysterhaven, Kinsale Harbours	Not known, possible competition	Cullinane and Whelan (1981)
Bonamia ostreae	Protozoan	Oyster movements, hulls	Cork Harbour, Galway and Clew Bays	Increased *O. edulis* mortalities	McArdle *et al*. (1991)
Anguillicola crassus	Nematode	Eel movements	Waterford Est., Erne, Shannon	Effects eel growth, may burst swimbladder	Evans and Mathews (1999)
Ficopomatus enigmaticus	Tubeworm	Boat hulls	Cork Harbour, Kilrush	Fouling of boats and immersed equipment	Kilty and Guiry (1973)
(*Calyptraea chinensis*)	Gastropod	Oysters	Clew, Ballinakill bays, Cork Harbour	Light fouling	Minchin *et al*. (1987)
Dreissena polymorpha	Bivalve	Overland transport	Shannon to Erne navigations	Trophic competition and fouling	Minchin *et al*. (2002)
Crassostrea gigas	Bivalve	Aquaculture	Widespread in culture	Natural settlements	Spencer *et al*. (1994)
Mytilicola orientalis	Copepod	Oyster movements	Dungarvan Bay	Parasite of the Pacific oyster	Holmes and Minchin (1995)
Mytilicola intestinalis	Copepod	Aquaculture, hulls	Many port regions	Parasite in gut of mussels	Murray (1972)
Mytilicola ostreae	Copepod	Oysters	Dungarvan Bay	Small sores on oyster gill tissue	Holmes and Minchin (1995)
Corophium sextonae	Amphipod	Natural spread, ships	South coast	Not known	Costello (1993a)
Gammarus tigrinus	Amphipod	Pond plants	Northern regions	Competition	Costello (1993a)
Gammarus pulex	Amphipod	Stocking, plants, aquaria	Northern regions	Competition	Costello (1993a)
Crangonyx pseudogracilis	Amphipod	Pond plants	Eastern region	Not known	Costello (1993a)
Balanus improvisus	Cirripede	Boat hulls	Shannon Estuary, Waterford Harbour	Fouling	O'Sullivan (1983)
Elminius modestus	Cirripede	Hulls, drift	Most bays, east, south and north	Fouling in estuaries	O'Riordan (1996)
Styela clava	Tunicate	Hulls, oyster movements	Cork Harbour	Trophic competition and fouling	Minchin and Duggan (1988)
(*Phallusia mammillata*)	Tunicate	Hulls	Bantry Bay	Not known	Minchin (2000)
Cyprinus carpio	Fish	Stocking	Isolated quarry	Grazer of aquatic plants	C. Moriarty, personal communication

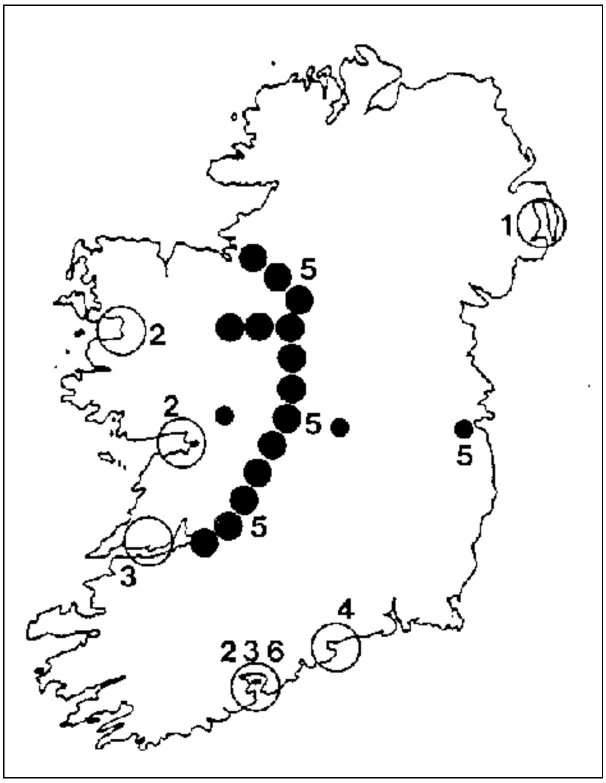

Figure 7.5. Species with a restricted distribution that are expected to expand their range in Ireland. 1. *Sargassum muticum*, an invasive North-West Pacific algae established itself in Europe in 1973 and was subsequently found in Strangford Lough (Boaden, 1995) and in 2001 was discovered on south-east, south-west and west coasts (S. Kraan, personal communication). 2. *Bonamia ostreae*, a blood parasite of native oysters resulting in premature mortality, probably originating from the eastern Pacific, and *Calyptraea chinensis*, a filter-feeding snail probably introduced with oysters from France in the 1940s to 1960s. 3. *Ficopomatus enigmaticus*, an Indo–Pacific tube worm that can form dense colonises in brackish water lagoons. 4. *Mytilicola orientalis*, a parasitic copepod that lives in the gut of Pacific oysters and introduced with half-grown imports from France in 1993. 5. *Dreissena polymorpha*, the zebra mussel lives in brackish and freshwater and forms extensive encrusting colonies; it had spread from the Black Sea to the Baltic Sea, then to Britain, all by 1824, and arrived in Ireland in 1993/4. 6. *Styela clava*, a sea squirt from Asia that can form dense colonises in brackish regions, first recorded in Ireland in 1972.

Further exotics will almost certainly arrive using routes and vectors used previously. The appearance of small numbers of an exotic may herald the vulnerability of that locality for an establishment by that species at some future time. For this reason, all exotic species records should be documented. As species continue to expand in Europe, opportunities for their further spread increase, as they may become imported from a greater number of localities with more vectors being involved. It has been convenient to apportion the species origin from the following regions (Fig. 7.6). Some examples of spread are shown in Fig. 7.7.

Britain: A large majority of the exotic species complement in Ireland occurs in Britain (Minchin and Eno, 2002) and because of the strong historical links many will have been carried from there by shipping (i.e. *Mercierella enigmatica*, Kilty and Guiry 1973), by aquaculture (*Crassostrea gigas*, *Venerupis philippinarum*, Minchin, 1996) and by natural dispersal (*Gyrodinium aureolum*, MacDonald, 1999). Fifty-one exotic marine species have been recorded as established in Britain (Eno *et al*., 1997) and this is almost certainly an underestimate of the numbers present. A special study of molluscs was undertaken by Eno (1998), who lists some gastropods and nine bivalves as being introduced.

Northern Continental Europe: There are more exotic species present on the northern Continental seaboard than occur in Britain and Ireland, probably reflecting a wider trading network worldwide. The large amount of shipping traffic over short distances between Britain and the Continent is almost certainly an important feature in exchanges of exotic species. Some of the species will have first arrived in Britain and will have subsequently spread to the Continent, as in the case of the snail *Crepidula fornicata* (Minchin *et al*., 1995), and so could now arrive in Ireland from both regions. It has been found with Pacific oyster (*C. gigas*) imports from France, along with two exotic parasitic copepods, now established in Dungarvan Bay (Holmes and Minchin, 1995). It is possible that the blood parasite *Bonamia ostreae* of the native oyster *Ostrea edulis* was imported with unauthorised oyster imports or as a result of infested native oysters carried on the hulls of ships. Some of the species that appear in Table 7.5 may become established

Table 7.5. Exotic species that may become established in Irish waters (species whose opportunities might be enhanced by increases in temperature are in bold font).

Species	Taxon	Likely vector	Nearest area	Nature of impact	References[1]
Gymnodinium catenatum	Dinoflagellate	Ships ballast water	Netherlands	Paralytic shellfish poisoning	Peperzak *et al*. (1996)
Prorocentrum minimum	Dinoflagellate	Ships ballast water	Netherlands	Paralytic shellfish poisoning	Jansson (1998)
Coscinodiscus wailesii	Diatom	Ships, natural spread	Britain	Covers nets with mucilage	Laing (1999)
Undaria pinnatifida	Brown alga	Fouling of ships or boats	Britain	Competition	Fletcher and Manfredi (1995)
Grateloupia doryphora	Red alga	Natural spread	Britain	? developed for carrageen	Eno *et al*. (1997)
Lomentaria hakodatensis	Red alga	Oysters, hulls	France	Competition?	Cabioch and Magne (1987)
Pikea californica	Red alga	Hulls	SW Britain	Not known	Maggs and Guiry (1986)
Cordylophora caspia	Hydroid	Ships, hulls	Britain	Fouling	Eno *et al.* (1997)
Haliplanella lineata	Anthozoan	Ships hulls, oysters	Britain	Fouling	Gollasch and Riemann-Zürneck (1996)
Pseudostylochus ostreae	Flatworm	Oysters	France	Molluscan predator	Gruet *et al*. (1976)
Urastoma cyprinae	Flatworm	Mussels	Spain	Parasite of mussel gills	Robledo *et al*. (1994)
Marenzelleria viridis	Polychaete	Ships or natural spread	Britain	High biomass	Essink (1999)
Gyrodactylus salaris	Trematode	Salmonid movements	Norway	Skin parasite of salmon	Johnsen and Jensen (1991)
Hydroides ezoensis	Tube-worm	Ship fouling	Britain	Extensive fouling	Zibrowius and Thorp (1989)
Janua brasiliensis	Tube-worm	Ship fouling	Britain	Can foul *Zostera marina*	Zibrowius and Thorp (1989)
Crepidula fornicata	Gastropod	Oysters	Britain, France	Competition, habitat changes	Minchin (1999)
Cyclope nerita	Gastropod	Oysters	France	Not known	Sauriau (1991)
Ocinebrellus inornatus	Gastropod	Oysters	France	Molluscan predator	Mueller and Hoffmann (1999)
Rapana venosa	Gastropod	Ballast, oysters, trade	France	Molluscan predator	Mann and Harding (2000)
Anomia chinensis	Bivalve	Oysters	France	Fouling	Gruet *et al*. (1976)
Corbicula fluminea	Bivalve	Aquatic plants	France	Extensive fouling	McMahon (1991)
Ensis americanus	Bivalve	Natural spread	Britain	High biomass	Voigt (1999)
Limnoperna fortunei	Bivalve	Ballast water, hulls	S. America	Heavy fouling	Ricciardi (1998)
Musculista senhousia	Bivalve	Oysters, hulls	France	Fouling	Zibrowius (1994)
Mytilopsis leucophaeta	Bivalve	Hull fouling	Britain	Extensive fouling	Oliver *et al*. (1998)
Mytilus trossulus	Bivalve	Ships hulls	Baltic Sea, Canada	Fouling	Penney and Hart (1999)
Nuttalia obscurata	Bivalve	Aquaculture	Canada	Potential species for culture	D. Kaiser, personal communication

Table 7.5. *Contd*

Species	Taxon	Likely vector	Nearest area	Nature of impact	References[1]
Modiolicola gracilis	Copepod	Mussels on ships hulls	Spain	Parasitic in mantle cavity and gills of mussels	Caceres-Martinez *et al*. (1996)
Pseudomyicola sinosus	Copepod	Mussels on ships hulls	France	Parasitic in mantle cavity and gills of mussels	Caceres-Martinez *et al.* (1996)
Caprella macho	Amphipod	Hulls	Netherlands	Fouling	Platvoet *et al.* (1995)
Corophium curvispinum	Amphipod	Ships ballast	France	Fouling	Haas *et al*. (2002)
Gammarus villosus	Amphipod	Aquaria, ballast	Netherlands	Competitor	Whitfield (2000)
Hemimysis anomala	Mysid	Ships ballast	Baltic Sea	High biomass in estuaries	Faasse (1998)
Limnomysis benedeni	Mysid	Ships ballast	Netherlands	Not known	Kelleher *et al*. (1999)
Cercopagus pengoi	Ostracod	Ships ballast	Baltic Sea	High biomass in estuaries	Ojaveer *et al*. (2000)
Eriocheir sinensis	Crab	Ships ballast	Britain	Predator, habitat changes	Clark *et al.* (1998)
Hemigrapsus penicillatus	Crab	Ships, oysters	France	Omnivorous, habitat changes	Gollasch (1999)
Rithropanopeus harrisi	Crab	Ships	Wales	High biomass locally	Eno *et al.* (1997)
Homarus americanus	Natantian	Trade, releases	North America	Hybridisation with *Homarus gammarus*	G.I. Van der Meeren, personal communication
Procambarus clarkii	Natantian	Aquarium trade, releases	Britain	Competition	Westman (2002)
Tricellaria inopinata	Bryozoan	Boat hulls	S. Britain	Localised fouling	Dyrynda *et al*. (2000)
Lepoma gibbus	Fish	Aquarium trade	Continental Europe	Likely competition with other species	Welcomme (1991)
Ambliopites rupestris	Fish	Unapproved stocking	Britain	Not known	Welcomme (1991)
Carassius auratus	Fish	Aquaria, pond releases	Britain	Not known	Welcomme (1991)
Ictalurus glanis	Fish	Unapproved stocking	Britain	Not known	Welcomme (1991)
Micropterus salmonoides	Fish	Stocking	France	Efficient predator	Welcomme (1991)
Neogobius melanostonus	Fish	Ships ballast water	Baltic	Not known	Skóra *et al*. (1999)
Stizostedion luciperca	Fish	Unapproved stocking	Britain	Predator	Welcomme (1991)
Trachemys scripta	Pond turtle	Aquarium trade	Continental Europe	Habitat alteration?	Servan and Arvy (1997)

[1]References provide information from a nearby region or elsewhere.

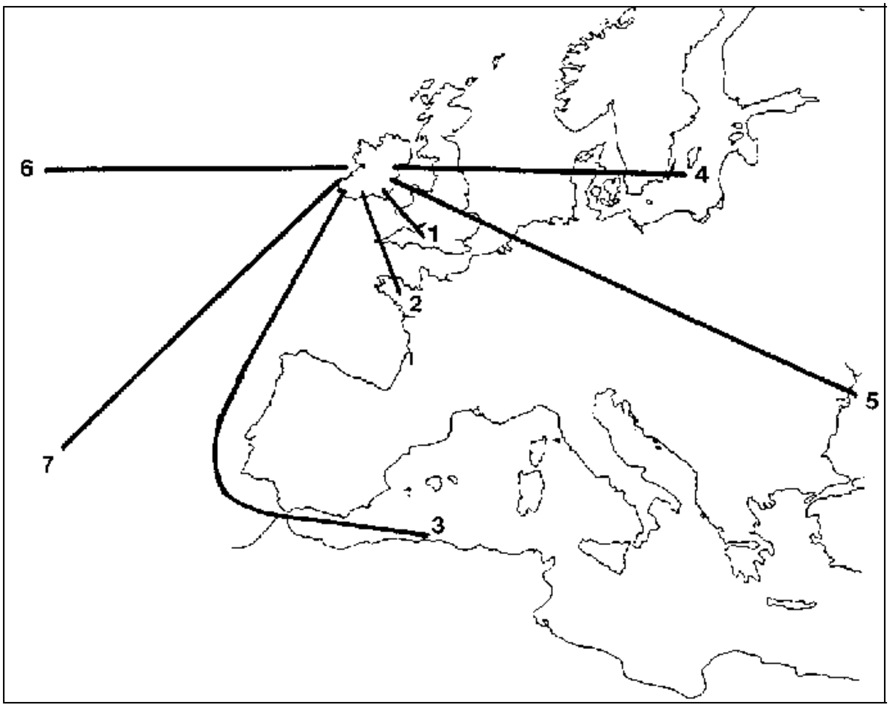

Figure 7.6. Exotic species are likely to spread to Ireland from the following regions: 1. Britain, 2. Northern Continental Europe, 3. Southern Continental Europe, 4. Baltic Sea, 5. The Ponto–Caspian region, 6. North America and 7. The South Atlantic and the Indo–Pacific.

in Ireland over the coming century. Jansson (1998) and Reise *et al.* (1999) have conducted reviews of exotics in northern Europe and several accounts are given by Boudouresque *et al*. (1993) and more recently by Goulletquer *et al*. (2002) and Reise *et al*. (2002).

Southern Continental Europe and the Mediterranean: Trans-national movements from the Mediterranean Sea to the Atlantic coasts of France and Spain have resulted in species expanding northwards (Goulletquer *et al*., 2002); many have been associated with aquaculture movements (i.e. *Undaria pinnatifida* – Fig. 7.6), and some are likely to have been transmitted by shipping. Small pleasure crafts arriving in Ireland from the Mediterranean have had extensive fouling by living *Balanus amphitrite.* It has recently been found attached to navigation buoys off the Belgian coast, indicating that it can recruit in northern Europe away from the thermal plumes of industry (Kerckhof and Cattrijsse, 2001). This barnacle, however, has not yet become established in Ireland. Some species that may arrive from this region are shown in Table 7.6. Boudouresque *et al*. (1993), Ribera (1995), Galil (2000), Galil and Zenetos (2002), Occipinti Ambrogi (2000, 2002), Ribera Siguan (2002) and Zibrowius (1991) have reviewed some of the exotic species in the Mediterranean Sea.

Baltic Sea: Species in the Baltic Sea are either brackish water tolerant or freshwater species and could be transmitted to Irish estuaries and inland waters. Ports where the species might become established include Limerick, Waterford, New Ross, Cork and Drogheda. As the Baltic has a large component of Ponto–Caspian species that have arrived via canals and their associated traffic, further transmission of these species is not only possible, but likely. A large number of the species occurring in the Baltic Sea will have arrived there from the Ponto–Caspian region. Leppäkoski and Olenin (2000) and Leppäkoski *et al*. (2002) have reviewed exotic species in the Baltic region.

Ponto–Caspian region: Much of the spread of species from the Black (Gomoiu *et al*., 2002) and Caspian (Aladin *et al*., 2002) seas and their rivers have resulted from the development of linking canals to separate river systems in western Europe (Jazdzewski and Konopacka,

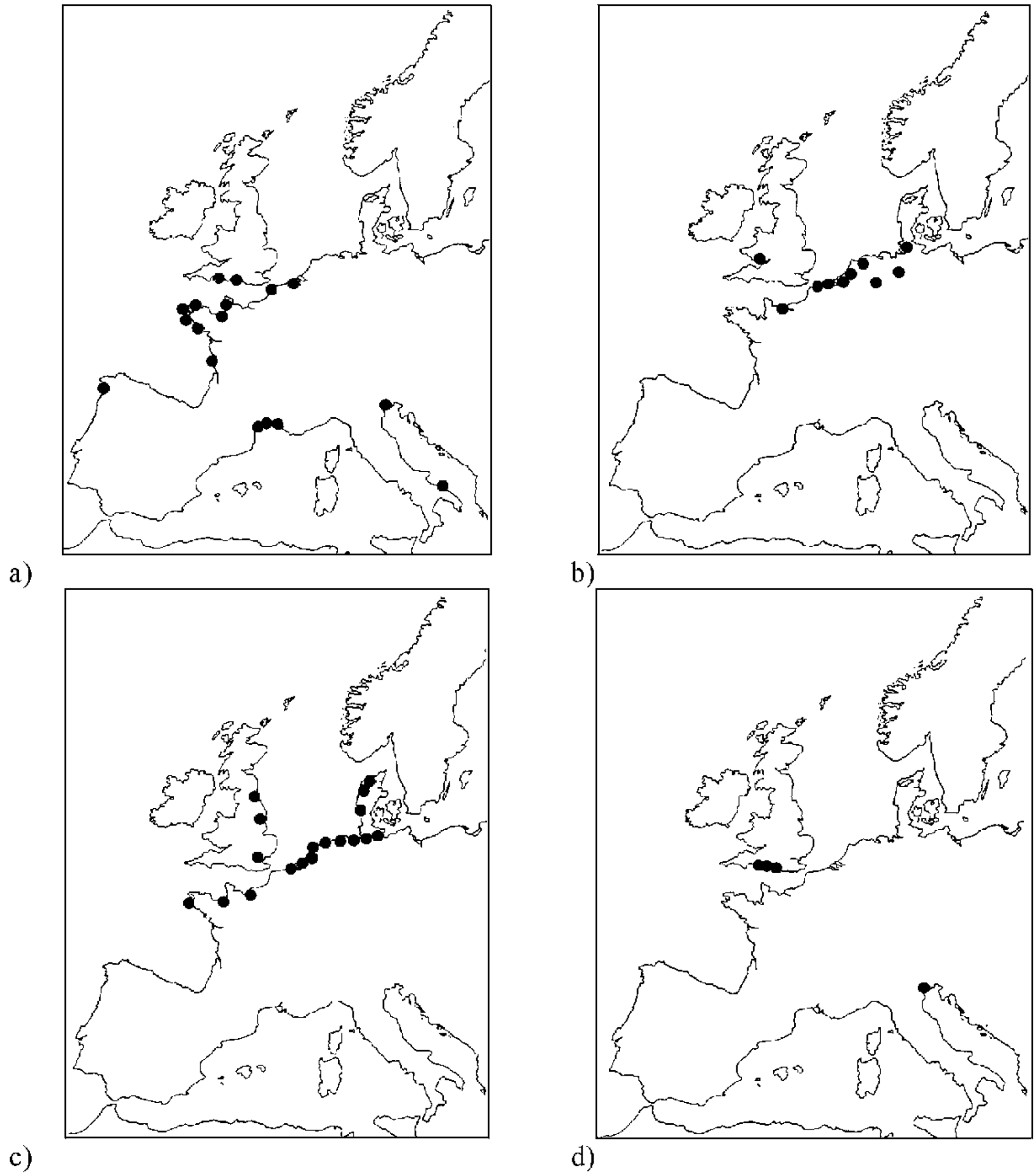

Figure 7.7. Examples of the distributions of some exotic species in Europe. Most exotic species become established in Europe or Britain before arriving in Ireland. The following species are expected to arrive in Ireland. Local increases in sea temperature may enhance opportunities for their establishment: (9a) *Undaria pinnatifida,* is a North-West Pacific kelp, first appearing in Europe in Southern France in 1971. It was cultivated in Brittany from 1983 and has spread from there to other areas on the Atlantic seaboard. (b) *Mytilopsis leucophaeta,* is a bysally attaching Indo–Pacific bivalve with a preference for brackish conditions, and is likely to be spread by ships' hulls. (c) *Eriocheir sinensis,* the Chinese mitten crab requires brackish to marine conditions for reproduction, juveniles ascend large rivers to burrow in river banks. It was first noticed in Germany in 1912, the species continues to expand its range gradually. (d) *Tricellaria inopinata,* is a bryozoan that is only recently described, its true origin remains unknown but the species is likely to spread and foul structures in sheltered estuaries.

Table 7.6. Some species that may invade Europe and that might eventually spread to Ireland. Note the likely origin does not indicate the native origin of the species.

Species	Taxon	Likely origin	Possible vector	Impact	Reference
Vibrio spp.	Bacteria	Worldwide	Ballast sediment	Risks to human and animal health	Epstein (1995)
Epizootic syndrome (EUS)	Bacterium	Indo–Pacific	Aquarium fishes, stock transfers	High mortality of cultured fishes	Shariff (1992)
Pfiesteria piscicida	Dinoflagellate	Eastern North America	Ships ballast water	Localised fish kills	Dykstra and Kane (2000)
Microcytos mackini	Protozoan	W. Canada	Oysters, hulls	Forms lesions in *C. gigas*	Bower *et al*. (1994)
Marteilioides chungmuensis	Protozoan	Japan, Korea	Oysters, hulls	Infects eggs of *C. gigas*	Bower *et al*. (1994)
Haplosporidium spp.	Protozoan	Korea	Oysters, hulls	Mortalities of *C. gigas*	Bower *et al*. (1994)
Mnemiopsis leidyi	Comb Jelly	Black Sea, Mediterranean	Ships ballast water	Trophic competition	Kideys (2002)
Sabella spallanzani	Polychaete	Mediterranean	Ships	Fouling, competition	Furlani (1996)
Maoricolpis roseus	Gastropod	SE Australia, Tasmania	Shellfish movements, ballast water	Trophic competition	Furlani (1996)
Potamocorbula amurensis	Bivalve	N. America	Ballast water, trade	Fouling	Carlton *et al*. (1990)
Hemigrapsus sanguineus	Crab	N. America	Ships ballast water or hull fouling	Shore predator	McDermott (1998)
Asterias amurensis	Sea star	Indo–Pacific	Ships ballast water	Predator of molluscs	Buttermore *et al*. (1994)

2002; Slynko *et al.*, 2002). One species originating in this region that arrived in Ireland via the Baltic and Britain is the zebra mussel *Dreissena polymorpha* (Minchin *et al*., 2002). There have also been some deliberate introductions to some rivers within the former USSR to enhance species diversity; these have included amphipods and mysids (Arbaciauskas, 2002). Several species of Ponto–Caspian origin are now widely spread through eastern, central and western Europe and are poised to enhance their ranges (Bij de Vaate *et al*., 2002). Although high salinity will act as a barrier, their spread to Ireland can be facilitated with ships ballast water and with the trade of living organisms.

North America: One of the early examples of a likely introduction from North America is the soft shell clam *Mya arenaria* to Northern Europe, carried by returning Vikings (Strasser, 1999). Their eventual establishment to Ireland may have been due to natural dispersal or further introductions. Ships in transit to Europe will carry ballast and hull-fouling organisms without undue temperature stresses to the carried organisms; risks from this source are likely to continue. There have been some special studies on bay-invading species in North America (e.g. Cohen and Carlton, 1998).

Indo–Pacific and South Atlantic: The oyster *Crassostrea angulata* (the Portuguese oyster) previously assumed to be native to Europe has been shown to be the same species as *C. gigas* the 'Pacific' oyster introduced in the 20th century for aquaculture. The former species may have been introduced to Europe about 500 years earlier (Korringa, 1976). Pan-tropical species, such as those that regularly appear as hull fouling on ships, may survive short periods but are unlikely to establish themselves, unless they become established within thermal plume discharges. However, the Indo–Pacific tubeworm *Ficopomatus enigmaticus* is able to do so and there are two known populations in Ireland. It is likely that further aquatic species will be carried from the Southern Hemisphere by aircraft and with ships' ballast water. There have been few in-depth investigations of exotic species in the Indo–Pacific (Nagabhushanam and Sarojini, 1997) and South Atlantic region (Orensanz *et al*., 2002) except for detailed studies in Australia, the first of which is Port Phillip Bay (Hewitt *et al*., 1999). It is not possible to state with certainty those species that will become established from outside of Europe. Some species that could cause serious impacts should they become established appear in Table 7.6.

7.2.3.3 Vectors and climate change

Vectors play an integral part in the expansion of exotic species and changes in climate may aid in furthering the formation of founder populations. Sometimes these populations will be short lived but could reappear in concert with a reversal or change in conditions. Changes in climate result in a geographical shift to the boundaries of physiological tolerance, which can vary according to species.

The arrival of an exotic species in the absence of anthropogenic vectors will rely on natural spread mechanisms. The residual directional flow of both wind and water currents and the mode of life of the carried organisms may be linked-in to storm events, wind patterns and changes of sea temperature. Such species may be carried considerable distances and may even recruit from parent populations in North America (Minchin and Minchin, 1994).

Many anthropogenic activities deliberately or inadvertently lead to the transmission of exotic species (Carlton, 1992, 1996a, 1996b; Carlton and Geller, 1993; Gollasch, 1996). A large component of these involve trade although recreational activities are also important for their spread. Most exotic species in coastal waters occur in port regions or have been introduced with aquaculture stock to culture areas. Ports and aquaculture sites are important because a species once established may subsequently have further opportunities of expansion via a wider range of vectors. Since aquaculture is often placed in shallow waters and these areas respond rapidly to air temperatures, the effects of warmer winters and summers may provide conditions whereby an exotic species of a southern origin, which requires high temperatures to replicate, may now become abundant.

Localities that have received several exotic species in the past will almost certainly do so in the future. Sheltered port regions, with a high retention of water may be most vulnerable, particularly docks where gates are used to retain a sufficient depth of water. Such port structures are normally used in areas with a large tidal range (Kilrush Lagoon, Limerick Docks) or where large sheltered inlets provide a wide range of habitats (Cork Harbour). Ships that unload cargo or ballast water in such sheltered harbours where there is stratified water may expose the fouling biota to significant changes in temperature that may promote spawning (Minchin and Gollasch, 2003).

In many cases it is presumed that increases in the frequency of transmission will enhance opportunities for creating founder populations. This may not be so. The ascribing of vectors is often a deduction based on a reasoned presumption. Indeed, the full suite of vectors that may operate in the transmission of a species may be poorly known. Usually an exotic is discovered some years following establishment making it difficult to deduce its means of arrival and this trend is likely to continue.

7.3 Implications for Fisheries and Aquaculture

7.3.1 Fisheries and seaweed harvesting

7.3.1.1 Fisheries

Figures available from the Department of the Marine and Natural Resources show that total sea fish landings, including wild salmon, were valued at €192 million in 1998 increasing to over €240 in 2002 (Table 7.7) and that over 6,000 fishermen were employed on board fishing vessels, with an additional 6,000 working in processing and ancillary jobs (Bord Iascaigh Mhara, 2003). In 2001,

Table 7.7. Profile of the Irish fishing and aquaculture industry 1998–1999 and 2002 (source data Bord Iascaigh Mhara, 2003).

	Tonnes		Million €	
	1999	**2001**	**1999**	**2001**
Sea fish landings				
Landings at foreign ports	94,063		42	35
Landings at home ports	225,146	293,868	150	206
Total	**319,209**		**192**	**241**
Aquaculture production				
Finfish	20,740	25,082	71	79
Shellfish	25,870	35,853	20	28
Total aquaculture production	**46,610**	**60,935**	**91**	**107**
Seafood imports				
Of which fish meal/oil	21,536		17	–
Total imports	**51,894**		**101**	**–**
Seafood exports				
Of which fish meal	16,510		12	–
Total exports	**252,778**	**310,879**	**303**	**433**
Home market				
Estimated total value of home market			184	290
			Numbers	
Industry employment			**1999**	**2002**
Fishermen (estimated)			6,000	>6000
Fish processing			4,000	4,000
Aquaculture			2,590	2,500
Ancillary			2,000	2,000
Total employment			**14,590**	**>15,000**

the total available supply of fish from fishing activity and from aquaculture had risen to nearly 355 thousand tonnes valued at €313 million at first point of sale. Sea fish landings at home and overseas amounted to 294 thousand tonnes valued at €206 million, of which €35 million of this value was from landing in overseas ports. Additional employment on shore is guaranteed when catches are landed in Irish ports through fish auctions, fishing co-operatives, processors and exporters. In total, the Irish seafood industry provides employment for up to 14,800 people and is a significant source of income in small coastal regions.

The effects of global climate change on fisheries in any given area are very difficult to predict. Scientific ability to predict how changed climate conditions will affect specific species is low. As with non-commercial species there are many environmental, physical (water temperature, salinity, oxygen concentration) and biological (food sources, predation, diseases, competition with other species) variables that all play a role in determining the health and abundance of fish stocks and that may be influenced directly or indirectly by climate.

The sensitivity of species to these attributes often changes as they pass through the different phases of their life cycle. Many fish species undertake annual migrations; salmon and sea-trout spend part of their life cycle in freshwater and part in the sea, and so are affected by changes in both these environments. Fish can only survive in water over a limited range of temperature. The upper and lower limits of the temperature range vary between species, and are one of the major factors that determine geographical distributions. Temperature also affects the growth rate of fish, by altering the efficiency of conversion of food into body tissue.

In addition, there is the added anthropogenic impacts that may result in a reduction in stock viability or recoverability. In any given area, variations in these factors, including changed climate conditions, are likely to result in a reduction of potential harvests of some species while increasing potential harvests of other species, including species not currently being fished. In Ireland, between 1973 and 1999, the number of different species commercially caught has more than trebled (Fig. 7.8) indicating that the industry is adaptable to exploit new stocks and changing market demands when necessary. The reason for the diversification in target species is not clear although these changes cannot be readily related to past changes in climate. As climate changes occur worldwide, market conditions for fish are also likely to change in ways that are almost impossible to predict. The European commercial marine fish stocks are at present judged by experts, reporting to the European Commission, to be currently 'depleted or exploited beyond safe biological limits' (Parry, 2000), suggesting that future fisheries will need to expand to as yet unexploited resources.

Although there are examples where long- and short-term changes in climatic conditions have resulted in direct effects on fisheries, in particular the devastating impact of El Niño on the fisheries of the eastern Pacific and the pilchard (*Sprattus sprattus*) fishery closer to Ireland, in many cases separating out changes due to anthropogenic or climatic impacts is difficult.

Many species of fish, shellfish and seaweed are caught or harvested in Irish waters both coastal and offshore. However, in global terms it is considered that 70% of the fisheries resource depends on nearshore or estuarine environments at some point in their life cycle (Everett *et al.*, 1995). Thus changes in these environments may also have a potential significant indirect impact on fisheries through loss of habitat for nursery or spawning areas.

7.3.2 Seaweed harvesting

The Irish seaweed industry employs nearly 500 people (full-time and part-time) of which seaweed harvesting accounts for about 400 people in a mostly part-time capacity (Irish Seaweed Industry, 2003). Up to 90% of its produce is exported, and had a turnover of over €6.35 million in 1996. The industry is mostly concentrated in the west of Ireland, in areas that are considered to be severely disadvantaged by the European Union and, therefore, the importance of the industry to the local economy is very high.

The main species collected and used in Ireland at present are dulse (*Palmaria palmata*), carrageen moss (*Chondrus crispus*), various kelps (*Laminaria* spp. and *Alaria esculenta*) and wracks (*Fucus* spp. and *Ascophyllum nodosum*). It was estimated that the total coastal area

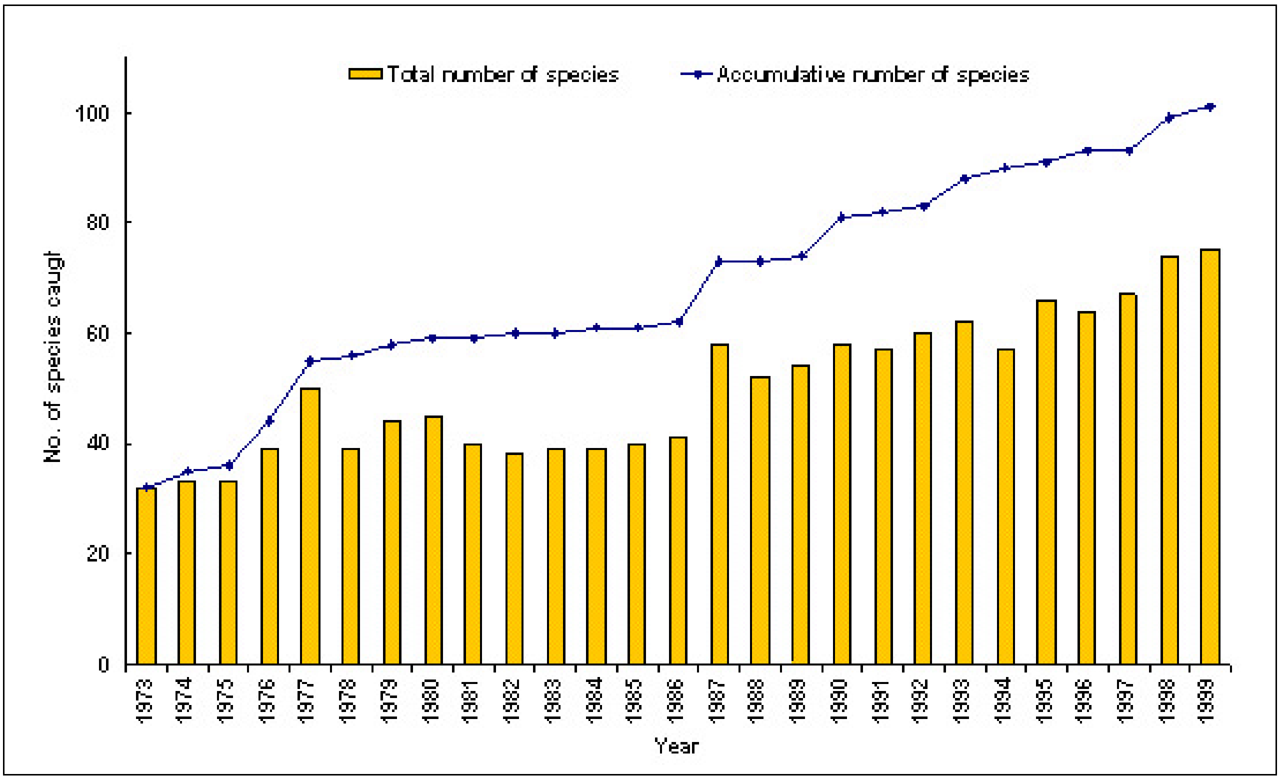

Figure 7.8. Number of species caught commercially around Ireland between 1973 and 1999. Source: ICES Fisheries Statistics.

could yield nearly 75 thousand tonnes of *Ascophyllum nodosum* and the kelp resource was found to be extensive, covering over 56% of the west coast of Ireland, and occurring in sites moderately exposed to wave action and in non-estuarine sites with a suitable rocky substratum (Hession *et al.*, 1998, 2000).

The calcareous seaweed, maerl, is also exploited around Ireland. The extent of the Irish maerl resource and its associated biodiversity is being examined with a view to potential expansion of the industry (de Grave *et al.*, 2000). Extensive beds are found all along the west coast of Ireland, particularly in the larger wave-sheltered bays. Maerl is considered to be potentially vulnerable to climate change (Harrison *et al.*, 2001) and is of high nature conservation value. Although current exploitation of maerl is restricted to dead material, future extraction may, in the long term, rely on the replenishment of old beds with living material. Any impacts due to potential changes in climate should be considered.

7.3.2.1 Change in water and air temperature

As described in the Section 7.2.1, Ireland lies between two major biogeographic provinces (Fig. 7.1), the Boreal (cold temperate) region to the north and the Lusitanian (warm temperate) region to the south, and represents a transition zone for some commercial marine fish species. On a broad scale, changes in distribution of these species may alter with increased temperature change.

Northern species such as the cod *Gadus morhua* prefer water temperatures between 4 and 7°C (Lythgoe and Lythgoe, 1991); herring (*Clupea harengus*), saithe or coalfish (*Pollachius virens*) which have an optimum temperature for spawning between 8 and 9°C (Lythgoe and Lythgoe, 1991), and haddock (*Melanogrammus aeglefinus*), which has a southern limit down to the south of Ireland (Bord Iascaigh Mhara, 2003), may all be limited in their southern distribution by increased water temperatures. Likewise, many southern species, such as hake (*Merluccius merluccius*), may have their range extended northwards (Aqua-Fact International Services Ltd., 1991).

In the past, several fisheries have developed based on periods of higher sea temperature (Minchin, 1993). The pilchard (*Sprattus sprattus*) fishery exhibited extreme fluctuations between periods of abundance to periods of absence or seldom captures (Went, 1946). The abundance of this species was correlated with small variations in sea and air temperatures in the south-west of Britain (Southward *et al*., 1988). In Ireland, there have been seven major occurrences of pilchard since 1600 and they have recently been recorded again off the west coast although not commercially caught. It is envisaged that an increase in sea temperature could result in an increase in the pilchard abundance and the reinstatement of a fishery.

Native oysters *Ostrea edulis* have occurred in Ireland for thousands of years and evidence of their exploitation and abundance is confirmed through the presence of shell middens (Minchin, 1993). Many of these historic middens occur in areas where no oysters occur today, suggesting that more suitable conditions for oysters occurred in the past. It is suggested that this could be the result of past higher mean sea temperatures influencing oyster recruitment (Minchin, 1993), as oyster beds are known to receive high recruitment during high sea temperature periods. Today, for example, Tralee Bay, Co. Kerry, is a shallow enclosed bay subject to high seasonal temperatures and supports a good population of native oysters.

Increases in sea and air temperatures are not likely to significantly reduce the extent of commercially collected algae. Although kelp (*Laminaria*) species have been identified as being sensitive to increases in temperature, particularly short-term changes, they can adapt to slower temperature changes. Growth rates may change with increased temperature but the likely impact on the extensive resource available due to climate change is likely to be negligible.

The more northern species of maerl, *Lithothamnion glaciale*, may retreat northwards with increasing water temperatures (Viles, 2001) and the southern species, *Lithothamnion coralloides*, may extend its range further north (Birkett *et al*., 1998). Such changes, however, are likely to have a small impact on any future potential exploitation. Considerations, however, would need to be given to the sustainability of such activities.

7.3.2.2 Change in sea level

Changes in sea level are likely to have a minimal impact on the fishing and seaweed industry in Ireland. Impacts will most likely be restricted to activities utilising intertidal areas, such as shellfish and seaweed harvesting. Such areas may be vulnerable to loss or change of habitat resulting in a loss of commercial species. Such changes, however, will be over the long term and likely to be minimal.

7.3.2.3 Change in precipitation level

Changes in the precipitation level and seasonality of precipitation may have an impact on the salinity gradients within estuarine systems and enclosed waterbodies. Such changes impacting on the primary production of Irish coastal areas are not known and would be difficult to predict and would require additional study. Any reduction in primary production could have an impact on the commercial capture fisheries. Estuarine systems are important nursery and breeding areas for many commercial fish species. Increased precipitation may disrupt the salinity gradients within such systems and, coupled with likely increased sedimentation, disrupt spawning and nursery grounds in such areas. Increased sedimentation loads may also affect nearshore coastal areas adjacent to large bays and estuaries (e.g. Dublin Bay, the Shannon Estuary, Cork Harbour). Increased turbidity may affect the primary production in these areas also. Herring may be particularly vulnerable to increased sedimentation as they form distinct breeding stocks which utilise specific breeding areas around the Irish coast (Southward *et al*., 1988). Any disturbance to these areas may increase the stress of the stocks and reduce viability.

Particular impacts may occur to anadromous (those which breed in freshwater and migrate to seawater to feed e.g. salmon and trout) and catadromous (those which breed in seawater and migrate to freshwater, e.g. the common eel *Anguilla anguilla*) migratory fish species. If water quality in river and estuarine systems deteriorates a barrier would be formed to their migratory passage. Salmon and trout have particular requirements for breeding, utilising clean gravel beds or redds. Increased precipitation inland may result in the siltation of these beds resulting in a reduction in viability. Any reduction in population size may have an effect on fisheries of all these species both in coastal marine waters and in freshwater systems.

The impacts of increased precipitation will most likely be restricted to coastal marine and estuarine waters; it is not envisaged that there will be a significant effect on the offshore capture fisheries around Ireland.

Increases in precipitation are unlikely to have a major impact on algal harvesting.

7.3.2.4 Change in ocean circulation patterns

As described in Section 7.2.1, climate change may alter ocean circulation patterns, vertical mixing and sea-ice cover, which in turn will affect nutrient availability, biological productivity, structure and functioning of marine ecosystems, and heat and carbon storage capacity. Such changes are likely to be significant with major changes occurring in the marine environmental conditions in Irish waters. Such considerations are, however, outside the scope of the climate change scenarios and not easily predicted. However, recently it has been identified that changes in ocean currents can affect the amount of food available to adult fish, and disrupt the normal pattern of dispersal of larval fish to the main fishing areas (Kerr *et al.*, 1999). Such changes will most likely have a significant impact on the fisheries and seaweed harvesting potential of Irish waters.

7.3.2.5 Change in occurrence of storm events

Increased storminess will most likely have little impact on the distribution of offshore commercial fish species. Impact, however, may occur in nearshore areas where nursery and spawning habitats for commercial species occur. If these habitats become unsuitable for such purposes, recruitment into the population may be reduced and thus a potential reduction in the fishery.

Storms and high winds will, however, have a direct impact on the activities of fishermen. Days at sea may be lost and boats damaged.

Ascophyllum nodosum cannot resist very heavy wave action so exposure to wave action is an important factor controlling the distribution of the species; thus it is only present in sheltered or moderately exposed locations. Much of the harvesting occurs in wave-sheltered areas where it is most abundant. Long-term exposure to increased wave action may have a direct impact on the distribution of *A. nodosum* but short-term exposure effects are likely to be minimal.

Although harvestable kelp resources are reduced at locations of high wave exposure, and *Laminaria hyperborea* is unable to survive where wave action is extreme, it is unlikely that the increased occurrence of storm events will significantly change the distribution of kelp species in Ireland (Hession *et al.*, 1998, 2000). However, if the average wave exposure is increased there may be localised losses of wave-sheltered species (*L. hyperborea*) and their replacement by more wave-tolerant species (*Alaria esculenta*). It is not envisaged that the overall resource available for harvesting will be significant.

7.3.3 Aquaculture

Aquaculture in Ireland is an expanding industry. Numerous species are cultured or grown on for the industry and the commercial value of aquaculture is high (Table 7.8). Aquaculture relies on suitable environmental conditions to produce a marketable product. Changes in these conditions through climate change could result in areas which become less suitable for cultivation and open up new areas which were previously unsuitable.

Salmon farming is the most commercially important fish farmed in Ireland. Over the last decade the value of the industry has increased significantly (Table 7.8). Numerous other species are cultured in Ireland with the possibilities for new species being investigated. Particular issues related to exotic species and aquaculture are dealt with in Section 7.2.3.

7.3.3.1 Change in water and air temperature

The temperature of the water in which an aquaculture facility will operate is an important aspect of site suitability and in some cases will directly impact on the decision to develop a facility. For example, the temperature ranges in which a given species of fish can survive is, in general, more restrictive than those of farm animals on land, and a change of a few degrees can mean the difference between a successful aquaculture venture and an unsuccessful one.

Table 7.8. Tonnage (t) and value (€'000) of shellfish and finfish aquaculture in Ireland between 1980 and 2002. Source data: Bord Iascaigh Mhara, 2003.

	Total shellfish volume	Total shellfish value	Total finfish volume	Total finfish value	Total aquaculture volume	Total aquaculture value
1980	5,214	1,350	601	1,135	5,815	2,485
1981	5,316	1,404	695	1,522	6,011	2,927
1982	6,492	3,045	800	1,925	7,292	4,970
1983	6,674	1,950	988	2,937	7,662	4,887
1984	14,225	3,573	1,097	3,948	15,322	7,521
1985	10,675	2,355	1,289	5,545	11,964	7,900
1986	10,963	2,689	1,778	7,250	12,741	9,940
1987	15,474	4,207	3,152	15,190	18,626	19,397
1988	13,222	4,108	5,105	27,528	18,327	31,636
1989	14,340	4,760	6,750	30,283	21,090	35,043
1990	19,221	7,061	7,352	30,152	26,573	37,213
1991	17,594	7,476	10,705	42,445	28,299	49,921
1992	15,985	9,035	11,093	43,335	27,078	52,370
1993	16,205	9,543	13,949	53,565	30,154	63,109
1994	15,529	9,827	13,083	51,771	28,612	61,598
1995	14,070	8,705	13,299	50,883	27,369	59,589
1996	19,025	13,152	15,905	52,327	34,930	65,479
1997	21,929	14,894	17,603	53,287	39,532	68,181
1998	25,239	20,142	17,085	57,929	42,324	78,071
1999	23,516	21,639	20,340	65,011	43,856	86,649
2000	31,110	21,512	20,170	75,167	51,280	96,679
2001	35,853	27,943	25,082	79,164	60,935	107,108
2002	33,675	32,783	24,511	81,924	58,186	114,707

Aquaculture ventures are not just looking for fish survival but optimum growth for minimum expense (food and husbandry). Each species cultured has an optimum temperature range for growth. Where efficient uptake of food is maintained, the health of the fish or shellfish stock will be more resilient in the range of temperatures preferred by the species, as the stress levels and vulnerability of the individuals to disease will be reduced.

It is not only the fish species themselves that are susceptible to temperature ranges. Temperatures will also restrict and expand the range of fish pests and parasites. Warmer waters will inevitably mean an increase in the incidence of outbreaks of unwelcome infections, for example sealice. Warmer winters in the late 1980s and in the past decade allowed parasitic sealice to produce two to three extra generations per year resulting in exponentially higher population sizes (Tully, 1989). This has led to sea lice being the most commercially important parasite on Atlantic salmon farms in Ireland, Scotland and Norway. The resulting epizootics have caused sea trout numbers to collapse in many rivers (Costello, 1993b). Fish, which could be further stressed by warmer water, will be more susceptible to these infections resulting in low productivity.

Temperature variations, again of only a few degrees, can also have indirect implications for an aquaculture facility. An increase in temperature can lead to increased phytoplankton production that can cause oxygen depletion. In addition, an increase in the incidence of harmful algal blooms that release toxins into the water may occur and cause fish kills. Caged fish are susceptible to algal blooms, as they cannot avoid contaminated waters. Reduction in oxygen may also bring fish close to the surface where they will be subject to increased irradiance that could lead to a higher increase in the occurrence of sunburn and ultimately result in a less economically viable product.

Salmon (Salmo salar)

Salmon farming in Ireland occurs towards the southern limit of its viable range, primarily due to the water temperature. The industry is very competitive, requiring the production of high quality salmon produced cheaply and efficiently. Any reduction in productivity could lead to farms being less competitive and, therefore, not viable. Increased sea temperatures can lead to early maturation of grilse, causing a reduction in production as energy is diverted from muscle production to gonad development.

It is also necessary to consider the likely impacts of climate change on freshwater aquaculture sites, particularly those producing salmon eggs and smolt. At such sites the impact of temperature is likely be substantially more serious than in marine locations. Enclosed waterbodies and small watercourses will be subjected to higher fluctuation in temperature, a greater degree of eutrophication and so will possibly be more quickly influenced by climate change. In lakes, the availability of natural nutrients and production may also be altered by changes to circulation patterns, but the result of such changes will vary from lake to lake. Reductions in smolt production could elevate salmon production costs and make farms less competitive or not viable.

Rainbow trout (Oncorhynchus mykiss)

Although not as important as salmon in terms of tonnage and value, rainbow trout production would be similarly impacted by changes in temperature. Freshwater-reared species transferred for on-growing in sea cages would face similar problems as salmon.

Mussels (Mytilus edulis)

Warmer sea temperatures may benefit mussel cultivation accelerating growth rates and thus improving productivity. However, an increase in the incidence of harmful algal blooms that release toxins into the water may occur and cause problems.

Native oysters (Crassostrea edulis) and Pacific oysters (C. gigas)

Oyster cultivation may benefit from warmer waters similar to mussel cultures. The native oyster is at the northern limit of its range and it may be possible to extend cultivation further northwards. As with mussels an increase in the incidence of harmful algal blooms may occur and cause problems.

7.3.3.2 Change in sea level

Increases in sea level will have a small impact on intertidal shellfish production through the gradual reduction in available seashore to farm. Changes will occur over long periods of time allowing farmers to adapt and find new locations for their facilities. Likewise, offshore farmers will be able to accommodate sea-level changes within the normal operational cycles of the aquaculture facility, for example in the replacement of longer moorings, etc., in the normal maintenance cycle.

7.3.3.3 Change in precipitation level

For inland water aquaculture, climate change will bring alterations to the evaporation and precipitation cycles that may well prove more serious and take place much more rapidly than in the marine environment. In the case of salmon production, and to a lesser extent rainbow trout, the two are economically linked. Predicted temperature rises due to climate change will cause increased evaporation but changes in rainfall may be much more variable. Inputs to lake or river systems will depend on duration of wet weather but also on intensity, with higher runoff associated with heavier rainfall events.

There are two main concerns with changes in precipitation: (a) a reduction in water flow during summer months reducing viable productivity during these periods, and (b) a decrease in water quality during heavy flow periods due to increased contamination from runoff. Freshwater aquaculture facilities that maintain their water levels artificially will not be troubled by high flow conditions although the major concern will be one of reduced water supply or reduced water quality.

For marine aquaculture areas, increased runoff may bring increased freshwaters to areas thus changing salinity and bringing increased nutrients, sediments or contaminants.

7.3.3.4 Change in ocean circulation patterns

Climate change may alter ocean circulation patterns, vertical mixing and sea-ice cover, and these in turn, will affect nutrient availability, biological productivity, structure and functioning of marine ecosystems, and heat and carbon storage capacity. Such changes are likely to be significant with major changes occurring in the marine environment in Ireland and thus having significant impacts on Irish aquaculture. Such considerations are, however, outside the scope of the climate change scenarios and not easily predicted.

7.3.3.5 Change in occurrence of storm events

Increased storm events may reduce the available areas in which offshore aquaculture facilities can be developed. The continued development of offshore aquaculture facilities capable of operating in extreme conditions may require a shift in the focus of the industry away from coastal sites. Intertidal shellfish facilities may also be impacted upon if they are sited in locations subject to increased storm events.

7.4 Recommendations and Conclusions

7.4.1 Implications for marine biodiversity

7.4.1.1 Biogeography

Changes in the distribution of marine species will occur with climate change. Although we are able to identify species which are potentially sensitive to climate change, the extent to which any changes will happen is very difficult to predict. Many of the impacts are likely to be indirect, where the reduction of one species allows for the development of another through loss of competition, or the reduction or loss of prey items results in the exploitation of other species. These changes will also influence patterns of marine biodiversity and will have consequences for the functioning of marine ecosystems and thus have implications for managing marine ecosystems.

Within this report, the potential changes of marine species due to climate change are only 'potential' and are described in general terms (Table 7.9). To fully understand the mechanisms of climate change and the potential impacts on the marine environment in Ireland, there is a real need for future research. There is a necessity to expand our knowledge of the Irish marine environment and to identify the baseline conditions from which we can make comparisons in the future. Few long-term studies are available in Ireland. Close co-operation and involvement with European studies looking at climate change at an international level will further improve our understanding of large-scale changes and our predictive power for what might happen at a national level.

We need to develop indicators for climate change so that changes can be readily identified and better understood. Once indicators have been identified, long-term monitoring programmes need to be established to rapidly identify potential changes.

7.4.1.2 Marine birds

Three new breeding species have been recorded in Ireland since the mid-1990s. Two of these are expanding their range northwards at least partly in response to climate change – the Mediterranean gull and the little egret. Their distribution within Ireland is likely to increase from current low levels. The third recent arrival, the great skua, is anomalous in that its arrival represents a southwards expansion of its existing range. Eider, an existing breeding species with a northern distribution, has also been extending its Irish breeding range southwards along the west coast in recent years. There are no current predictions of additional seabird species extending their range northwards into Ireland as a result of climate change, although there are a number of bird species of terrestrial habitats which are expected to extend their breeding presence to Ireland (e.g. hobby, golden oriole, Cetti's warbler).

Overall, there may be a greater potential for Ireland to lose existing seabird and coastal bird species as a result of climate change than to gain new species. Little tern colonies increasingly require active conservation measures including wardening of colonies to ensure successful breeding. Herring gull populations are significantly reduced, particularly in east coast colonies, and are likely to be classified as endangered in the near future. Individual sites are vulnerable to changes that could lead to re-distribution of species, and loss of international importance for some species at some sites.

Table 7.9. Summary table of possible impacts of climate change on marine species.

Factors	Certainty of potential impacts
Increase in temperature	
Biogeography	
Range shift for species on limit of distribution	Likely
Restriction of Northern species range	Likely
Extension of Southern species range	Likely
Loss and gain of species at local level due to alteration in habitat suitability	Likely
Increase in exotic species	Very likely
Fisheries	
Reduction in spawning capabilities for some species	Possible
Loss or reduction of 'colder-water' species	Likely
Gain or increase in 'warmer-water' species	Likely
Aquaculture	
Shift in habitat suitability leading to the loss of 'cold-water' species and increase in production of 'warm-water' species	Possible
Increase in harmful infections	Likely
Increase in exotic species	Very likely
Increase in algal blooms	Likely
Loss of production in salmon due to reduction in maturation time	Likely
Reduction in availability in local smolt	Likely
Increase culture possibilities for other species	Very likely
Increased precipitation	
Biogeography	
Range shift for species on limit of distribution	Less likely
Restriction of Northern species	Less likely
Extension of Southern species	Less likely
Loss and gain of species at local level due to alteration in habitat suitability	Likely
Fisheries	
Reduction in spawning capabilities in coastal areas	Less likely
Aquaculture	
Development of husbandry techniques and technologies	Likely
Sea-level rise	
Biogeography	
Extension of habitats inshore	Likely
Loss of intertidal habitats in low-lying areas (coastal lagoons and estuaries)	Likely
Fisheries	
Reduction in suitable spawning grounds	Less likely
Aquaculture	
Reduction in available intertidal sites	Less likely
Increased storm events	
Biogeography	
Local change in intertidal species from wave-sheltered species to wave-exposed species	Less likely
Fisheries	
Loss of fishing days	Likely
Aquaculture	
Reduction of suitable intertidal and coastal sites	Likely
Requirement to develop offshore sites	Likely

Recommendations

Concentrations of breeding seabirds and wintering waterfowl are well known, and it is unlikely that many previously unknown internationally important sites remain to be discovered. Smaller, previously unknown seabird colonies are still being located, with new tern colonies found during 2001 during a shingle bank habitat survey in Clew Bay, for example (T. Curtis, personal communication). Current seabird colony and winter waterfowl monitoring programmes need little adjustment, although additional resources would enable more seabird colonies to be surveyed annually, and also to increase the number of months and sites in which winter waterfowl are monitored. A non-estuarine wintering waterfowl survey also merits further inputs.

Need for increased information on physical environmental variables

There is a need for more IBA site-specific information with regard to sea level, tidal variables, and freshwater inputs including volumes and sediment loads. An enlarged network of automatic gauging stations would be very valuable, both in coastal sites and in river catchments. Meteorological stations should accompany these. Tidal velocity data, controlled for weather conditions, would also be useful in predicting likely change in individual sites.

Habitat change

Monitoring of habitat change will be important in predicting and monitoring impacts of climate change on coastal wintering waterfowl, so that mitigation measures can be planned as appropriate. Monitoring of the extent of critical coastal margin habitats is recommended: sand dune, shingle ridge and saltmarsh erosion/accretion patterns are all relevant, as are changes in littoral habitats. Hand-held GPS systems could be used to record habitat edges, which are often clearly defined on the ground. National grid corrected aerial photography at regular intervals would also be useful in monitoring coastal habitat change. Monitoring in fixed position quadrats is also recommended to monitor flora and invertebrate fauna as well as topographical change, taking care to standardise the time of year sampling is carried out in order to ensure that data are comparable between years. As regards changes in fish species and stock monitoring, data on non-commercial as well as commercial species should be collected to avoid unnecessary replication of survey effort.

National database requirements

Information collected by different agencies is not available from a centralised source at present, and a biodiversity monitoring rationale, database and administrative arrangements are still awaited. It is recommended that such a database is established as soon as possible, to enable research and monitoring personnel to access and cross-reference environmental data efficiently. Physical environmental variables should also be included as a part of this database.

Increased analytical and policy inputs

Additional resources, principally personnel, will be needed to provide the analytical inputs required to handle bird data, and cross-reference it with other ecological and physical variables. Policy development and implementation will become more important as evidence of climate change impacts accrues, and the need for pro-active management to ensure the survival of individual protected sites, habitats and species increases.

Exotic species

Further exotic species will invade Ireland; some of these species are expected because they have rapidly expanded their range elsewhere in either Britain or Europe, or both, and with climate warming these events are almost certainly likely to be enhanced. Some of these species have consequences for human health, the economy and ecology with the expansion or appearance of some species. The apparent spread of toxic phytoplankton species is of particular concern and the poor knowledge of the movement of pathogenic microorganisms and disease agents, with consequences for aquaculture and fisheries, must be a priority area for future investigation. The great majority of known coastal introductions have been via aquaculture and shipping and further introductions from these vectors can be expected. Improved management of port areas through a better knowledge of local exotic species distributions, seasonal abundance and oceanography may result in reducing new introductions. Also, reducing the opportunities of taking on exotic species from a port region will reduce the risk of infesting other ports. Nevertheless, there are ongoing investigations on more efficient exchanges and improved sterilisation techniques of ships' ballast water and active research into more appropriate anti-fouling agents that may considerably reduce opportunities for exotic species establishment in the future. However, changes in port activities, including reduced toxicity, alterations to trading patterns and frequencies, and climate change will ensure that further exotic species will arrive.

7.4.2 Implications for fisheries and aquaculture

7.4.2.1 Fisheries

An overview of the potential climate change impacts on fisheries is summarised in Table 7.9. As with all potential impacts on the marine environment it is very difficult to provide an accurate assessment of likely changes. Such changes are again generalisations. Most of the commercially exploited species of sea fish are close to, or beyond, safe biological limits with many possible causes. Over-fishing is generally considered to be the major cause of the decline; however, pollution, eutrophication (enrichment of water with nutrients from, for example, agricultural runoff or sewage sludge), acidic runoff from forestry and changes in predator numbers may all contribute. More recently, changes in ocean currents can affect the amount of food available to adult fish, and disrupt the normal pattern of dispersal of larval fish to the main fishing areas (Kerr *et al.*, 1999). It is very difficult to disentangle the potential impacts due to climate change and those due to fishing itself and other factors. Resource over-exploitation has been described as the most important single factor directly affecting the sustainability of many fish species (Parry, 2000) and over-exploitation itself may also make fisheries more vulnerable to climate change. As shown in Fig. 7.8, the fishing industry is adaptable and as fish stocks change, new geographic areas and species are being targeted for exploitation and this will most likely continue.

7.4.2.2 Aquaculture

The belief that climate change could disrupt the aquaculture industry in Ireland appears to be well founded. Deleterious changes may have a serious economic impact on the expanding industry.

For salmon production, climatic changes may have serious consequences. Salmon are near the southern range of their distribution and any increases in water temperature could result in farms becoming less commercially viable, subject to increased harmful algal bloom events and a number of pests and diseases. Pressures on freshwater smolting facilities and egg-rearing farms through decreases in water quality will add to that.

For other species, increased temperature may result in a longer growing season, lower natural winter mortality and faster growth rates, particularly of shellfish.

The aquaculture industry is also adaptable and although climatic conditions may shift so too will the focus of the industry to more profitable and viable species.

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8 The Impacts of Climate Change on Sea Level and the Irish Coast

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8.1 Introduction

Ireland with a shoreline of approximately 6500 km is situated on the north-western edge of Europe within the main depression tracks. These mobile weather systems dominate the Irish climate and are responsible for a substantial amount of the heat transfer between low and high latitudes. These mid-latitude depression systems produce the familiar mild winters and cool wet summers. As a consequence of its position in relation to the main storm tracks, Ireland's location acts as a buffer zone against which these depression systems dissipate their energy.

It is these depressions in conjunction with the large expanse of ocean off the west coast which produce the high energy waves (10^{11}–10^{12} J m^{-1} $year^{-1}$) (Carter, 1990a) that have helped carve the Irish coastline, resulting in the headlands and enclosed bays found along the west coast. In contrast, on the east coast, low energy waves (10^{8}–10^{9} J m^{-1} $year^{-1}$) (Carter, 1990a) interacting with mainly unconsolidated glacial material have produced a more linear outline to the coast (Devoy, 2000).

Variations in past sea levels have also helped shape the present-day coastline, producing the drowned valleys (rias) and raised beaches found around the Irish coastline. Though sea level globally has remained relatively stable over the last few thousand years (Carter *et al.*, 1989), one anticipated impact of the effect of increased concentrations of greenhouse gases in the atmosphere is a rise in global sea level. Early studies suggested a sea level rise in the order of 2–3 m (Jelgersma and Tooley, 1992). Current estimates have been revised downwards and range from 0.09 to 0.88 m, or a central value of 0.48 m by 2100 (IPCC, 2001). This chapter reports on the possible implications of a sea level rise for Ireland and the impacts this may have. In order to place a potential increase in sea level in context, however, it is necessary to review past conditions.

8.2 Sea Level Fluctuations

Sea level may change as a result of either a change in the elevation of the sea, due to an increase/decrease in volume, or to a change in the elevation of the land (Pethick, 1984).

A change in absolute sea level, termed a eustatic change, occurs over all the oceans, while a localised sea level change resulting from a change in the absolute level of the land is termed an isostatic change. An isostatic change is due to local processes that affect changes in the distribution of weight on the land (Pethick, 1984). Tectonic uplift can also act to raise the land elevation. Isostatic changes and tectonic uplift are generally termed 'local effects'.

Eustatic changes in sea level occur when water volume is increased or decreased. During periods of glaciation, oceanic water is diminished through evaporation, leading to precipitation which accumulates as snow on land surfaces. Thus, the normal hydrological cycle is temporarily disrupted and ocean recharge is halted. This process of water being held on land as snow and ice during glaciation acts to reduce the volume of water in the ocean and leads to reductions in global sea level.

As Fig. 8.1 illustrates, sea level has varied considerably over the last 20,000 years, with levels at times more than 100 m less than at present. These variations can be explained by past changes in the growth and decay of glaciers and ice sheets, which can be attributed to changes in climate and solar forcing (Milankovitch Cycles). These changes in sea level played a pivotal role in allowing humans, animals and plants to colonise new regions of the earth through the formation of temporary land bridges (Mitchell, 1976). During the last glacial stage for example, Ireland's land mass was joined to that of continental Europe. This allowed plants and animals to colonise the new areas of land that were being exposed as the ice margin retreated northwards (Fig. 8.2).

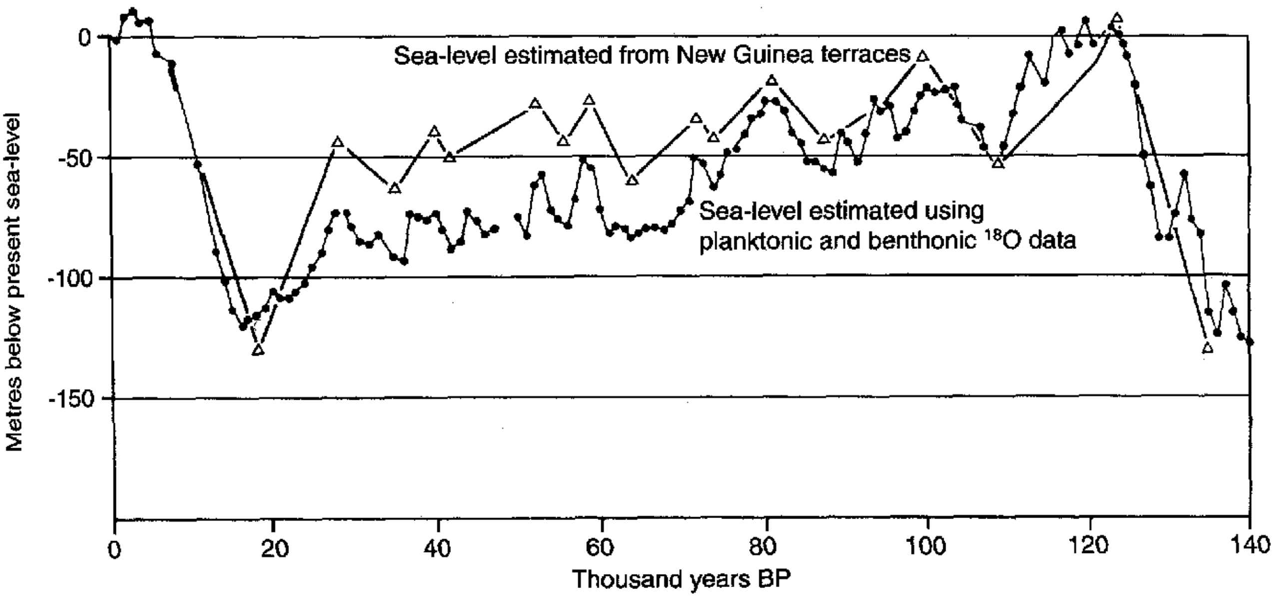

Figure 8.1. Reconstructed eustatic sea level histories (Benn and Evans, 1998).

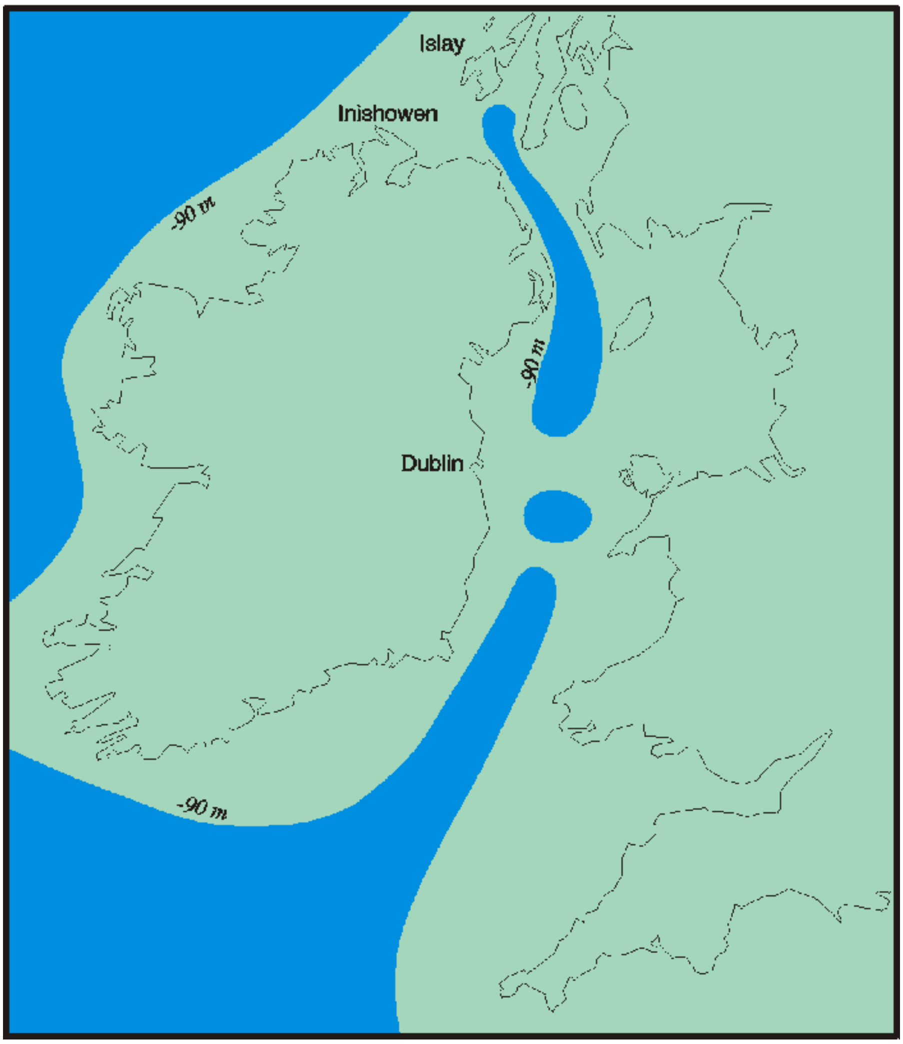

Figure 8.2. Coastline extent and landbridge towards the close of the last glacial period. Source: Mitchell, 1976.

Localised events, such as folding, tectonic displacement, or isostatic rebound, have the effect of raising or lowering the absolute elevation of the land relative to the surrounding sea. In the case of Ireland, Armorican folding has produced the 'Atlantic' coastline of the south-west of Ireland whereby the headlands of the Cork and Kerry coast are comprised of anticlines (upward thrust) while the bays and inlets in between the headlands are synclines (downward thrust). Ireland is currently considered relatively stable in terms of tectonic activity and this influence is not considered further here in assessing coastal changes.

Of greater importance to sea level in Ireland is the effect of isostatic rebound. Isostatic rebound occurs after a weight has been removed from the land surface, such as by the removal of the large ice sheets that once covered most of the island. Rates of isostatic rebound vary around the country as a consequence of the location of the main ice dome or ice sheet centre where the maximum weight was concentrated. In Ireland, the ice dome was centred in the north of the island and hence this was where the greatest depression of the land took place. South of a line from Galway to Dublin, isostatic rebound is slight, while north of this, the land is continuing to rise in response to the removal of the ice mass after the last glaciation. Local sea level measured at Malin Head was estimated by Carter *et al.* (1989) to be falling at 2.4 mm year^{-1} while global sea level is currently rising at a rate of *ca* 1.0 mm year^{-1} (Devoy, 2000) – a difference that is explicable in terms of local isostatic rebound. However, this isostatic rebound estimate may have to be revised downwards as it is now suggested that uplift at Malin Head is currently keeping pace with rising sea levels (Wilson and Orford, 2002).

There is much evidence of past fluctuations in sea level (Plate 8.1) around the Irish coastline. These include raised beaches, such as those found in Cushendun in Co. Antrim or in Malin Head in Co. Donegal, drowned forests found extensively at low tide around the south and south-west coasts and peat bogs located at present-day

Plate 8.1. Drowned forest and peat bog at low water. Photo: Tommy Williams.

shorelines. Some archaeological sites also exist which are today flooded at high tide, such as the passage tomb, north-east of Baltimore in Co. Cork (Mitchell and Ryan, 1997).

8.3 The Coastal Zone and Population Distributions

The population of the Republic of Ireland is more than 3.9 million (CSO, 2002), of which approximately 25% live in a coastal District Electoral Division (DED). Figures 8.3 and 8.4 illustrate the population density changes from 1971 to 1996 and current population density around the Irish coast, respectively. Population density change displays a marked contrast between the east and west coasts. Between 1971 and 1996 there are marked decreases in the coastal population of rural western Ireland in favour of urban centres. During the same period, there are marked increases in the east-coast

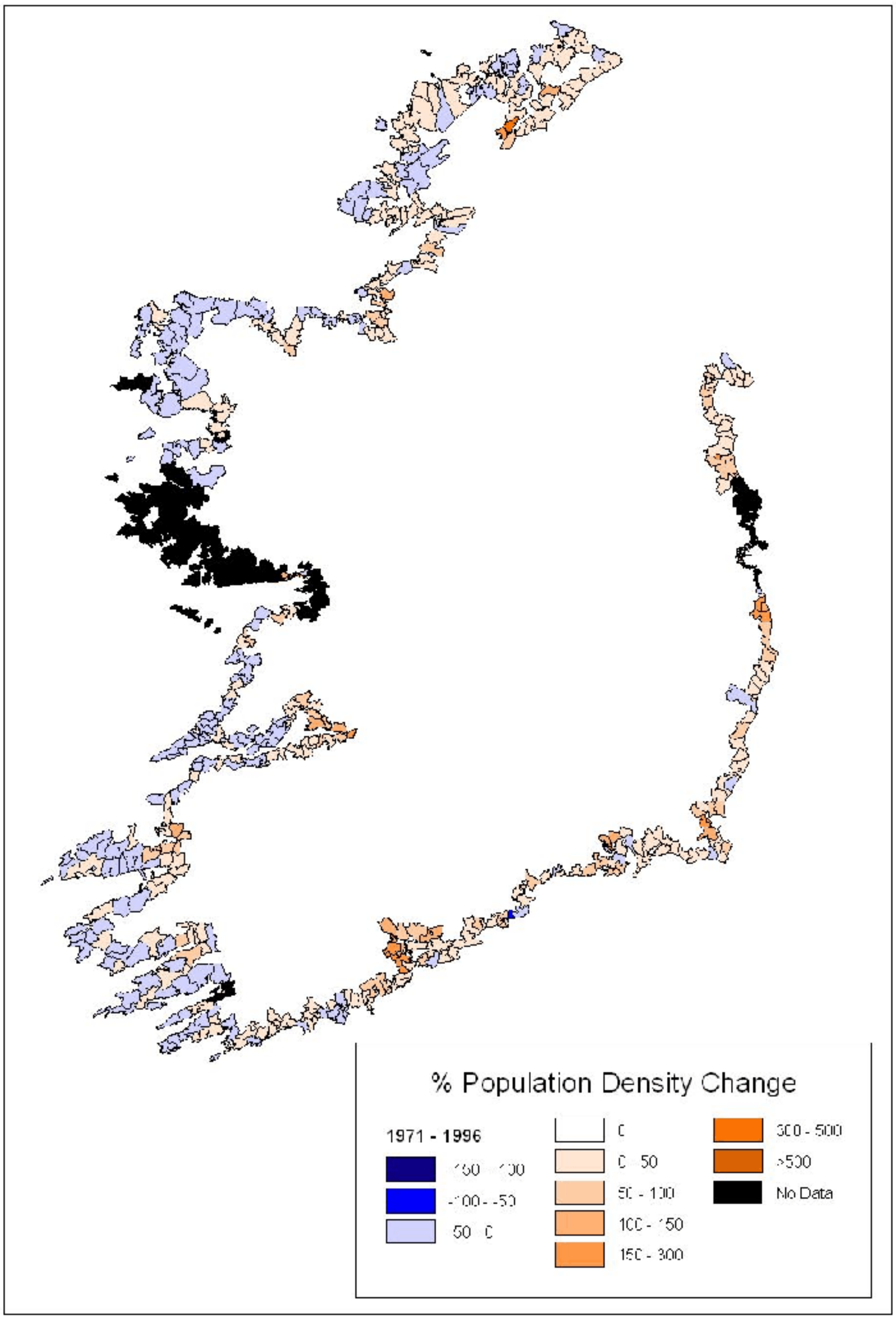

Figure 8.3. Percentage population density change 1971–1996.

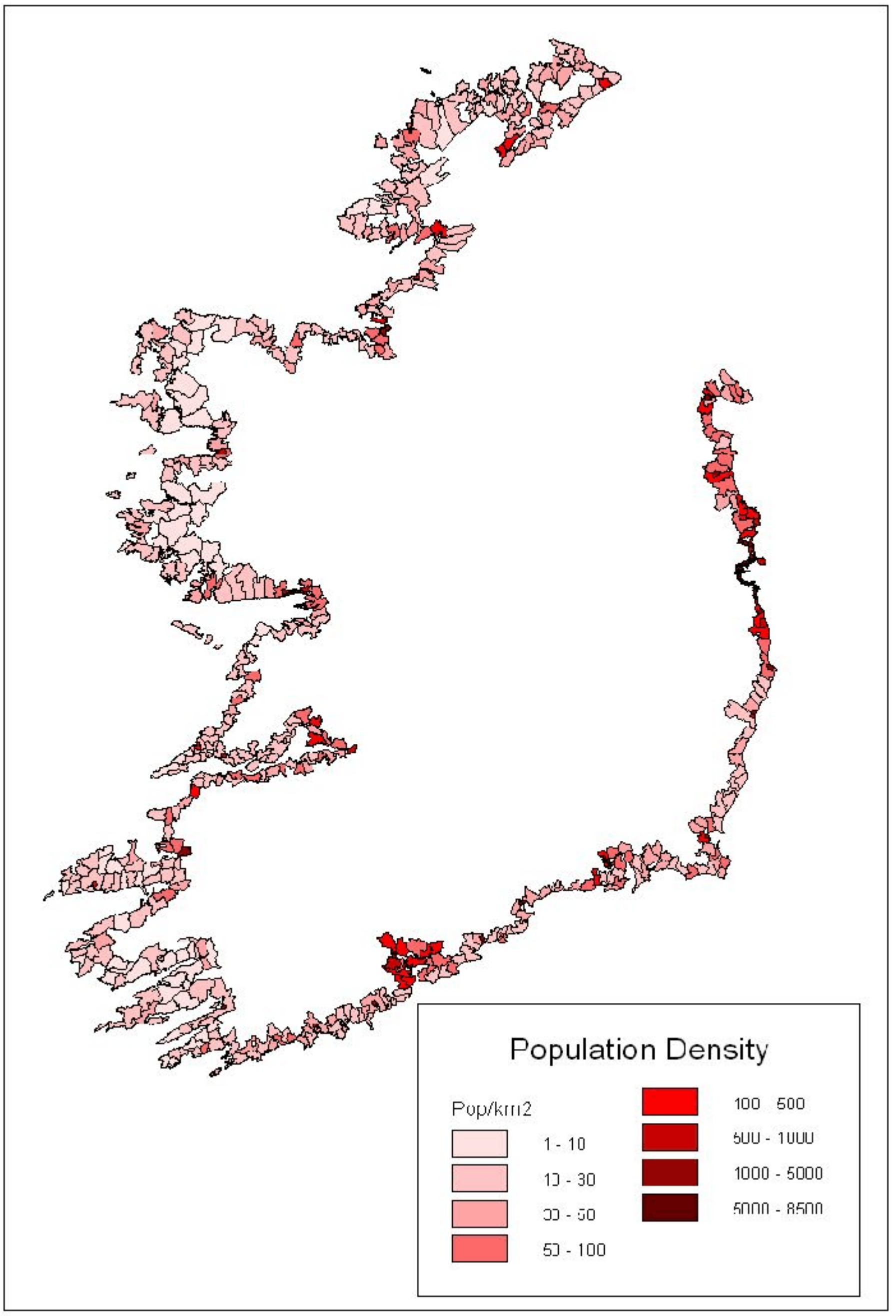

Figure 8.4. Population density 1996.

population in both rural and urban areas. Coastal DEDs comprise approximately 20% of total land area, of which, approximately 21% lies below the 10-m contour line.

8.3.1 Physical characteristics

The morphology of the Irish coastal landscape (Fig. 8.5) comprises many different landform types. The western and northern seaboards are dominated by areas of high relief (~500 m) and cliffed coastlines interspersed with bays, producing a distinctive, crenellated, coastline, while the east and south-east are mainly low-lying coasts composed of unconsolidated sediments and glacial tills.

Coastal characteristics (Fig. 8.6) predominantly result from two processes, erosion and deposition, through wave action on geological structures of varying resistance and composition. These coastal processes operate on varying temporal and spatial scales. On short time scales, unconsolidated sediments are easily eroded while, on longer time scales, even resistant rock

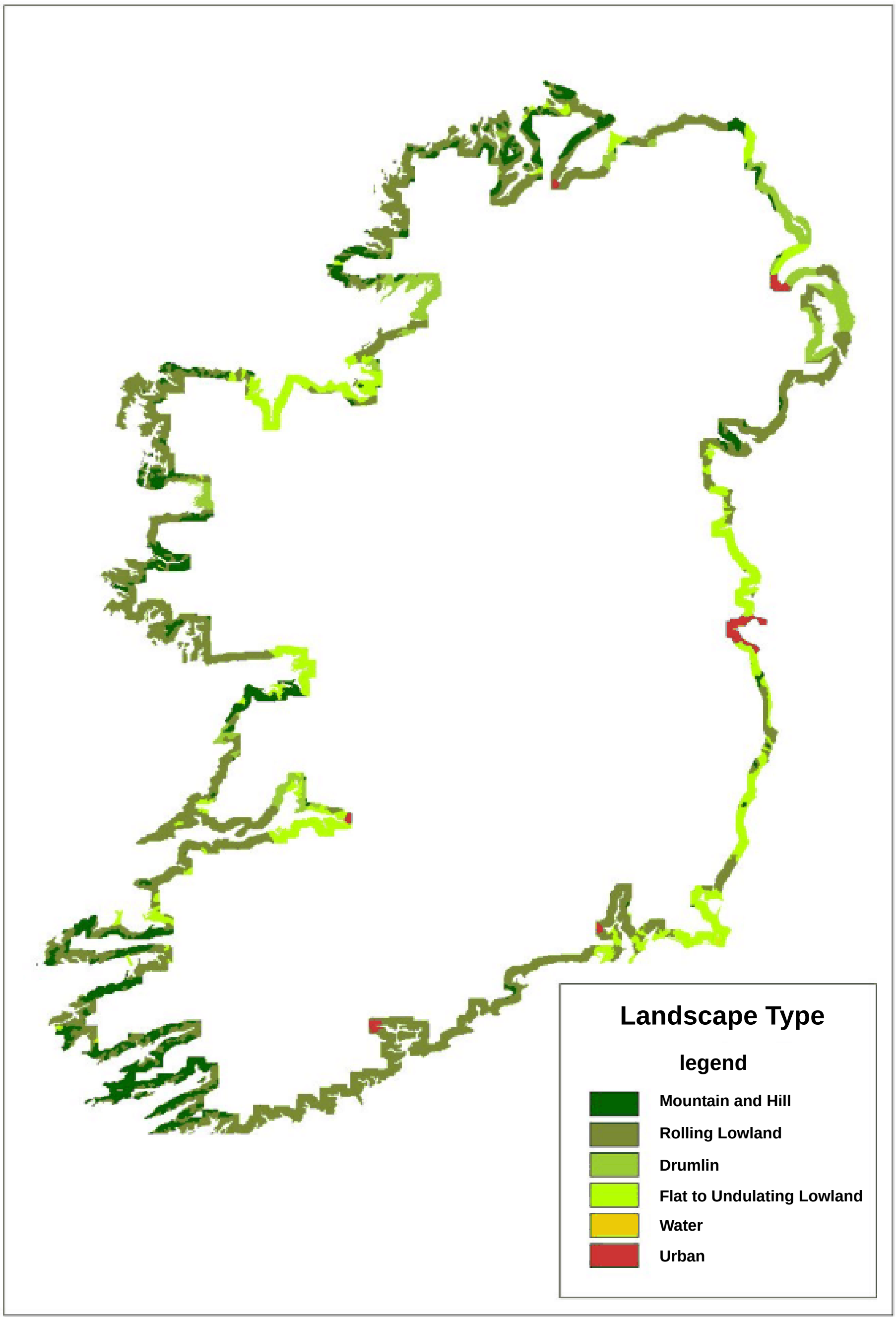

Figure 8.5. Morphology of the coastal zone landscape (1 km).

structures weaken and can eventually collapse. Landforms of erosion are largely a feature of the west coast where wave energy is substantially higher than that measured in the Irish Sea (Devoy, 2003). Landforms of deposition, such as tombolos and sandspits, like the Maharees in Co. Kerry and Rosslare Point in Co. Wexford, are formed when material eroded along the coast or offshore is transported and subsequently deposited. Both types of landform are intimately affected by changes in sea level.

The coastline is in a continuous state of flux in response to changing conditions in both the ocean and the land. Increases or decreases in wave energy and alterations of the coastline, both natural and man-made, such as the construction of piers, coastal defences and other

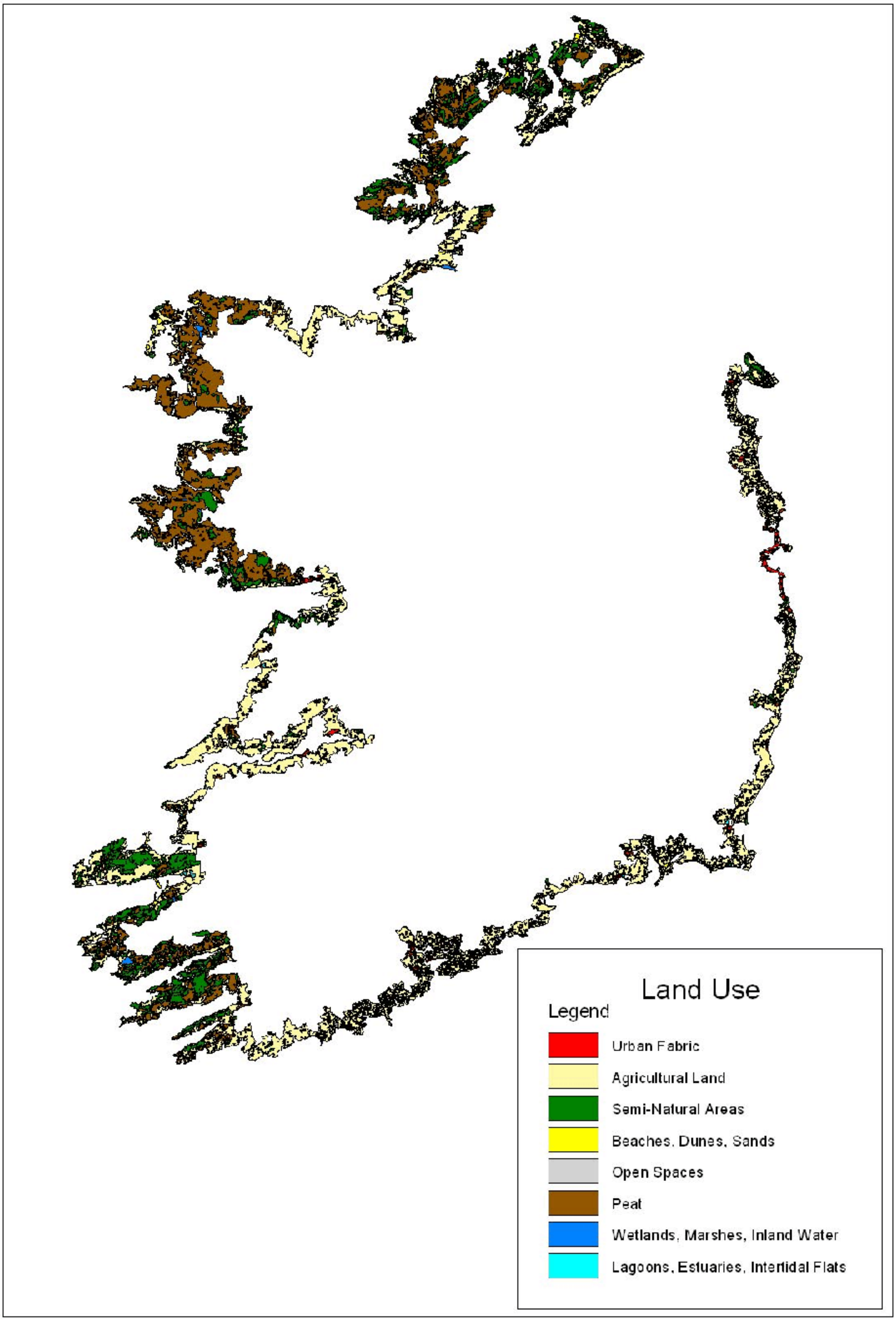

Figure 8.6. Coastal Land Use derived from CORINE land cover.

structures that may inhibit or affect the local wave regime, all act to shape the present-day coastline.

8.4 Dynamic Controls on the Coast

8.4.1 Waves

Waves are the driving force behind every coastal process (Pethick, 1984). Wave heights are determined by the distance of uninterrupted open water over which a wave-forming wind can travel, called the fetch. On the Atlantic coast, a south-westerly wind can have a fetch in excess of 5000 km, dramatically enhancing wave heights (Lewis, 1971). Wave heights in excess of 24 m have been recorded in the Atlantic (Pethick, 1984), although these are considered extreme.

Wave energy is related to wave heights by means of the following formula:

$$E \propto {}^{1}/_{8}\, H^2$$

where E is wave energy and H is wave height.

Wind waves, or sea waves occur when the wind has a direct influence over a body of water. Swell waves are initially generated by wind but have propagated out from the centre of action where they were initially generated. Wind waves tend to appear as chaotic and less well structured while swell waves appear as structured and regular wave movements. The interaction between both sea and swell waves can enhance wave heights causing unusually high waves.

Figures 8.7 and 8.10 represent the mean significant wave height and variance for the Atlantic and Irish Sea for the period 1993–1997. Significant wave heights are derived from the mean of a series of wave height measurements taken over a particular time period and are indicative of average wave height conditions. Offshore (>30 km), significant wave heights in the Atlantic are in the order of 2.5–3.5 m, while in the Irish Sea they range from 0.5 to 2.0 m. Variance around the mean is also higher in the Atlantic at ± 2.5–3.5 m, than in the Irish Sea at ± 0.5–1.5 m. Figures 8.8 and 8.11 illustrate the seasonal difference in significant wave heights between winter and summer. In the Atlantic, the seasonal variation is approximately 3 m, double that of the Irish Sea. This difference in wave height between the west and east coasts results in a significant difference in wave energy between these two coasts.

Figures 8.9 and 8.12 illustrate the 1- and 25-year return-period significant wave heights that this part of the North Atlantic experiences. These return-period wave heights represent a substantial increase on average conditions off the coast.

Figures 8.7–8.12 were produced by Satellite Observing Systems Ltd, as part of the British National Space Centre supported JERICHO project.

8.4.2 Tides

Tidal waves result from the gravitational pull of the moon and sun on the oceans. The body of water directly under the moon experiences a gravitational pull that is slightly larger than the centrifugal force exerted by the rotation of the earth, producing a bulge in the direction of the moon (Fig. 8.13). In contrast, on the opposite side of the earth the gravitational pull of the moon is less than the centrifugal force, producing a bulge that is attracted away from the moon (Pethick, 1984). It is these tidal bulges that produce tidal waves (not to be confused with tsunamis).

Tidal waves in the open ocean are of the order of 50 cm in height. However, as a tidal wave approaches shallow coastal water, its height increases and wave energy is concentrated. Bays and estuaries act to funnel the water and further enhance wave height, and resonance within estuaries may also produce further increases. With an increase in tidal range, current speeds also increase in order to accommodate the volume of water (Pethick, 1984).

On the west coast, typical wave magnification produces a tidal range of approximately 2–4 m (ECOPRO, 1996). On the east coast, the tidal range increases outwards from an amphidromic point located along the Wexford coastline. Tidal range around this point is generally less than 2 m. Water removal from this point via the southern Irish Sea is compensated for by the delayed inflow of water from a clockwise flow around the north of Ireland and down the east coast which acts to diminish the tidal range.

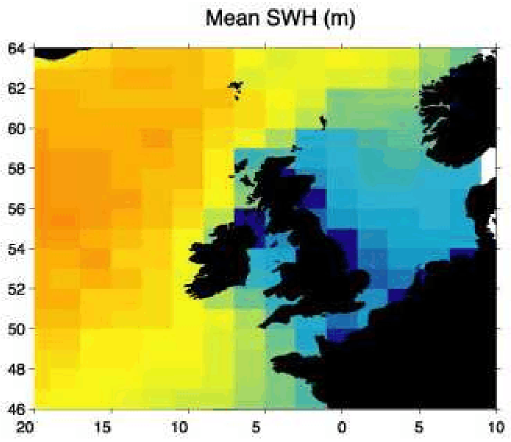

Figure 8.7. Mean significant wave heights for the period 1993–1997 from altimeter data.

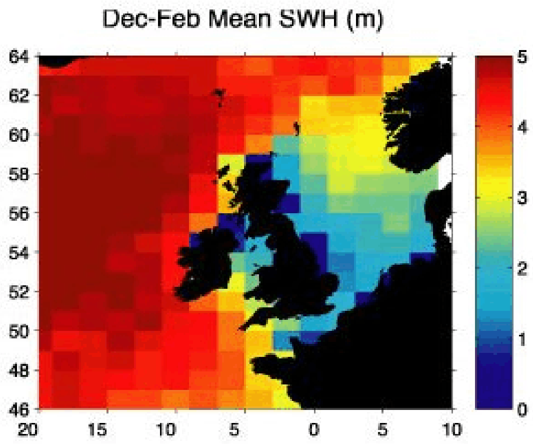

Figure 8.8. Mean winter significant wave height for the period 1993–1997 from altimeter data.

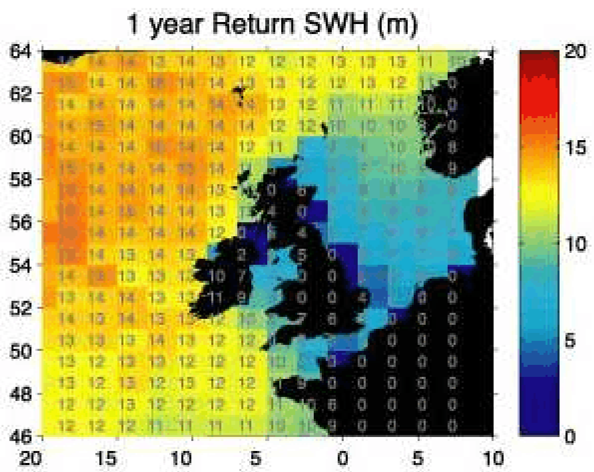

Figure 8.9. 1-year return value of significant wave height from altimeter data (JERICHO).

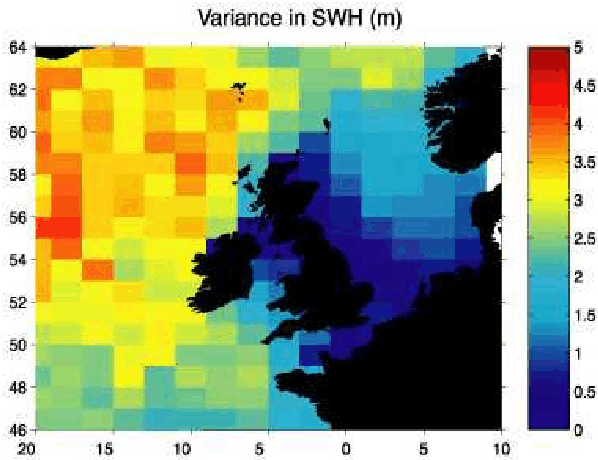

Figure 8.10. Variance in significant wave heights for the period 1993–1997 from altimeter data.

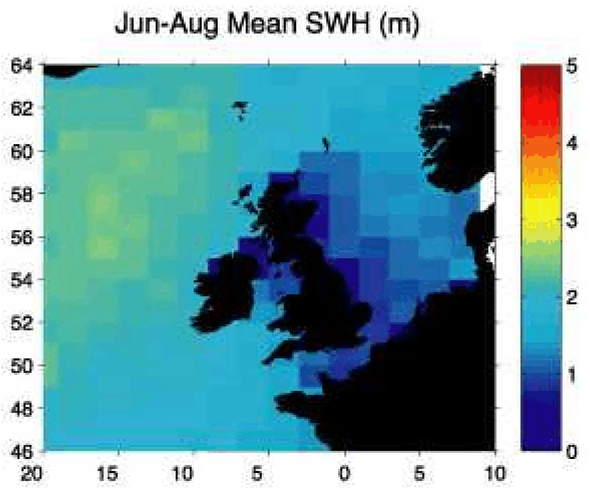

Figure 8.11. Mean summer significant wave height for the period 1993–1997 from altimeter data.

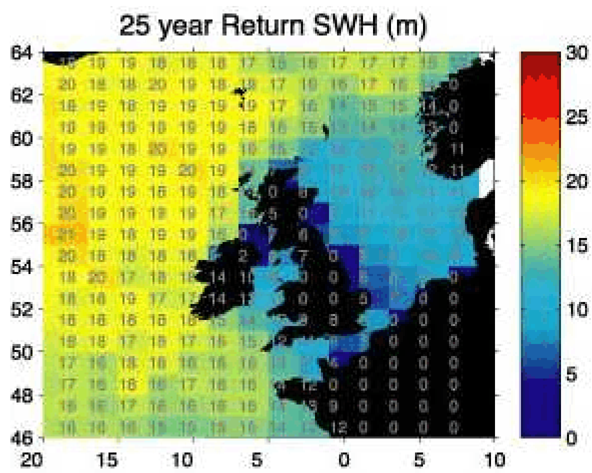

Figure 8.12. 25-year return value of significant wave height from altimeter data (JERICHO).

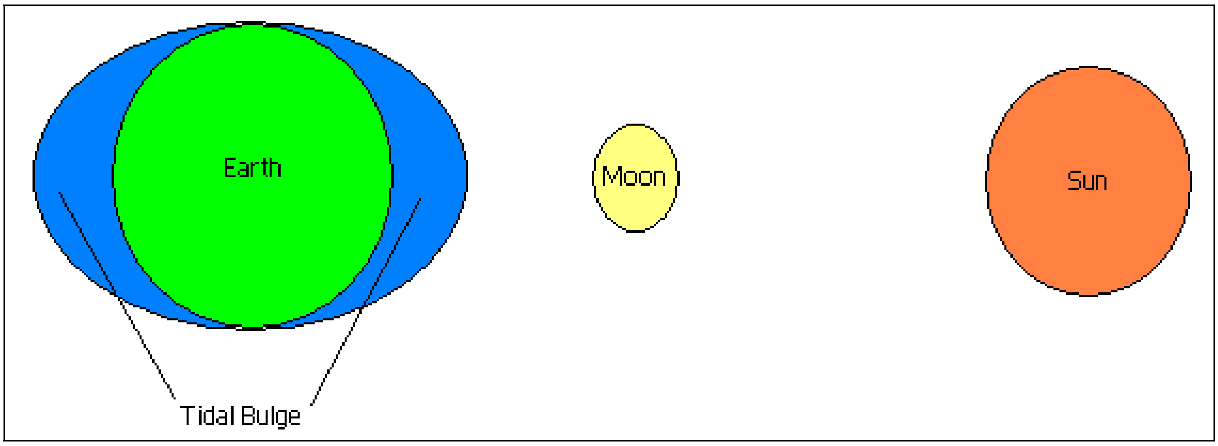

Figure 8.13. Representation of tidal bulge resulting from the gravitational pull of the moon and sun and centrifugal force of a rotating earth.

The progression through the lunar cycle takes one lunar month or 29 days. Figure 8.14 shows the neap tide occurring around Day 6 and Day 21. Spring tides occur around Day 14 and Day 27 of the lunar cycle. The tidal range for a neap tide is low in comparison with that of the spring tide. This difference is due to a variation in the size of the tidal bulge.

The variation in tidal range between the west and east coast is also illustrated in Figs 8.14 and 8.15. Dingle Harbour has a spring tidal range of approximately 3.5 m and a neap tidal range of approximately 1.5 m while Arklow has a tidal range of approximately 1 m with very little variation between spring and neap tides.

8.4.3 Surges

Surges are generated when meteorological variables, such as barometric pressure and winds, depart substantially from average conditions. This can produce negative or positive surge conditions, which are reflected in the difference between actual tidal height and predicted tidal height, based on average conditions, at a location.

Barometric pressure acts to lower or raise the elevation of the sea surface. A decrease of 10 hPa in pressure can raise sea level locally by approximately 1 cm (ECOPRO, 1996). An area of extreme low pressure over the ocean associated with a strong wind acts to enhance the resulting storm surge elevation. In Irish coastal waters, this can result in increased water levels at the coast by up to 1 m (ECOPRO, 1996).

As a depression moves, the generated swell can become coupled with a tidal wave, further enhancing the surge elevation. The effects of a storm surge as it moves onshore depends on a number of factors, including local topographical features of the sub-surface, strength and direction of an onshore wind, occurrence with a spring or neap tide and location of the tidal bulge. The elevation of a storm surge can also be greatly enhanced if it becomes coupled with wind waves. The duration of a surge event also has implications that determine its potential damage.

The coastline responds dynamically to changes in any of the processes above. It is the result of a set of inputs in the form of potential energy delivered by waves, interacting with, and setting in motion, near-shore processes that convert the wave potential into kinetic energy (Pethick, 1984). Processes such as erosion, transportation and deposition of sediments are set in motion as this energy is converted from one form to another. Pethick (after Tanner, 1974) ties these processes together in his definition of an equilibrium coastal landform:

"…an energetic wave system will establish in due time and barring too many complications, a delicately adjusted balance among activity, three-dimensional geometry and sediment transport such that the system will tend to correct short or minor interference".

8.5 Mean Sea Level

Mean sea level is defined as an average of the elevation of the sea measured over a time period that is significant

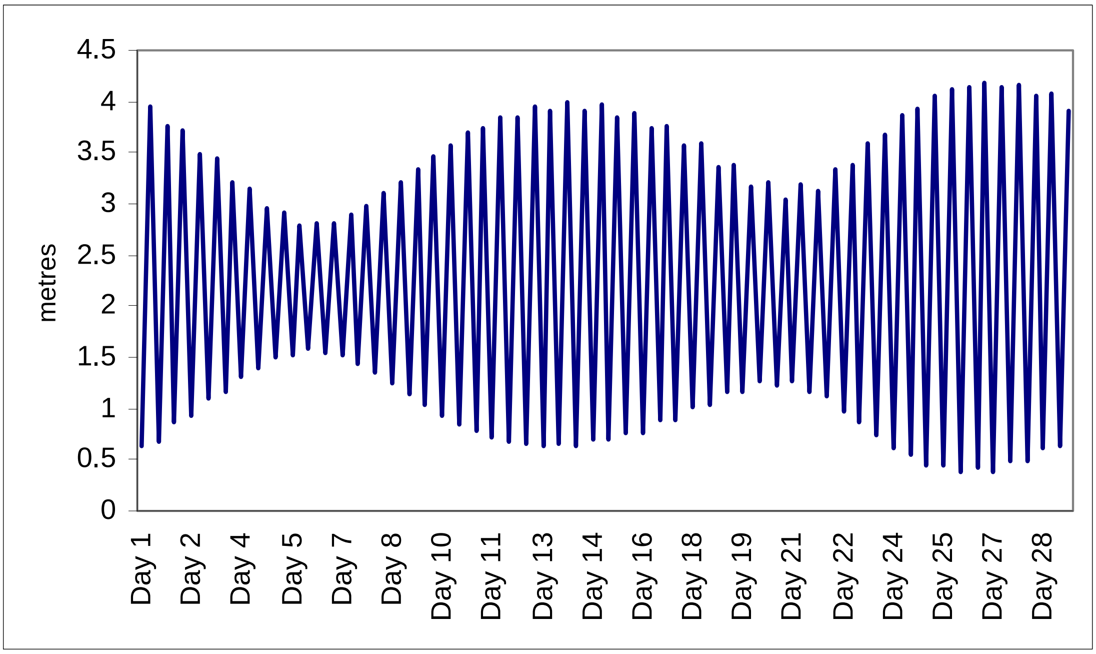

Figure 8.14. Tidal cycle of astronomical spring and neap tides for Dingle Harbour for November 1996. Source: Poltips–Proundman Oceanographic Laboratory.

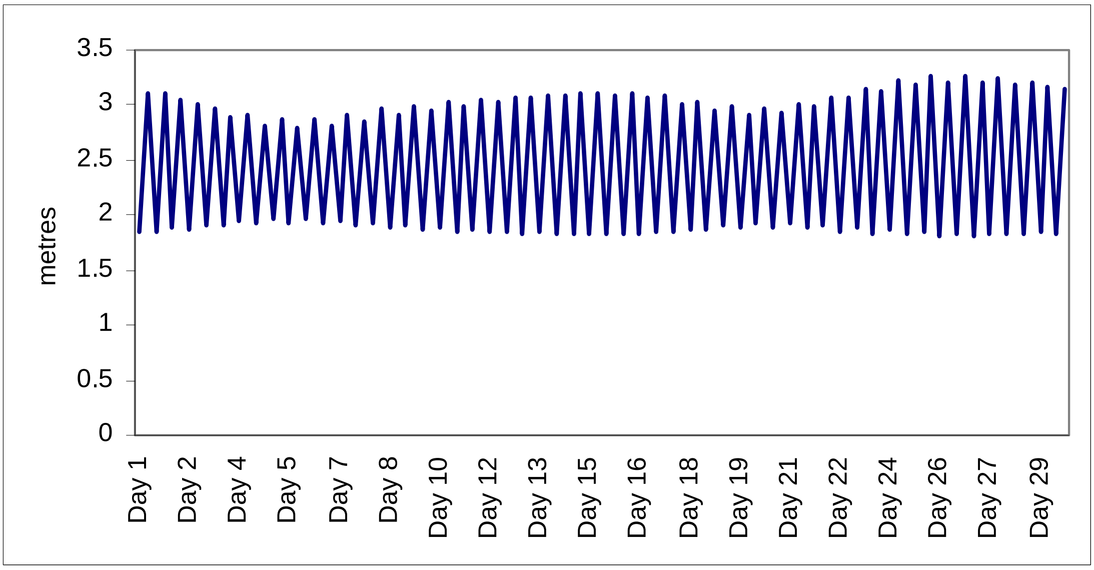

Figure 8.15. Tidal cycle of astronomical spring and neap tides for Wexford for November 1996. Source: Poltips–Proundman Oceanographic Laboratory.

so as to remove localised effects from the measurement, such as tides and surges and other cycles relating to lunar and solar forcing. Sea level is generally measured against the height of a known local datum on land, called the Tide Gauge Benchmark (TGBM). Changes in mean sea level relative to the TGBM are called ‘relative sea level changes’ and are a measure of the difference between vertical movements of the sea level and of the land (UNESCO, 1985). In order to determine actual sea level changes at a location, changes in vertical movement of the land or local isostatic changes need to be subtracted from the relative sea level.

Observed level = mean sea level + tide + meteorological residuals + crustal movements

Globally, during the 20th century, sea level rise was estimated to be occurring at a rate of 1.0–2.0 mm year^{-1} (IPCC, 2001). This rate is believed to have been higher during the 20th century than during the 19th century, although no significant acceleration appears to be occurring in the record in the 20th century (IPCC, 2001).

In Ireland, there are eight stations measuring sea level: Belfast, Derry, Bangor, Larne, Portrush, Malin Head, Galway and Castletownsend all provide hourly measurements. From these and other records from northern Europe, it is estimated that 'relative sea level' in the North Sea area has risen at a rate of approximately 1.0 mm year^{-1} more than expected based on extrapolation of past trends (Woodworth, 1999). This is consistent with the global average of 1.5 mm year^{-1}. However, significant variation within the records occurs (Table 8.1).

The negative values recorded for Belfast indicate that the north of the island is rising as a consequence of glacial isostatic adjustment. This adjustment is occurring at a rate that, from the data, appears to be exceeding current sea level rise. This is observed as a local drop in sea level. Dublin and Malin Head are also emerging. However, the rate of emergence is outweighed by sea level rise. This results in a small change in sea level, relative to the global average.

Table 8.1. Secular mean sea level trends (mm year^{-1}) for a selection of tide gauge stations derived from Revised Local Reference Data (negative values are indicated by an asterisk). Source: Proundman Oceanographic Laboratory.

Source	Tide gauge station	Latitude	Longitude	Years of record	Mean sea level change (mm year^{-1})	Standard error	σ residual values
Global	Milner Bay	13 50 S	136 30 E	1994–1999	33.4	±5.61	65.3
	Valencia	39 28 N	00 20 W	1995–1997	29.0	±12.70	18.0
	Tauranga	37 42 S	176 11 E	1985–1987	–33.5*	±18.76	26.5
	Champerico	14 17 N	91 55 W	1971–1974	–33.6*	±48.17	107.7
Britain	Aberdeen I	57 09 N	02 05 W	1932–1999	0.73	±0.17	25.4
	Aberdeen II	57 09 N	02 05 W	1862–1965	0.58	±0.10	30.1
	Sheerness	51 27 N	00 45 E	1834–1999	1.61	±0.09	39.1
	Dover	51 07 N	01 19 E	1961–1999	2.03	±0.39	24.2
	Portsmouth	50 48 N	01 07 W	1962–1997	1.30	±0.56	31.8
	Devonport	50 22 N	04 11 W	1962–1999	2.86	±0.85	54.5
	Newlyn	50 06 N	05 33 W	1916–1999	1.66	±0.11	25.3
	Holyhead	53 19 N	04 37 W	1938–1996	2.96	±0.49	49.6
	Birkenhead	53 24 N	03 01 W	1956–1972	1.60	±1.46	26.8
	Liverpool	53 24 N	03 00 W	1858–1983	1.03	±0.15	51.0
	Douglas	54 09 N	04 28 W	1938–1977	0.26	±0.70	39.6
	Portpatrick	54 51 N	05 07 W	1968–1998	1.27	±0.53	24.5
	Millport	55 45 N	04 56 W	1969–1999	1.26	±0.68	29.2
	Stornoway	58 12 N	06 23 W	1977–1999	0.97	±1.43	35.1
Ireland	Belfast	54 36 N	05 55 W	1957–1969	–0.99*	±2.17	28.5
	Belfast 2	54 36 N	05 55 W	1918–1963	–0.25*	±0.34	30.5
	Malin Head	55 22 N	07 20 W	1959–1997	0.06	±0.56	34.9
	Dublin	53 21 N	06 13 W	1938–1996	0.23	±0.30	38.3

8.6 Factors that Contribute to Mean Sea Level

Global sea level is affected by a number of factors such as the thermal expansion of the oceans, the contribution made by small glaciers, and the influence of changes occurring in the large ice masses of Greenland and Antarctica.

8.6.1 Thermal expansion of the oceans

Eustatic changes in sea level during periods of glaciation (where the volume of water returning to the oceans is diminished as a consequence of land storage in the form of ice) have already been discussed. However, eustatic changes can also occur as a consequence of density changes in oceanic water. As the atmosphere warms, the resultant increase in oceanic temperature leads to the water column expanding. Observational estimates suggest that thermal expansion of the oceans has produced an increase in sea level of approximately 1.0 mm year^{-1}, over the past number of decades (IPCC, 2001).

8.6.2 Contribution of small glaciers (excluding Greenland and Antarctica)

Small glaciers, some of which are remnants of the large ice sheets that once covered the northern hemisphere, are currently in retreat. Although there are geographical variations in the rates of retreat, on the whole, mass balance reductions of small glaciers are occurring globally (Plate 8.2 and Fig. 8.16). Rates of retreat are highest at the equator where some permanent ice fields and small glaciers have disappeared or will disappear within the next decade.

Meier (1984) estimated that a total of 0.46 ± 0.26 mm year^{-1} was added to sea level as a consequence of melting of small glaciers between the period 1900 and 1961. For the 1961–1990 period, he estimated that a further 0.25 ± 0.10 mm year^{-1} was added, equivalent to 14–18% of the observed sea level rise over the same period (Dyurgerov and Meier, 1997). The contribution of small glaciers to sea level rise has increased since the middle of the 1980s (Dyurgerov and Meier, 1997). This increase in melting of small glaciers can be attributed to concurrent increases in global mean temperature over the period.

8.6.3 Contribution of ice sheets (Greenland and Antarctica)

The Greenland and Antarctic ice sheets are critical to any sea level rise since these two ice sheets store approximately 70% of the earth's freshwater resources (Oerlemans, 1993). However, the exact nature of the role

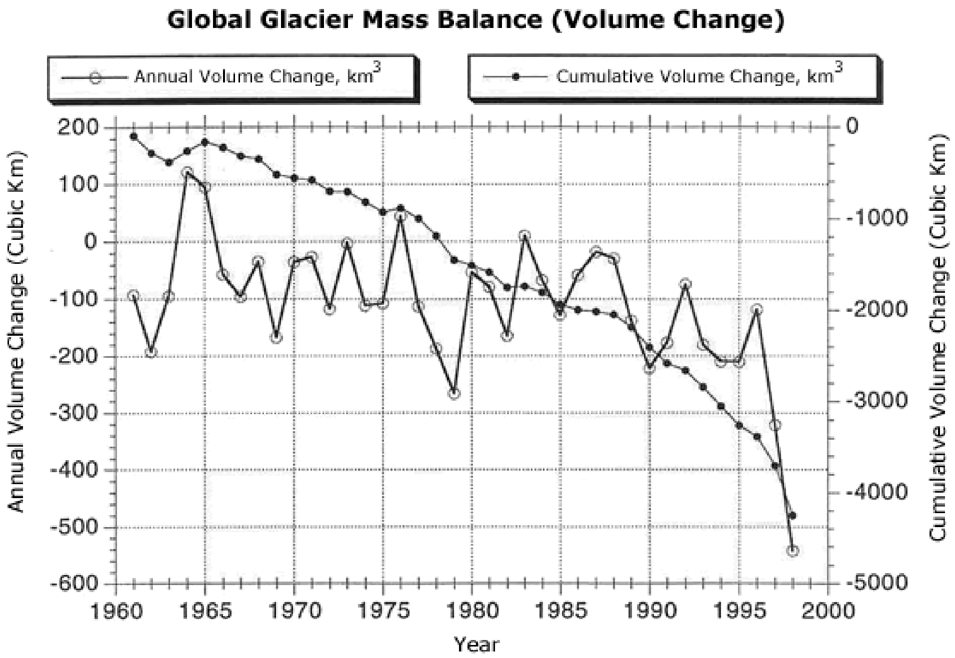

Figure 8.16. Volume change South Cascade Glacier. Source: USGS.

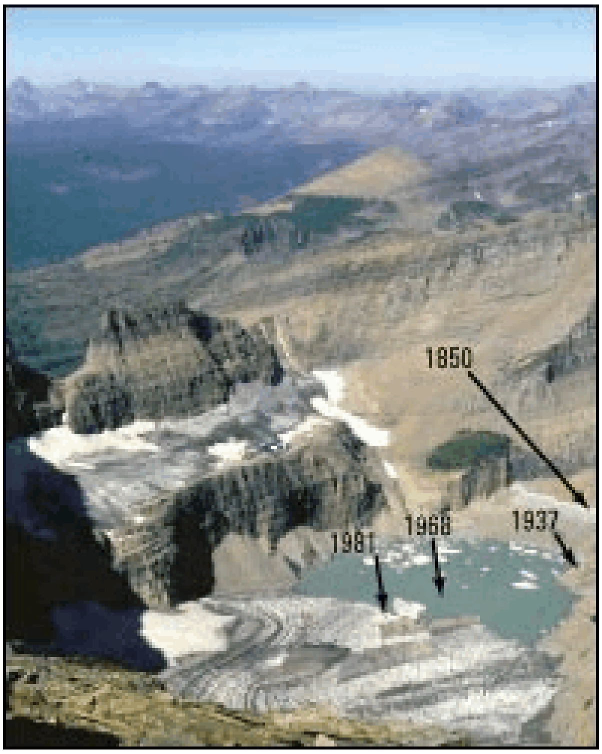

Plate 8.2. Extent of Grinnell Glacier, Glacier National Park, Montana (Carl H. Key, USGS).

they play is somewhat uncertain and as a result only rough estimates of what their potential contribution to sea level could be is possible. Part of this uncertainty arises due to lack of information concerning the response time of the ice sheets to changes in global mean temperature. This response could be on the scale of 10^1, 10^2 or 10^3 years (Oerlemans, 1993).

8.7 Projected Sea Level Rise

Sea level changes are a response and not a 'driver' of change. They result from changes that occur in external forcing mechanisms, such as changes in the redistribution of heat between the equator and the poles and other atmospheric changes.

Figures 8.17 and 8.18 illustrate projected sea level rise over the next 100 years derived from the Hadley Centre Global Climate Model (HadCM3). The HadCM3 is an atmosphere–ocean general climate model (AOGCM) that generates climate output based on historical and predicted changing concentrations of greenhouse gases, sulphates and other atmospheric gases. This model output enables the generation of future climate scenarios, such as changing patterns and intensity of precipitation, increases in temperature (Chapter 2) and sea level rise.

The higher prediction is as a result of considering greenhouse gases only, whereas the lower prediction includes the influence of sulphates which act to reduce the rate of global warming by backscattering/reflecting incoming short-wave radiation into space and by modifying cloud structure. Figure 8.18 illustrates total sea level rise, comprised of thermal expansion, melting of small glaciers and mass balance changes for Greenland and Antarctica. Again, the influence of sulphates act to reduce the overall predicted rise in sea level. These projections for sea level are similar to those produced from other modelling centres and suggest that a rise of approximately 0.2 m is likely during the period to 2050.

Table 8.2 demonstrates the range of predictions for sea level from various modelling centres. Some of the variations are due to differences in how the mass balance of Greenland and Antarctica are handled by the different models. The Central Value reported in the table is derived from the IS92a forcing, which represents an increasing of

Table 8.2 Shows projected sea level rise 1990–2100 derived from different AOGCM experiments with the IS92a forcing and Best Estimate and Range for the updated SRES scenarios. (Source: IPCC, 2001).

Experiment		Min (m)	Max (m)
CGCM1 GS		0.45	0.77
CSIRO Mk2 GS		0.29	0.60
ECHAM4/OPYC3 GS		0.19	0.48
GFDL_R15_a GS		0.37	0.67
HadCM2 GS		0.21	0.48
HadCM3 GSIO		0.18	0.46
MRI2 GS		0.11	0.31
DOE PCM GS		0.12	0.37
Range		0.11	0.77
Central Value		0.44	
TAR	**Best Estimate**	0.48	
	Range	0.09	0.88

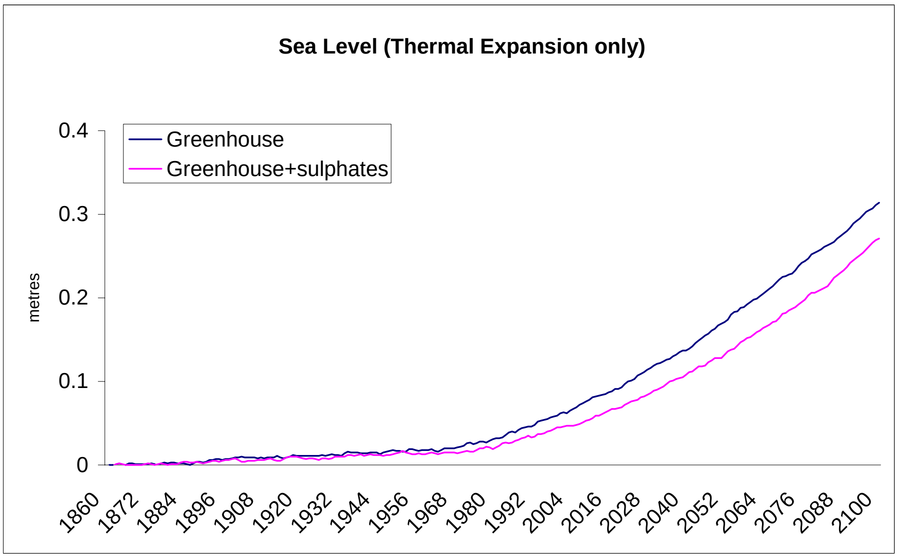

Figure 8.17. Sea level rise as a consequence of thermal expansion (HADCM3-IS92a after 1990).

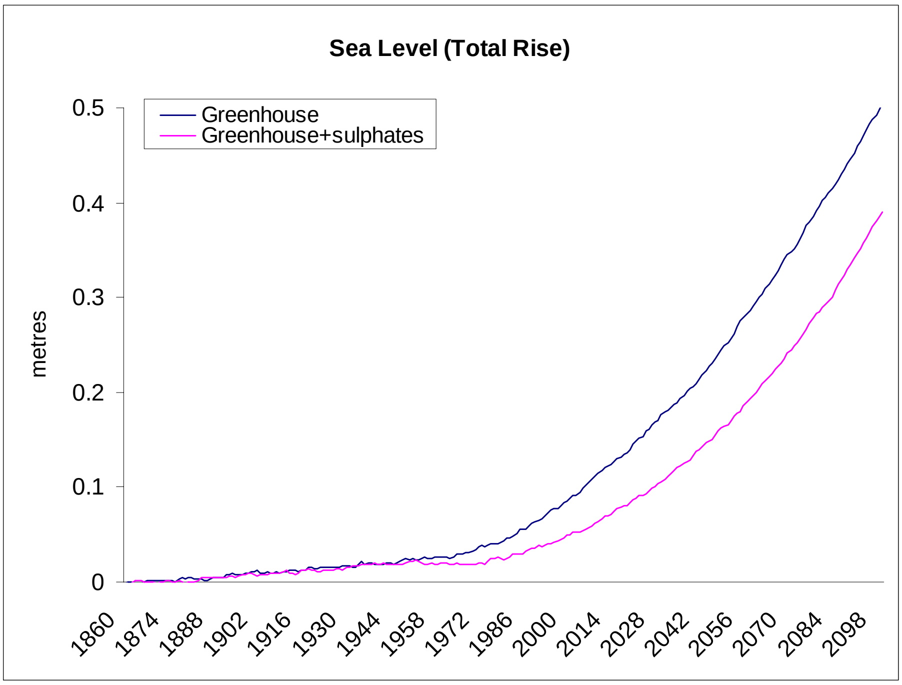

Figure 8.18. Sea level rise as a consequence of thermal expansion plus additional melt water from glaciers and other sources (HADCM3-IS92a after 1990).

effective CO_2 concentration by 1% per annum after 1990, and is based on the various model values as shown. The Best Estimate value reported in the table is based on data from the more recent Third Assessment Report (TAR) and is derived from the output of 35 Special Report on Emissions Scenarios (SRES). The range of predictions suggest an increase in sea level over the next 100 years of 0.09–0.88 m. The reported ensemble mean figure is 0.48 m sea level rise by the end of this century.

An area of uncertainty exists in relation to whether the grounded, submerged portion of the West Antarctic Ice

Sheet (WAIS) remains stable or becomes unstable (Table 8.3). Floating ice, such as at the North Pole, which melts, does not contribute further to sea level rise as it already displaces its own volume. If the North Pole ice melted, it would, however, have a dramatic effect on ocean currents which redistribute heat from the equator northwards. An increased loading of freshwater into the oceans as a consequence of melting in the North Pole could also affect the salinity of the oceans, producing a less dense layer of water. Antarctica, unlike the North Pole, is a land-based ice sheet which extends out into the surrounding ocean. If the grounded ice around the West Antarctic Ice Sheet (Ronne/Filchner and Ross Ice shelves) collapsed under the influence of global warming, some studies suggest that it could result in a rapid flow of grounded ice into the Southern Ocean, resulting in the catastrophic collapse of the WAIS. The consensus view at present, however, is that this is considered unlikely during the present century (British Antarctic Survey, 1999).

The current consensus is that Antarctica could mitigate sea level rise as global warming proceeds (British Antarctic Survey, 1999). This could occur if the mass balance of the Antarctic ice sheet was to increase due to greater snow and ice accumulation. The scenario envisaged is as follows. As a column of air is heated, its water vapour holding capacity increases, and as temperatures over Antarctica seldom reach above 0^{o}C, precipitation of this increased moisture component would fall as snow, thereby reducing the amount of water returning to the oceans.

8.8 Evidence for Climate Change

There appears to be convincing evidence that changes on land and in the ocean are occurring as would be expected with an increase in global temperature. While the evidence is as yet incomplete for oceanic areas, there does appear to be a consistent signal of change. Data from the North Atlantic and other areas suggests that ocean layers are warming, with very few areas cooling (IPCC, 2001). Changes in salinity have also been documented in the upper layers of the ocean. Whether or not this represents a climate trend is as yet unclear (IPCC, 2001).

In the North Atlantic, analysis of wave data observed from ships and buoys has shown significant increases in wave heights between the 1960s and 1980s. Satellite altimetry indicates that this trend has continued into the early 1990s (Cotton *et al.*, 1999). Figure 8.19 illustrates the percentage increase in offshore significant wave heights for winter between the periods 1985–1989 and 1991–1996 for the North Atlantic. These findings demonstrated a strong relationship with the North Atlantic Oscillation (NAO). The NAO (Fig. 8.20) is an index of the pressure difference between Iceland and Portugal (Marshall and Kushnir, 1997). Over these two periods, the NAO was in a negative and positive phase, respectively. When the NAO is in a positive phase (early 1990s), it produces stronger than average westerlies over the mid-latitudes, thereby enhancing wave heights. Between 1960 and 1990, the NAO index has displayed a significant increase in intensity. This increase is characterised by a transition from anticyclonic to cyclonic conditions in the North Atlantic (Gulev and Hasse, 1999).

Table 8.3. Potential sea level rise estimates from glaciers and ice sheets. Source: Williams and Hall, 1993.

Location	Volume (km^3)	Potential sea level rise (m)
East Antarctic ice sheet	26,039,200	64.80
West Antarctic ice sheet	3,262,000	8.06
Antarctic Peninsula	227,100	0.46
Greenland	2,620,000	6.55
All other ice caps, ice fields and valley glaciers	180,000	0.45
Total	32,328,300	80.32

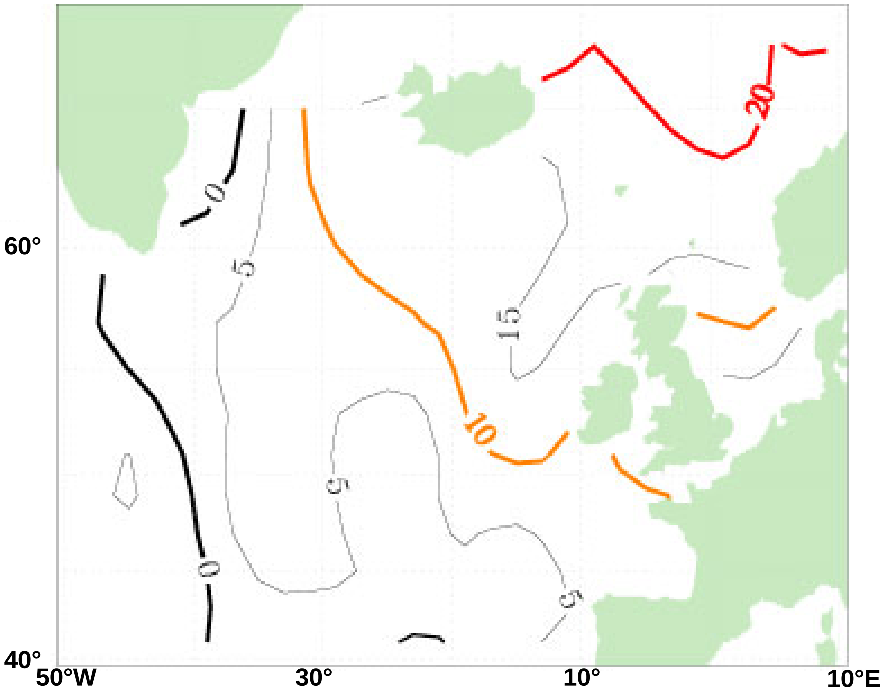

Figure 8.19. Percentage increase in mean winter significant wave height, 1985–1989 to 1991–1996 from altimeter data (JERICHO).

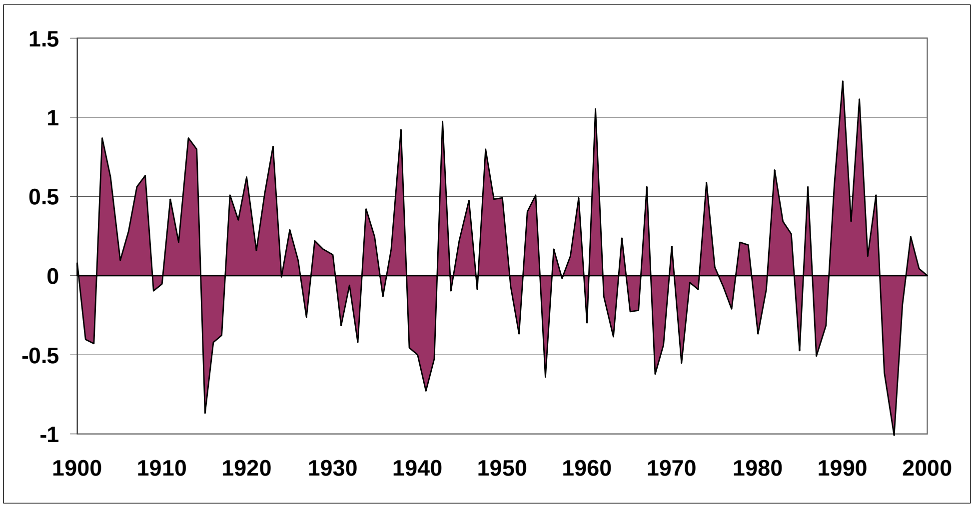

Figure 8.20. North Atlantic Oscillation 1900–2000 (data provided by Climate Research Unit).

In a study conducted by the WASA Group (Waves and Storms in the North Atlantic), data compiled from wave charts suggest that wave heights off the west coast of Ireland have been increasing at a rate of 0.3% year^{-1}. Hindcast modelling work carried out during the course of the WASA study indicates that this figure might be lower if a longer time period of analysis was used (WASA, 1998). However, the trend over the period was for increasing wave heights in the North East Atlantic (Bouws *et al*., 1996). This trend appears to have occurred over nearly the whole of the North Atlantic, with significant wave heights increasing by between 10 and 30 cm decade^{-1} over the whole region, for the period 1961–1993 (Gulev and Hasse, 1999). Gulav and Hasse (1999) attribute these increases to a change in swell height as opposed to an increase in locally generated wind waves (which they term ‘wind sea’). They also found an increased correlation between the NAO and swell height rather than ‘wind sea’.

Increases in storminess in the Northeast Atlantic over the last number of decades have been found to be consistent with natural variability (IPCC, 2001). However, some of the increases in frequency may be linked to large-scale circulation changes which could be attributed to global warming (Sweeney, 2000). Bárdossy and Caspary (1990), in an analysis of European atmospheric circulation patterns between 1881 and 1989, detected an increase in zonal (westerly) flow during the winter months of December and January.

While the overall annual frequency of zonal circulation has remained the same, the monthly frequency was found to have changed dramatically, with increased frequencies apparent in December and January and decreases in April and May. The rate of increase over the last two decades, was found to be almost three times higher than that of the 1893–1918 period. This increase in zonal frequency was accompanied by concurrent decreases in meridional (southerly) circulation types. In Fig. 8.20, the period 1900–1915 was marked by a positive NAO, similar to the closing decades of the 20th century. However, the intensity of the NAO has increased between these periods. The main increase in frequency of zonal flow appears to occur after 1973. Figure 8.21 also displays an increase in storm frequency, which is consistent with an increase in zonal over meridional flow, since the mid-1970s.

This trend in storm frequency is consistent with predictions from both the HadCM2 and HadCM3 experiments. While they predict an overall decrease in storm frequency over Northern Europe and the Mediterranean, storm frequency will tend to increase over the British Isles and Ireland. Storm intensity is also predicted to increase substantially as a consequence of enhanced global warming (McDonald *et al.*, 1999).

8.9 Implications for Ireland

As average global temperatures continue to increase and the effects are felt, environmental systems, which may currently be in a state of equilibrium, will have to adjust to these changes. How these systems will change or what their rate of change might be is still uncertain. This uncertainty presents many problems for assessing the potential of coastal inundation at a regional scale. Some of this uncertainty derives from limited understanding of how phenomena such as sea level, increases in wave heights, and storm surges, will respond to external forcing. These forcing mechanisms will in turn, and at various timescales, affect the coastal environment.

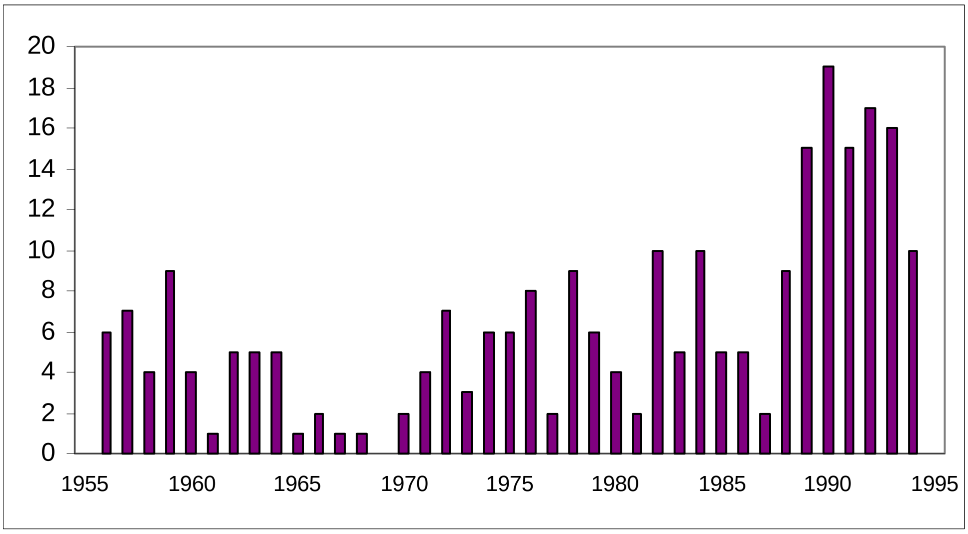

Figure 8.21. Number of North Atlantic low pressure systems with pressure less than 950 hPa. Source: Deutscher Wetterdienst, 1994.

At the regional scale, the major effects of a sea level rise are loss of land as a consequence of inundation and increased erosion (Titus, 1993), and increased risk of flooding both at the coast and inland along major river networks during storm surge events. Flooding risk would also be enhanced if a storm surge is coupled with intense or long duration precipitation events. The likelihood of this occurring is enhanced due to projected increases in precipitation during the winter season, as detailed in Chapter 2. It is likely that precipitation increases will result from more frequent short duration/high intensity events which would result in increased runoff increasing the potential for river flooding. Coastal aquifers, along with estuaries and wetlands, are also at risk due to saltwater intrusion. Increases in rates of erosion due to changes in coastal currents and sedimentation rates are also likely (Titus, 1993).

8.9.1 Coastal erosion

Coastal erosion is part of an overall natural process of shoreline adjustment to short-term changes in tidal range, waves, longshore currents and storm surge activity. It is also a response to longer-term changes in sediment supply, and eustatic and isostatic changes in sea level. Coastal erosion needs to be understood in terms of an ongoing natural process of adjustment. However, human activities are increasingly believed to have an influence on coastal erosion around the Irish coast (Carter *et al.*, 1989). Between 1850 and 1900, over 270,000 m^3 $year^{-1}$ of sand was dredged from the inshore region around Youghal which led to a lowering of the beach profile and subsequent shoreline recession (Carter *et al.*, 1989).

In the early 1800s, reclamation of Wexford Harbour led to a modification of the wave pattern which, in 1929, resulted in the beheading of over 2 km from the Rosslare Spit (Carter *et al.*, 1989). Similarly, the construction of Courtown Harbour, which commenced in 1828, appears to have resulted in a shoreline recession of 50 m between 1921 and 1991 (Bell *et al.*, 1997). The Wexford shoreline is still adjusting to these and other human activities (Orford, 1988). Thus, human activities can be seen to initiate or enhance the process of erosion.

Despite the fact that coastal erosion presents itself as a problem in Ireland (Plate 8.3, Plate 8.4), little work has been done in trying to determine rates of erosion around

Plate 8.3. Road setback as a consequence of coastal erosion on a soft coastline.

Plate 8.4. Coastal squeeze – protection to prevent further erosion.

the coast. Carter and Bartlett (1990) conducted a survey of erosion on 'soft' shorelines (beaches, dunes and estuaries) for a portion of the north-east coast between Lough Foyle and Larne. This survey was based on map comparison, charts and photographs compiled from a 150-year period. Slow shoreline recession was found to be occurring at almost all sites. At a number of sites, both erosion and accretion had occurred. Table 8.4 illustrates erosion rates for various different shoreline types from selected locations around the coast.

In extreme cases, erosion rates in excess of 3.0 m $year^{-1}$ were reported from the north-west coast of Magilligan (Carter and Bartlett, 1990). This was attributed to natural shoreline adjustment to secular or long-term changes in sea level. However, extraction of sands and gravels was found to greatly enhance the rates of erosion occurring at sites.

Sand dunes provide a degree of 'natural' protection to the shoreline. They are an integral part of the coastal cell, encompassing the beach and inshore zones. They act as regulators of exchange processes that occur within the coastal cell, storing or providing sediment, to replenish losses on the beach (Carter, 1990b). However, the stability of a dune system is dependent on supplies to, and demands on, dune sediment. If the sediment supply is cut off or altered, dune erosion can occur through net losses, or dune growth through net gains. Vegetation is also crucial and dunes are highly vulnerable to overgrazing or trampling by livestock. Most of the dunes and marshes on the exposed west coast are grazed by livestock, while those on the east coast are rarely grazed (Curtis and Sheehy-Skeffington, 1998).

According to the Bruun Rule of erosion as a consequence of sea level rise, under generalised conditions for sandy shores, for every centimetre rise in sea level there is a shoreline retreat of approximately 1 m (UNESCO, 1997). While this would result in a landward movement of the shoreline and dunes, it would also provide additional sediment for zones of sediment deficit (Devoy, 2003).

Table 8.4. Coastal erosion rates for various shoreline types at various locations (Carter, 1990). *Associated with the commercial removal of material involved.

Site	Type of shoreline	Erosion rate ($m\ year^{-1}$)	Period of measurement
Ballyness, Co. Donegal	Sand dunes	0.20	1837–1920
Rossapenna, Co. Donegal	Sand dunes	1.50	1974–1983
Lough Foyle, Co. Derry	Low dunes/beach ridge	0.75	1833–1961
Portrush, Co. Antrim	High dunes	0.11	1850–1966
Cushendall, Co. Antrim	Alluviate terrace/dunes	0.79*	1903–1963
Killiney, Co. Dublin	Boulder clay cliff	0.39	1837–1975
		0.47	1971–1972
Greystones, Co. Wicklow	Beach/low earth cliffs	0.18	1838–1937
		0.89	1937–1973
Rosslare Strand, Co. Wexford	Boulder clay	0.30	1840–1925
Ballycotton, Co. Cork	Gravel ridge	1.60	1837–1957

Coastal zones on the south and east coasts, where there is a plentiful supply of glacigenic material, may also provide an additional source of sediment available for transport and subsequent deposition in areas of net losses (Devoy, 2003).

Salt marshes (Fig. 8.22), which are comprised of fine silts and clays, are generally found in areas where there is a high tidal range and that are sheltered from the effects of wind waves (Pethick, 1984). The upper boundary is found at or within the limits of the high water mark and only becomes flooded at high water or by storm surge events. Salt marsh initiation began in Ireland as a result of post-glacial sea level changes where previously non-marine land was inundated (Curtis and Sheehy-Skeffington, 1998; Devoy, 2003). Salt marshes play an important defensive role of the hinterland by dissipating wave energy and may initially act as a local buffer to sea level rise as long as there is a constant supply of sediments for vertical or horizontal progradation (Simas *et al.*, 2001). A number of marsh sites along the south and west coasts are currently displaying increased rates of accretion in the range of 4–8 mm $year^{-1}$, an order of two to four times higher than background levels (Devoy, 2003). However, an increase in wave energy can also initiate or accelerate erosion where there is limited sediment supply (Bird, 1993). With sea level rise, salt marshes would be expected to migrate landward in response to a changing intertidal range. Slope or other factors, which include defensive structures and coastal infrastructure, may impede this landward migration. The resulting 'coastal squeeze' could present itself as a problem to any shoreline recession that may occur as a consequence of sea level rise.

The effect of a sea level rise on estuaries will tend to enlarge their vertical and horizontal extent, resulting in the penetration of tides further upstream (Bird, 1993). The outflow from rivers would be impeded as a consequence, which, in a high intensity rainfall event where runoff is high, would increase the risk of flooding. These changes in estuary morphology would also diminish sediment supply to the coastal zone as the sediment would be retained within the confines of the estuary. This has important implications for the coastal zone as off-shore sediment supply has almost ceased requiring reworking of existing sediment within the coastal zone. The inland penetration of saltwater could also result in the contamination of low-lying coastal aquifers and other freshwater sources.

Salt marshes and sand dunes are ecological strongholds providing a variety of habitats for a range of different species. Many of the marsh systems in Ireland provide over-wintering feeding grounds for many species of migratory birds. The loss of these habitats could present major problems for species numbers and diversity, aspects dealt with in the previous chapter.

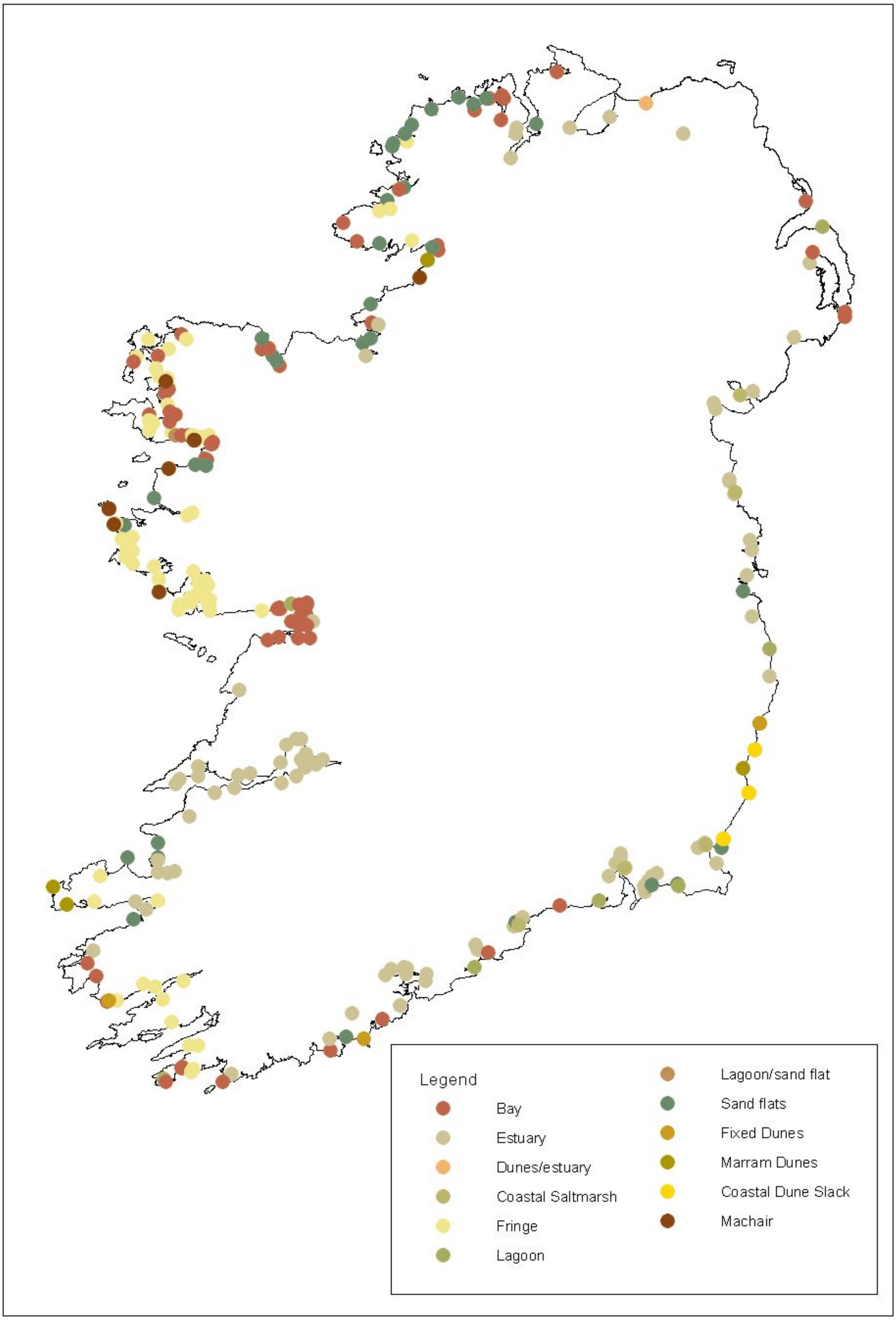

Figure 8.22. Location of salt marshes and dune systems in Ireland (compiled from various sources).

Erosion rates for ‘hard’ shorelines (cliffs) are more difficult to determine due to the response time of these features to changes in conditions. Hard structures may catastrophically collapse after an extreme storm event, but erosion may have been acting to weaken the structure, over very long time scales. Collapse of hard shorelines can occur in a number of ways and is generally related to the type of material that the structure is comprised of.

Rates of recession for cliffs comprised of glacial till are generally in the range of 0.2–0.5 m year^{-1}. However, rates in excess of 1.0–2.0 m year^{-1} have been found on the Wexford coast (Carter, 1990b). On the north-east coast, erosion on glacial cliffs is occurring at approximately 0.25 m year^{-1}. Rates of erosion on ‘soft’ or poorly consolidated cliffs could be expected to accelerate as wave attack becomes intensified as sea level rises (Bird, 1993). Results from a study in Britain suggest that cliffs that are currently undergoing a rate of retreat of 1 m year^{-1} could accelerate by 0.35 m year^{-1} for every 1 mm rise in sea level (Bird, 1993). An increase in precipitation would also enhance erosion rates on ‘soft’ cliffs due to water logging and subsequent slumping. This eroded debris would provide additional material for abrasion at the cliff base, further enhancing erosion. Table 8.5 provides some general long-term rates of recession for various cliff types found around the Irish coast.

The response of these systems to a change in conditions, whether natural or anthropogenic in origin, needs to be examined in the context of an overall adjustment of the shoreline that occurs over time and space. Different coastal landforms exist within and are the product of different energy regimes. Energy is supplied to the coast through wind, waves and currents. The level of energy that a location receives will depend on a number of factors, such as aspect in relation to the dominant wave direction or exposure unit, tidal range, water depth, and location with regards to the surrounding morphology which acts to concentrate or reflect incoming wave energy. All these factors affect the energy gradient of a specific location (Pethick, 2001) producing the various coastal landforms. These landforms exist and maintain their location with reference to a particular energy gradient. As sea level rises, resultant increases in energy will induce low energy systems, such as salt marshes, to migrate landward and upward towards a lower gradient. These landforms may in turn be replaced by higher energy systems, such as beaches (Pethick, 2001).

Table 8.5. Long-term erosion rates for various lithologies (ECOPRO, 1996).

Lithology	Rate of recession (m year^{-1})
Glacial till	1.0–10.0
Sandstone	0.1–1.0
Shales	0.01–0.1
Limestone	0.001–0.01
Granite	0.001

Studies conducted on the east coast of Britain predicted that estuaries could migrate landwards at a rate of 10 m year^{-1}, assuming a sea level rise of 6 mm year^{-1}, while open coast landforms could migrate longshore at 50 m year^{-1} (Pethick, 2001). However, man-made modifications at the coast could act to inhibit these migrations, resulting in net losses through the onset of erosion resulting in new equilibria being reached.

8.9.2 Coastal inundation – areas at risk

In order to assess areas around Ireland at risk from an increase in sea level, three sea level rise scenarios were chosen: 0.09 m, 0.48 m and 0.88 m. These values are best estimates based on a range of model predictions forced with SRES (Table 8.2) and do not include the effects of induced surges or wind waves. This range of estimates was used in conjunction with a digital elevation model (DEM), which had a spatial resolution of 50 m, to produce probability maps of inundation. This approach allows for the incorporation of errors associated with the input data. The DEM has a vertical resolution of 1 m and a vertical accuracy of ±5 m. Therefore a value of 6 m on the DEM has a probability of lying between 1 and 11 m and a probability of inundation can be attributed to each 50 m cell based on the various estimates of sea level rise by incorporating this probability.

Despite the fact that the vertical resolution of the DEM is larger than the predicted rise in sea level, the vertical accuracy of the elevation model can be incorporated into a probability analysis type approach in the absence of higher resolution elevational data.

This approach is considered superior to producing national maps of sea level rise, which take no account of errors within the data. Such maps assume that the elevation values have no associated error and therefore any elevation lying under a specific value will be inundated. In order to produce the maps, it was assumed that errors in the elevation data had a normal distribution and that 90% of all values fell within ± 5 m; under these assumptions the standard deviation is then equal to the root mean square error (RMSE). To determine probability values for each cell in the DEM, values were converted to z-scores.

$$Z = \frac{X - \mu}{\sigma}$$

where X is the predicted rise in sea level, μ is the cell value of DEM and σ is the standard deviation or RMSE.

The resulting z-scores were then classified according to predefined probability ranges (Table 8.6).

This approach allows for a critical threshold to be determined for a particular risk and is of particular importance to engineers, planners and other bodies that may have different risk threshold requirements.

The effects of the various scenarios are demonstrated in Table 8.7 and Figs 8.23–8.25. Due to the grid resolution of the DEM, a number of areas are further illustrated, such as Clew Bay, the Shannon Estuary, Tralee Bay, Dublin Bay and Wexford and Cork Harbours. It is important to note that these figures represent a change in mean sea level only and do not include the effects of surge activity. Also, these maps do not take account of isostatic rebound which varies around the Irish coast. The reason for the exclusion of isostatic rebound is due to the way elevation is measured with reference to a datum. The datum for Ireland is located at Malin Head and is derived from tide gauge measurements taken between 1960 and 1969. Tide gauge measurements are taken over a long time duration in order to determine mean sea level.

Malin Head is also located in an area that is active in terms of post-glacial rebound. Local differences also occur in terms of mean sea level as measured at Malin and elsewhere around the Irish coast. In the absence of a geoidal surface, which represents the gravimetric or level surface of the oceans, mean sea level measured at Malin Head is assumed to be representative of conditions nationally as this is the reference for the height data used in this study. The magnitude of change is such that areas of risk would remain the same but their respective probability class may increase or decrease with the inclusion of higher resolution data.

Table 8.6. z-scores and associated probabilities.

z-score			Probability %
–338.689	to	–3.091	0
–3.091	to	–2.326	<1
–2.326	to	–1.645	1–5
–1.645	to	–1.282	5–10
–1.282	to	–0.841	10–20
–0.841	to	–0.524	20–30
–0.524	to	–0.253	30–40
–0.253	to	0	40–50
0	to	0.253	50–60
0.253	to	0.524	60–70
0.524	to	0.841	70–80
>0.841			>80

Table 8.7. Potential area of land (km^2) inundated under different sea level scenarios and risks associated with Digital Elevation Model.

Risk	0.9 cm	49 cm	86 cm
>10%	382	382	382
>20%	193	287	287
>30%	100	193	193
>40%		100	100

In order to determine the effects of a sea level rise coupled with a storm surge event, the ensemble mean scenario of 0.48 m is used in conjunction with an extreme water level of 2.6 m ordnance datum (OD) (Fig. 8.26). An extreme water level (surge coupled with tide) of this magnitude represents a surge for the present period with an expected return period of 12 years on the west coast (Carter, 1990a), and a return period of 100 years on the east coast, at Dublin (Carter, 1990a). Under enhanced global warming, the return frequency of a storm surge

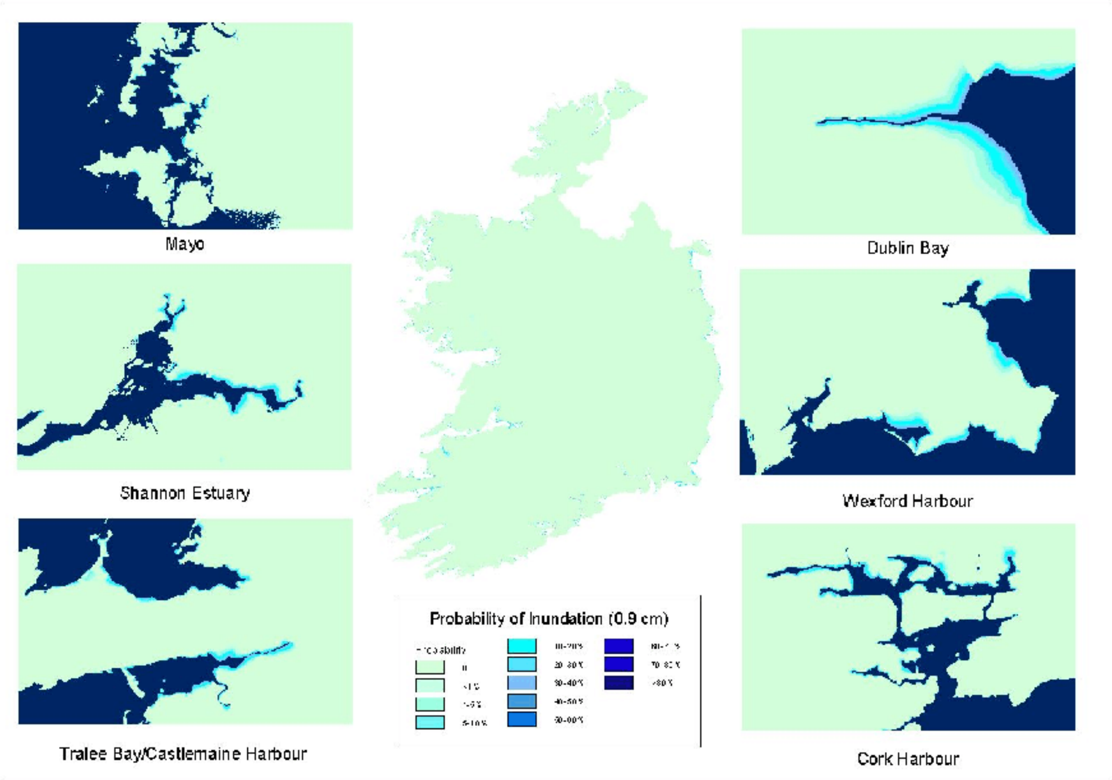

Figure 8.23. Probability of inundation with a sea level rise of 0.9 cm.

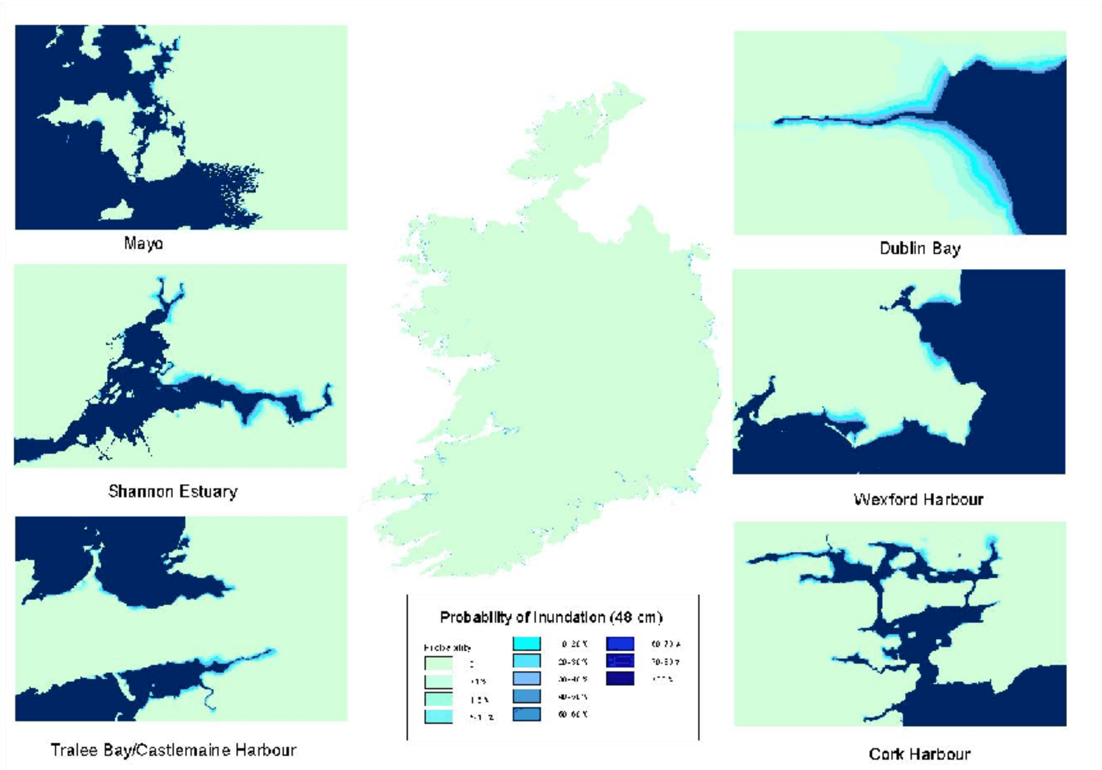

Figure 8.24. Probability of inundation with a sea level rise of 48 cm.

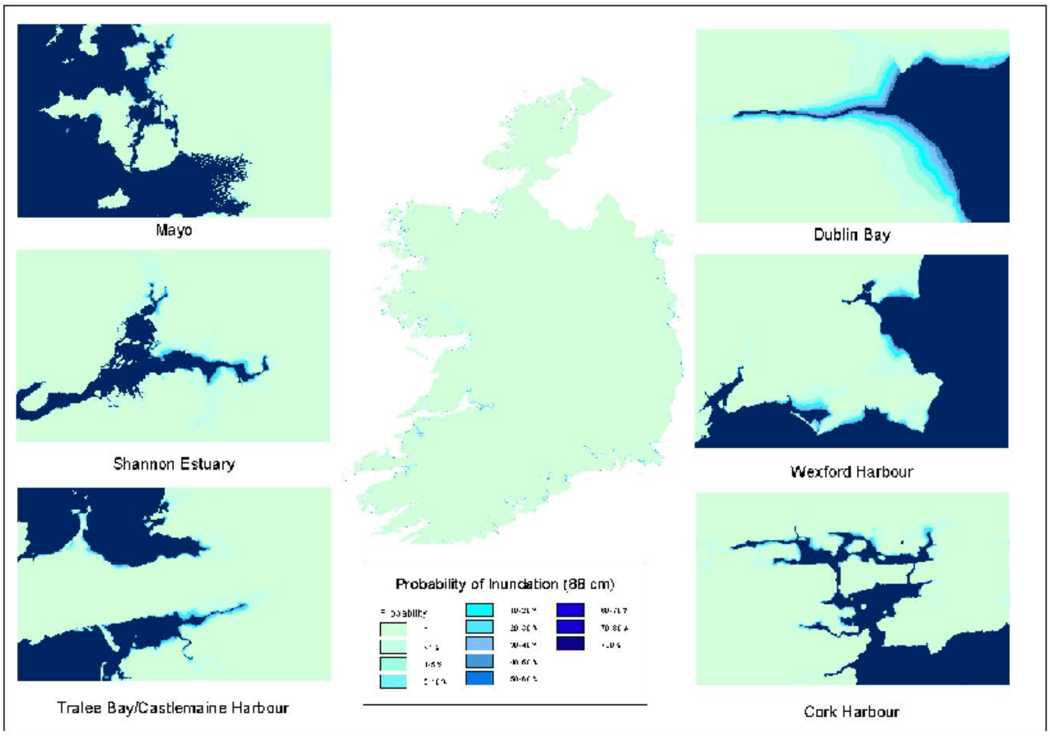

Figure 8.25. Probability of inundation with a sea level rise of 88 cm.

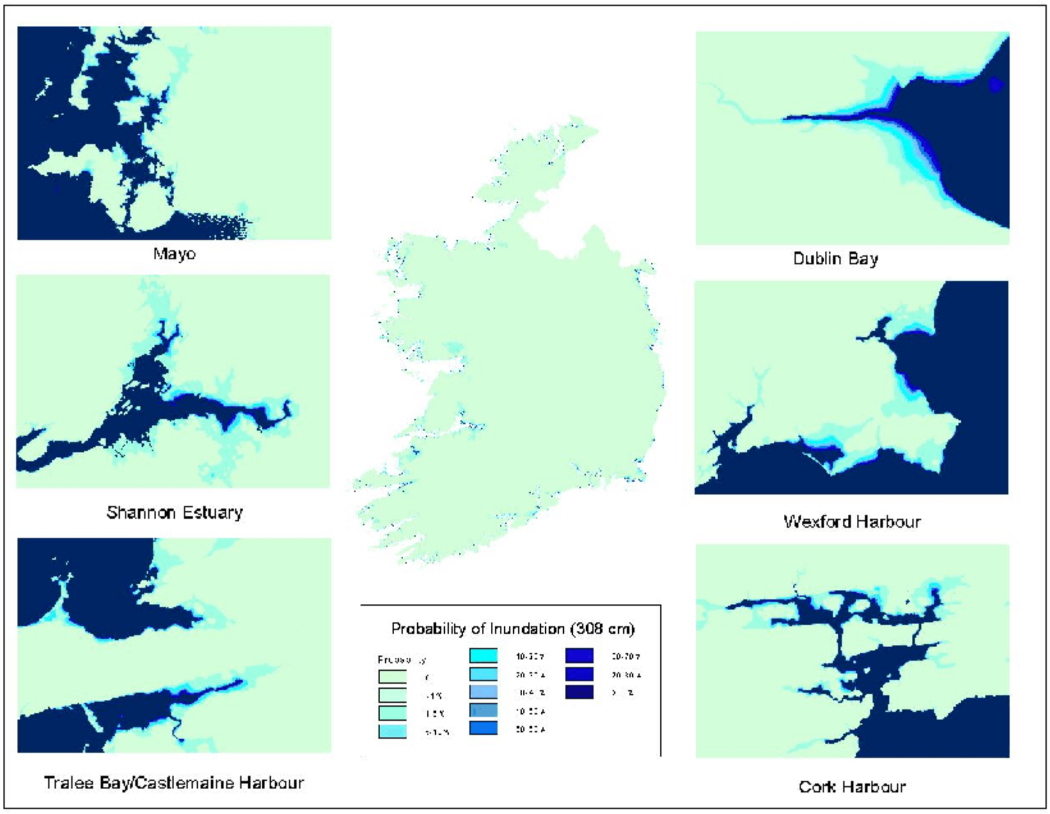

Figure 8.26. Storm surge 260 cm coupled with a sea level rise of 48 cm.

producing extreme water levels of this order is expected to increase in frequency under all scenarios.

The effects of such an extreme water level would tend to be diminished on the more open locations on the west coast while being enhanced on the more enclosed north and east coasts. Localised surge levels may be further enhanced by enclosed bays, which can be found around the Irish coastline (Orford, personal communication).

An extreme water level of this magnitude puts approximately 300 km^2 of land in the >50% probability of inundation class (Table 8.8). While the current return period for such an event is lower on the east than on the west coast, an increase in frequency on both coasts represents a substantial amount of land that could potentially be inundated on a more regular basis.

Under future scenarios of global warming, the current 100-year extreme water level is likely to reoccur every 1–2 years with 2100 AD sea levels (Orford, personal communication).

8.10 A Case Study Using LiDAR Data

As part of the research conducted for this report, it was deemed important to incorporate new data sources of relevance which have become available in the last number of years. As well as incorporating DEMs (Digital Elevation Models) to assess the potential land at risk from sea level rise at a national level, it was possible for this report to include a recent LiDAR (Light Detection And Ranging survey of the east coast) (Department of Marine and Natural Resources). Airborne LiDAR data acquisition is a fast and effective way to collect high-resolution topographic data. The horizontal resolution is in the order of metres while the vertical resolution is of the order of centimetres thus allowing very detailed and accurate topographical information to be obtained.

Table 8.8. Potential area of land (km^2) inundated under medium sea level scenario of 0.48 m and an extreme water level of 2.6 m.

Probability	Area (km^2)
>10%	681
>30%	382
>50%	287
>70%	100

Figure 8.27 illustrates the level of detail that can be obtained from LiDAR data. Estuary channels can be seen clearly in the Wexford Slob, and groynes along Rosslare or South Bay can also be distinguished. The ‘beheading’ of Rosslare Point Sandspit is also evident from this image: where it initially almost enclosed the harbour mouth, it has subsequently been eroded back almost to the southern part of the harbour.

This very important new data source will prove invaluable in the future to assessing sea level rise scenarios and also the impact of sea level rise on coastal erosion and deposition. The ability to generate ‘difference maps’ between survey periods to assess land loss/gain over time and also assess quantitatively the amount of loss or gain will be hugely beneficial to this type of research.

Due to the high resolution of this type of data it is possible to extract profile lines or cross-sections that allow a more in-depth analysis of the data (Fig. 8.28). These cross-sections provide a valuable tool, in conjunction with other data sources, to assess coastal defences and areas at risk from a sea level rise.

Profiles 1 and 2, shown in Figs 8.29 and 8.30, have been extracted from areas dominated by alluvium and aeolian sand. While the seaward sides of both profiles are in excess of 8 m in elevation, the nature of the underlying material is very prone to any changes in the local sediment budget and hence erosion. Within 280 m from the shoreline, the elevation of profile 1 rapidly decreases to *ca* 1 m. Similarly with profile 2, the back slope elevation decreases to approximately 1 m. According to the Bruun Rule of shoreline recession for ‘soft’ coasts with an increase in sea level, the land area between these profiles could be dramatically affected, resulting in enhanced erosion and subsequent inundation. An initial consequence would result in net losses to the land-based sediment budget contained within the dune system reducing the amount of available material for dune migration. However, its removal to enhance or augment offshore bars may mitigate against continued erosion occurring.

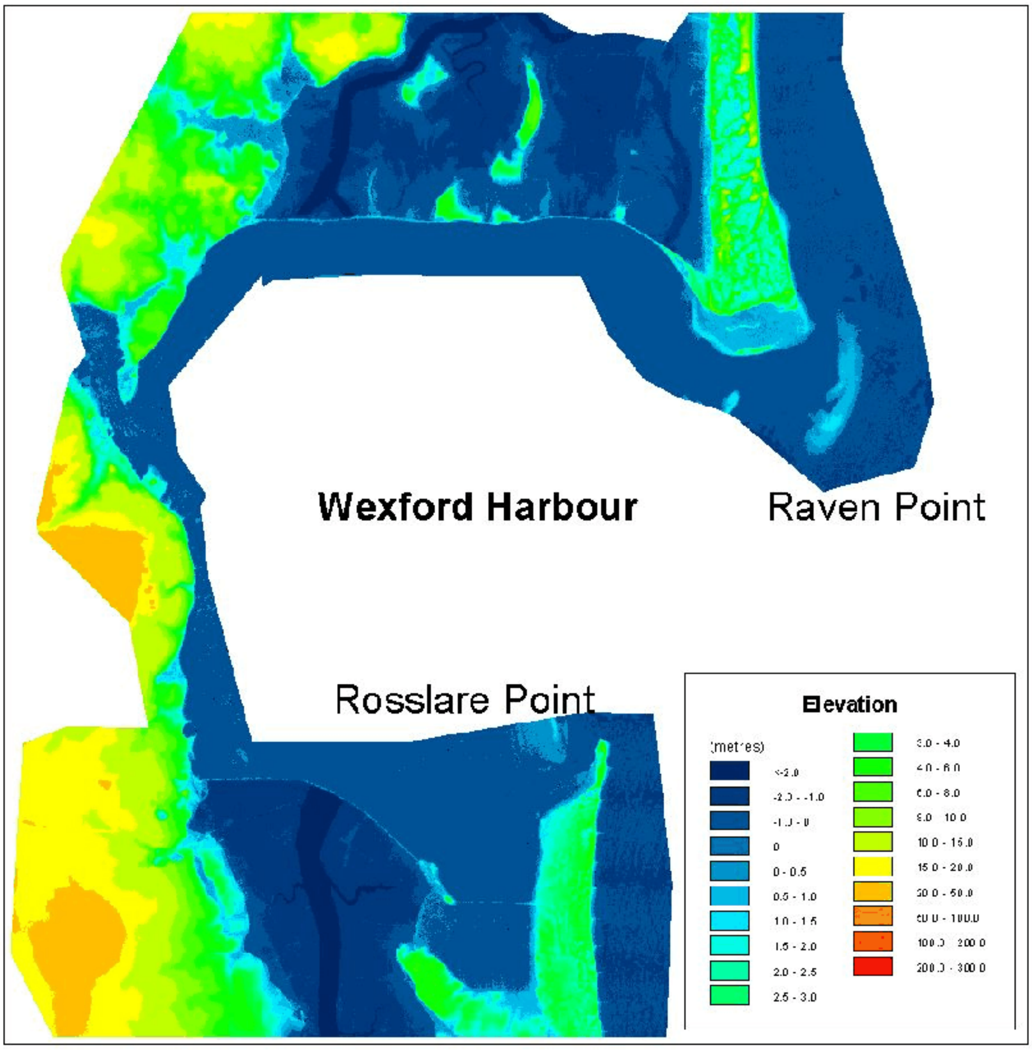

Figure 8.27. LiDAR data of Wexford Harbour.

Profiles 3 and 4, displayed in Figs 8.31 and 8.32 were extracted from locations comprised mainly of morainic sands and gravels and blown sands. The elevation gradient suggested by Profile 3 and its material composition may provide some degree of protection against any sea level rise. However, a river channel just south of this cross-section, provides a routeway that may increase the level of vulnerability that this area has during a storm surge event, which may result in temporary inundation.

The low-lying area depicted in Profile 4 may become permanently inundated as a consequence of any rise in sea level, due to the probability of shoreline recession and inundation from the Wexford Slob. South of profile 4, glacial outwash sands and gravels give way to alluvium and aeolian deposits, increasing the potential for erosion along this section of coastline. The loss of this barrier to erosion would significantly affect the sediment budget of the harbour resulting in potential gains further up the estuary mouth.

On the whole, this east coast section of the Wexford coastline should be considered as ‘at risk’. The composition of this portion of the coastline is dominated by the soil series known, respectively, as the Screen and Macamore Series, both of which are comprised largely of sandy material (Gardiner and Ryan, 1964). While elevation differs greatly along this stretch of coast, the potential for collapse of the weaker structures may provide ideal routeways for attack from sea level rise coupled with increased storm surge activity. The

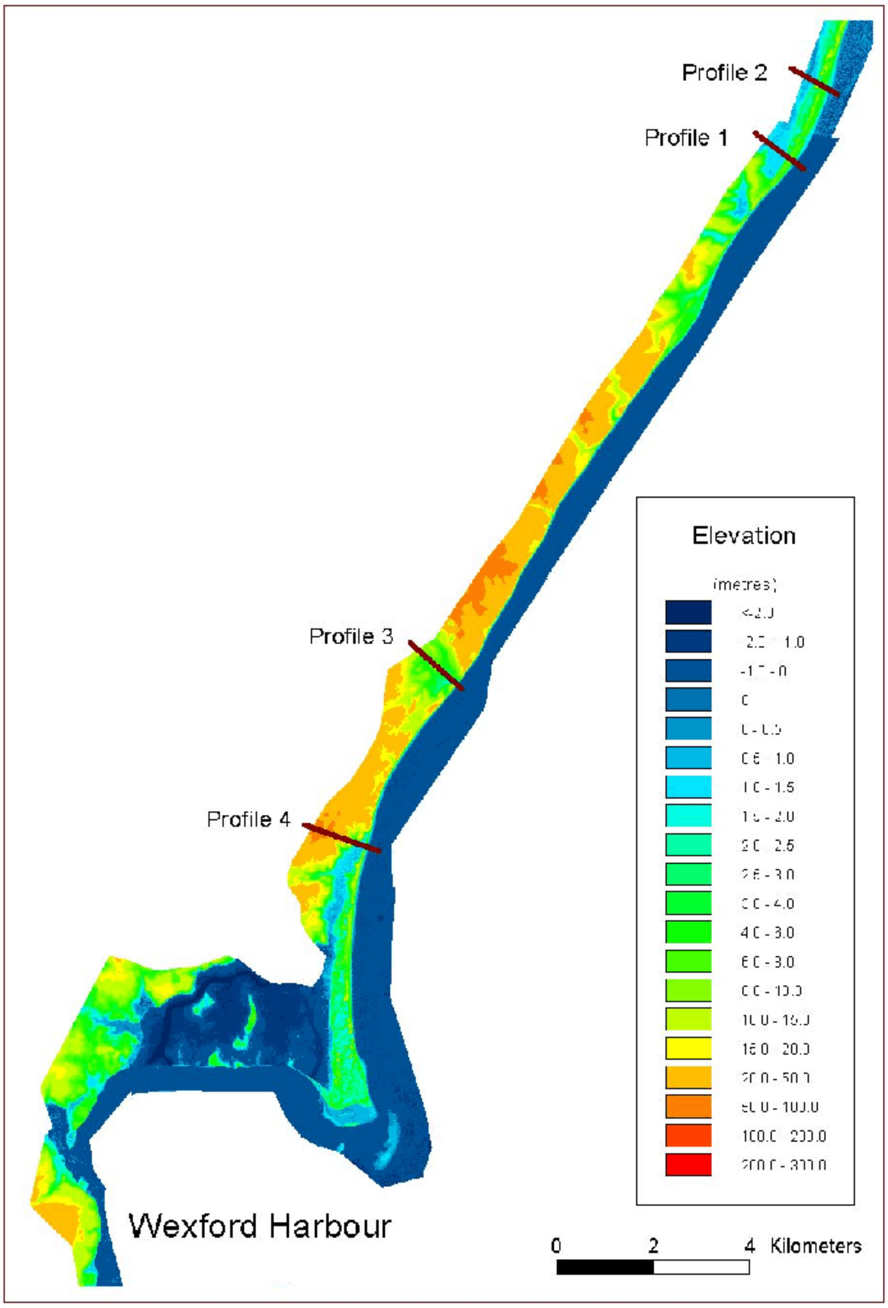

Figure 8.28. LiDAR data for a portion of the Wexford coastline with profile lines illustrated.

weakening of current natural coastal defences would occur due to an increased potential for waterlogging, both from an increase in sea level and precipitation. Regeneration and landward migration of the dune systems may initially be hampered due to removal of material to off-shore banks, but would act to reduce shoreline recession in the long-term (Devoy, 2003).

There are many advantages to using high performance LiDAR data for coastal studies of this nature. Rapid acquisition of data providing a real-time potential to end users and its ability to accurately determine elevation, both of the earth's surface and of the vegetation canopy, recommend this data source as one of high value to any assessment of coastal change as a consequence of sea level rise.

The two case studies illustrate the need for and utility of high-quality elevation data. It is evident that national estimates are difficult to scale down to a local level, while

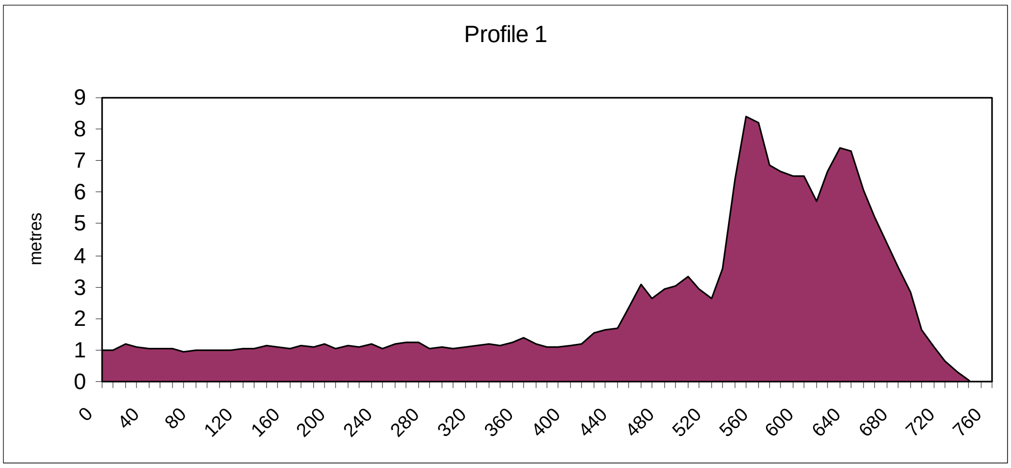

Figure 8.29. Profile 1 extracted from LiDAR data displayed in Fig. 8.28.

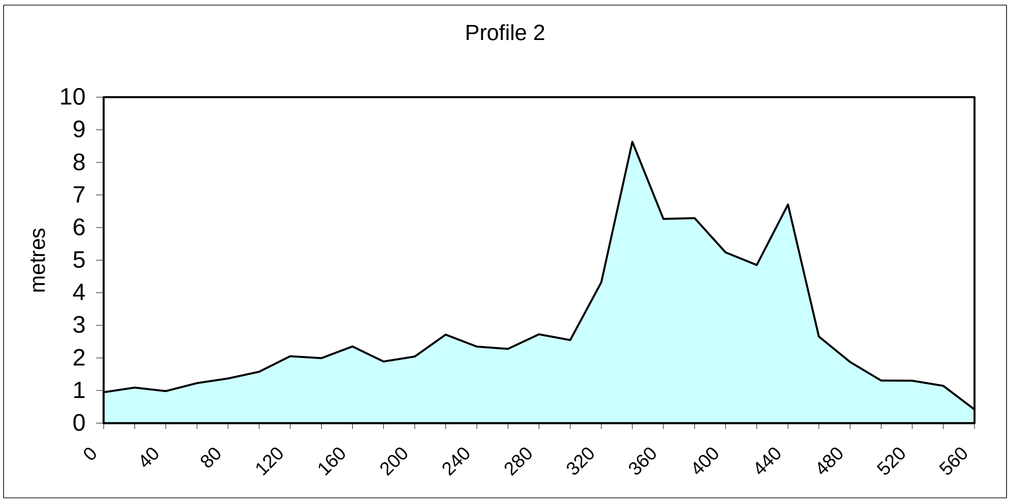

Figure 8.30. Profile 2 extracted from LiDAR data displayed in Fig. 8.28.

local scale studies of sea level rise are not readily scalable to a national level. Thus, there is a mismatch in scales which also needs to be addressed. Key sensitive areas as delineated by the national scale analysis can then be targeted for higher resolution data resolution and modelling using such techniques as described in this case study.

8.11 Conclusions

There is clear evidence from around the world that sea level rise is not just a perceived, but a very real threat. Submerging coral atolls, deltas and islands, increased erosion or deposition along nearly all coastlines, loss of ecologically valuable coastal wetlands and other coastal habitats, saltwater inundation, all demonstrate the fact that the impact of a sea level rise is a global one.

Current increases in global sea level can almost certainly be attributed to enhanced global warming. Melting of terrestrial glaciers, warming of deep oceanic water layers, an increase in global temperatures all point to the fact that the earth is warming at unprecedented rates. Output from Global Climate Models would appear to corroborate this.

Ireland is quite fortunate in that the effects of sea level rise on the coastline may not be felt as severely as in some other countries in Europe. Areas in the south of the

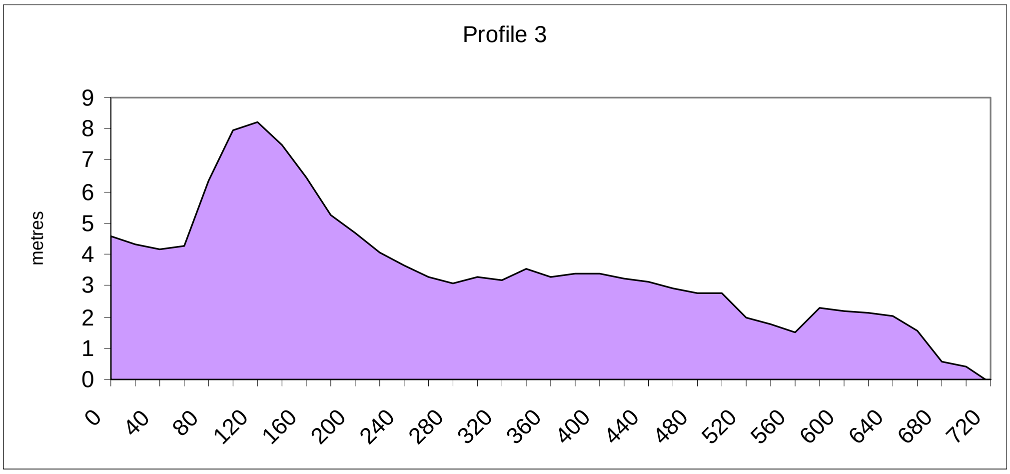

Figure 8.31. Profile 3 extracted from LiDAR data displayed in Fig. 8.28.

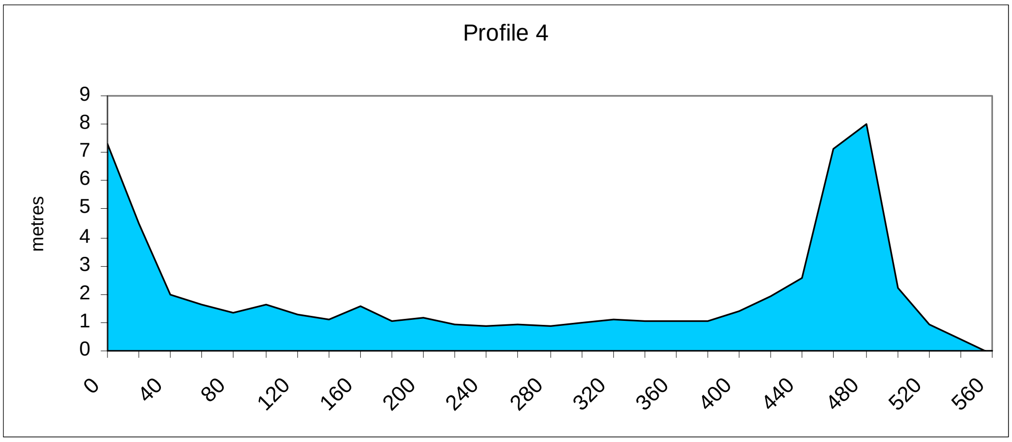

Figure 8.32. Profile 4 extracted from LiDAR data displayed in Fig. 8.28.

country are likely to feel the effects first, particularly low-lying coastal locations with little or no natural protection and located on 'soft' or easily eroded material. Coastal floodplains are especially at risk on occasions when a high tide and storm surge couple with a period of intense rainfall lead to a breach in the carrying capacity of the drainage network, a situation in Ireland which has become evident over the last decade.

Sea level rise presents itself as a serious problem where there is infrastructure at risk of inundation. In Ireland, the impacts of sea level rise will be most apparent in the major cities of Cork, Limerick, Dublin and Galway. The inability of the shoreline to adjust naturally to a change in conditions in areas of dense infrastructure may enhance any impacts as the system tries to attain a new equilibrium between erosion, transportation and deposition. Leatherman (2001), in an assessment of the social and economic costs of sea level rise, sums up this conflict between human and natural systems as

"increasing populations and development are placing significant stresses on coastal resources; rising sea level is causing land loss, creating a collision course of social and sea level trends".

It must be stated that the medium value of 0.48 m used in this report for sea level rise is a conservative one. Thus, the results presented in this report cannot be used as a justification for complacency in regards to the impact of sea level rise in Ireland. There is an immediate requirement to put in place strategies that are consistent with assessing short- and long-term impacts of sea level rise both at the local and national level. Policy must not just address what the local implications of sea level rise impacts and responses are but how these may affect surrounding areas. This will require enlightened policy to assess any changes that occur in the context of a natural system that is trying to reach a new equilibrium due to a change in forcing mechanisms. In order to protect areas of importance along the coast, whether human or natural, this approach would require the abandonment of other areas of less importance. 'Hard' engineering of the coastline should be viewed as a last resort and only then if the benefits outweigh the loss of land. Evidence has shown that this type of engineering can have dramatic effects further along the coastline.

The recommendations outlined by Carter (1990b) (subject to one modification) remain a sensible approach to coastal management for sea level change:

- no new building or new development within 100 m of 'soft' shoreline (Carter (1990b) advocated a distance of 50 m)
- no further reclamation of estuary land
- no removal of sand dunes, beach sand or gravel
- all coastal defence measures to be assessed for environmental impact.

Where possible, the landward migration of coastal features, such as dunes and marshes should be facilitated. These features form an integral part of the coastal system, physically and ecologically, and provide protection against wave energy through dissipation.

8.12 Further Research

The complexity of the coastal system is only slowly being unravelled. Variations in wave energy, current velocity, sediment budget, erosion and deposition link local areas to global changes. In order to assess the large- and small-scale changes and impacts, these linkages require much more research. To facilitate this, there is an immediate requirement to collect more information to measure these changes and to incorporate new sources of information to provide a more comprehensive picture. The two case studies illustrate the need for and utility of high quality elevation data.

Human activities, whether at the global or local level, can no longer be viewed as purely passive. We are a part of and interact with our surrounding environment, socially, economically and physically. Thus, decisions made on either of these interactions can affect our physical environment. Nowhere is this relationship clearer than around our coasts. The coastal zone provides for domestic, economic and leisure activities and plays a vital role in the State in terms of tourism and other activities. It is of crucial importance that the coastal zone be given careful protection, especially in light of the predicted changes outlined in this report.

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9 Conclusions

9.1 Introduction

Natural and human systems show varying degrees of sensitivity to climate change. Some may be highly adaptive allowing new opportunities to be exploited while others may be incapable of responding and rendered vulnerable to destabilisation or destruction. In Ireland, several natural and human systems can expect to be particularly affected by anticipated changes in climate. These include water, air and soil resources, ecosystem functioning and biodiversity, agricultural and forestry activities, coastal environments, biophysical and health systems, and a variety of other areas of significance for economic well-being and quality of life.

Impacts in these areas would have major significance for secondary systems such as energy, recreation and tourism, cultural heritage, property values, insurance and environmental management and planning in its broadest sense. Climate change issues must be seen as a central concern in fostering future sustainable development in Ireland. The stakes are, therefore, high, implying a need to assess sensitivity in key sectors, identify vulnerable systems in Ireland and begin to address issues of mitigation and Ireland's contribution to international efforts in this area.

This report assesses the likely implications of climate change on several key strategic sectors in Ireland. From the results outlined, an analysis is provided of where further efforts are required to position Ireland better to cope with the threats and opportunities posed by what is likely to be the most important environmental issue of the 21st century.

9.2 The Observational Evidence and Future Climate Scenarios

Analysis of the Irish observational records indicates that significant changes in Irish climate are occurring (Sweeney *et al.*, 2002). An increase in annual temperature of 0.5°C occurred during the 20th century, with a marked period of rapid rise commencing in the last decade. Significant decreases in frost frequency and increases in 'hot' day frequencies are also occurring. At the same time, substantial increases in winter precipitation have occurred in north-western parts and decreased summer rainfall is apparent in the south-east. These are all changes which are compatible with predicted trends from Global Climate Models (GCMs), and lend credibility to these as tools for assessing the future impact of climate change.

Since global climate models are constructed using grid sizes inappropriate for detailed impact assessment, techniques of spatial downscaling have been developed. This study has employed a standard technique, statistical downscaling, to provide plausible climatic scenarios for Ireland to the end of the present century at a 10 km^2 spatial resolution. An extensive downscaling exercise was carried out on 250 stations for precipitation and 60 stations for temperature. This represents a much more spatially concentrated downscaling effort than is the norm for characterising an area the size of Ireland. Against this, it must be emphasised that only one GCM was used for this purpose and future work using multiple GCMs is considered desirable to determine the robustness of the results and also to enable more detailed analysis of extreme events.

Prior to deriving these downscaled scenarios, a detailed baseline climatology for the island as a whole was constructed at a resolution of 1 km^2 using the entire observational record for the period 1961–1990 provided by Met Éireann. The climate scenarios suggest that, by the middle of the present century, mean winter temperatures will have increased by approximately 1.5°C, bringing the mild conditions currently associated with the far south-west coast to almost all parts of the island. Commensurate changes in secondary parameters such as frost frequency and growing season can be expected. Summer temperature increases of approximately 2°C are suggested from the analysis, with the greatest increases away from south and west coasts.

Precipitation changes constitute the most significant conclusion of this study. These indicate increases during the winter months, predominantly in the north-west, of over 10%. Of greater importance, however, are projected decreases of approximately 25% in amounts of summer receipts. Geographically, these are most significant in the south-east where decreases of summer rainfall amounts in excess of 40% are anticipated over the next five decades. Coupled with increased evaporation amounts, such changes would significantly impact on a number of key sectors.

9.3 Sectoral Impacts

9.3.1 Agriculture

The agricultural sector accounts for over 5% of Irish gross domestic product. Changes in the viability of crop or animal production as a result of future climate change are thus of considerable strategic importance. However, the interactions between agriculture and climate are complex and multifaceted. Atmospheric carbon dioxide concentrations generally provide a stimulus to crop growth, while the ensuing climate changes may have a contrary effect. Adaptive farm management practices may considerably mitigate negative climate impacts, while macroscale considerations such as regional/EU policies provide an economic environment which may outweigh the importance to the farmer of local yield changes. Changes in the viability of pests and diseases also require consideration. Crop productivity changes were a primary focus of the study. Farm management issues were also considered. Further work on the latter is, however, required to provide a clearer picture of agricultural impacts in Ireland.

The climate scenarios derived from the downscaling exercise were used as input to a number of crop growth and soil models to ascertain how they performed under changed conditions. Grass, maize, barley, potato and soybean were selected as representative of present or potential future crops which might indicate how climate change would impact on Irish agriculture. Though significant changes in the crops grown and their yields will occur, no catastrophic effects on Irish agriculture are envisaged over the next century. Geographical changes in agriculture are, however, likely to occur.

The results suggested that barley would remain a viable crop, particularly where summer precipitation changes are less pronounced. By 2075, the crop will be harvested on average 3 weeks earlier than at present. It will however be displaced in large parts of Ireland by maize, which will show significant yield increases, particularly on the grey-brown podzolic soils with their good water-holding capacity. High-energy fodder and grain maize yields will render this a valuable crop, particularly in the wetter western parts where grain yield increases of more than 150% of today’s national average values may be expected. As the climate warms further and summers become drier, soybean will become favoured and, although yields will remain quite low, they may still out-perform those of potential competitors further south in Europe. An extension of soybean cultivation westwards and northwards will occur with time at the expense of other cereals. The principal casualty of climate change is likely to be the potato which will suffer increasing water stress during the summer months. Its value as a commercial crop is likely to depend on irrigation requirements being satisfied, as happens under present climatic conditions in many areas.

Livestock farming may be strongly influenced by changes in grass productivity, especially in the south-east and east of Ireland. Stocking rates will increase in the west where turnout dates will also be earlier than at present. However, early turnout dates may not be realisable on heavier wetter soils in some parts and increased difficulties with slurry storage and spreading may also occur in these areas. In contrast, the current average losses of grass production experienced in the extreme south-east due to soil moisture deficits are likely to be experienced extensively east of the Shannon.

Clearly, irrigation demand from Irish agriculture is likely to increase substantially in the years ahead. At present, with respect to dairy farming, this is only financially justified in the extreme south-east if water is available free of charge. If, however, Irish farmers have to construct storage reservoirs and/or compete with other water users for a shrinking water resource, the economics of agriculture may change significantly in some areas, and considerable strategic policy implications may arise.

9.3.2 Water resources

The Dublin Statement, agreed at the International Conference on Water and the Environment in 1992, advocated that water should be used in a sustainable manner to ensure that neither the quantity not the quality of available resources should be degraded. Climate change, acting in conjunction with present demand trends, threatens the attainment of both these objectives in Ireland.

Water resource changes were investigated using the climatic scenarios to drive a hydrological model at a grid scale of 10 km^2. Soil textural characteristics, land cover, groundwater and channel hydraulic parameters were also incorporated into the model which was validated over six catchments: the Feale, Suir, Slaney, Upper Shannon, Brosna and Bonet.

Significant effective runoff changes are projected for the mid-century. A marked reduction in annual runoff is projected in the east and south-east, with a slight increase annually being projected for a relatively small area of the west and north-west. This is principally as a result of increased winter flows and increases in flood frequencies during winter may also be expected in the west and north-west. Seasonal flooding is likely to be more extensive than at present in these areas and also to persist longer into the spring. Further research is needed, however, to establish the magnitude and frequency of changes in extremes. What is clear is that all areas of Ireland will experience reduced river flows in summer over the next few decades. East of the Shannon, summer runoff reductions of approximately 30% are likely by the mid-century. Long-term deficits in soil moisture, in aquifer storage, and in lakes and reservoir levels are predicted to be likely consequences.

The most significant reductions in water availability are suggested as occurring in those parts of Ireland currently experiencing most rapid urban and industrial-led growth in demand. These parts are also likely to be the areas generating a significant demand for irrigation water for agriculture in the future. While the augmentation of supplies through greater groundwater exploitation will be possible in some areas, and while inter-basin transfers will also be possible, very careful assessment of the hydrological impact of both these measures may be required.

Water quality management will also require greater conservatism. With increased frequency and duration of low flow events, the dilution of pollution will be less effective. Minimum flow constraints will require revision and incorporation into planning systems based on future, not past, river flow regimes. Aquifer protection will become more important also as increased risk of contamination from surface waters may occur.

9.3.3 Forestry

Forests cover 9% of the land area of Ireland. About half of the Irish forests are less than 25 years old and relatively free from the problems of pests and diseases which afflict many other European forests. Within the next quarter of a century, it is envisaged that forest cover will double in Ireland. It is thus crucial that future climate change considerations are built into the management and economics of this relatively long-run crop. Forecasting the productivity of Irish forests has to date taken only a limited account of likely future climate changes.

Individual components of likely climate change may exert significant influences on future forest productivity. Increased CO_2 levels can be expected to stimulate tree growth and improve their water use efficiency. Increased temperatures are of themselves likely to produce a rise in Yield Class, though phenological responses are in reality quite complex. Winter chilling thresholds exist for some species such as Sitka spruce, Norway spruce, ash, beech and sessile oak, and warmer winter temperatures may thus delay bud flushing on lowland areas. On upland areas, this is likely to be less important, and reductions in late spring frost damage will enable growth to commence earlier in the season at upland sites.

Up to 30% of the annual harvest in Ireland can comprise windthrown material and any future change in storminess is, therefore, important for forestry economics. Irish forests are often located in exposed, poorly drained locations and are, therefore, particularly susceptible to windthrow. However, further work is needed in this area before quantitative impact assessments can be made. This conclusion also applies to the influence of increased soil moisture deficits and summer drought for newly established plantations.

The projected climate changes may result in a range of secondary impacts on Irish forestry. These include increased nutrient mineralisation and changed incidence of pests and disease. Pests such as the green spruce aphid, the pine weevil, the great spruce bark beetle and the

European sawfly, and fungal infections such as honey fungus, fomes and *Phytophthora*, may pose an increasing threat to productivity, though quantifying this impact is difficult at present.

A more integrated approach to modelling forest response to climate change in Ireland is clearly needed. This should incorporate the sometimes divergent influences climate change is likely to have, and also consider alternative provenances and species (particularly of Douglas fir and western red cedar) which might offer improved productivity in Ireland's future climate.

9.3.4 Biodiversity

Ecosystems are dynamic entities constantly responding to pressures such as land-use change, human population change or the demands made on them for particular biomass resources. To this mix, the addition of climate change represents an external forcing factor capable of changing the internal organisation of ecosystems and the competitive balance between organisms. Climate also plays a central role in determining the spatial distribution and abundance of species.

A dearth of information and baseline monitoring seriously hampers the drawing of conclusions in this area. This extends from basic distributional information concerning species and habitats to experimental data on their likely response to changes in climate variables. However, some changes in Irish species are likely to occur where species are close to the limits of their distribution range. In the aquatic environment, Arctic and Boreal relicts such as the Arctic char, smelt and pollan as well as some copepod species are considered most vulnerable, while terrestrial species in a similar category might include the oyster plant and sandbowl snail. In contrast, species at their northern margin could be expected to extend their range. Among the winners might be cottonweed, glaucous shears moth, natterjack toad and the lesser horseshoe bat. Warming is also expected to benefit many insect species, especially butterflies, though this will also include insect pests and predatory insect species. Introduced species may also be favoured in some cases. Invasive plant species, such as montbretia, New Zealand willowherb and rhododendron, may become more of a problem while in the animal world the Budapest slug, the slow worm, the bank vole and the dragonfly colonist migrant hawker may increase in abundance.

Evidence from the Irish phenological gardens suggests that bud burst of trees is occurring earlier in spring and leaf fall later in autumn at some locations. Such growing season changes are indicative of increased warming, and can be expected to become more pronounced over the next few decades. This warming could also be expected to produce behavioural responses in several species and ecosystems. Increased generations of insects, greater winter survival rates of many invertebrates, earlier breeding of amphibians, changes in fish migration, hatching, development and spawning and changes in bird migration are just a few of the likely impacts of the projected climate changes.

Habitats of nature conservation importance in Ireland have been designated under Annex 1 of the Habitats and Species Directive (1992). Some of these are considered to be particularly vulnerable to climate change and may require particular attention. These include sand dunes, lowland calcareous grassland, active raised bogs, calcareous fens, bog woodlands and turloughs. Of these, extreme pressures already exist on some due to human activities and it is imperative that they be given particular attention. Most critical in this category are sand dunes and raised bog which are highly vulnerable to the climate changes projected. Loss of peatland in particular will lead to a substantial loss of stored carbon. Peatlands contain an estimated 5,000 t of carbon per hectare compared with 300 t per hectare for a mature broad-leaved forest (Feehan and O'Donovan, 1996).

Despite the suggested consequences detailed above, many unanswered questions remain concerning the impact of climate change on biodiversity. If these impacts are to be reliably anticipated it is essential that baseline ecological monitoring be expanded and that integrated long-term experiments and modelling exercises, based on a holistic ecosystem approach, be undertaken. Such a strategy should not, however, preclude the immediate implementation of appropriate protective measures where vulnerable habitats and species are involved.

9.3.5 Marine environment

The projected climate changes will exert a strong influence on the physical, biological and biogeochemical characteristics of the seas around Ireland, and of its littoral zone. The ecological structure and functioning of the marine environment will be affected by both positive and negative factors, and the capability of the marine environment to supply particular goods and services will be changed.

As with the terrestrial environment, projected climate change is likely to have impacts on species distribution and abundance. Changes in wave exposure, water temperature, inter-tidal zones, salinity and water quality are just a few of the variables that may be implicated in such impacts. To these must be added biological factors such as food supply, predators/competitors, disease and human influences. Complex interactions between all of these mean that a clear picture of impacts is difficult to discern. Some inter-tidal and sub-tidal species (such as kelp, barnacles and some species of starfish) may suffer from increases in irradiance during low tide or from warmer water temperatures close to the coast, while other more heat-demanding species (such as cuttlefish and the purple sea urchin) may extend their range. A number of fish species may also extend their range in response to warmer sea temperatures. These include mullet, bass, garfish, red mullet and red gurnard. Increased summer catches of tuna off the west coast are likely to indicate an extension of range, and such formerly scarce species may be joined by bonito and trigger fish. Warmer sea temperatures are also likely to encourage increased incidences of algal blooms.

Changes in sea level may result in significant losses of lagoon and estuarine habitat and coastal 'squeeze' may prevent migration inland of these habitats in many parts of Ireland. Estuaries may also be affected by decreased runoff, which may reduce flushing. This would allow increased penetration of predators and pathogens of shellfish into estuarial zones.

Approximately 60% of Irish wintering waterfowl use coastal habitats, mostly bays, lagoons, estuaries and polder lands (Marine Institute, 1999). Based on evidence from the UK, it seems likely that warmer winters will make it less essential for northern migrants to travel on to the extreme south-west. Ringed plover, knot, sanderling, dunlin, black-tailed godwit, bar-tailed godwit and redshank are among the species likely to be affected.

Exotic marine species will also establish permanent populations more easily under warmer conditions. To date most of these have been introduced via aquaculture and shipping, and this is likely to be the pattern in the future. Included among these might be: *Undaria pinnatifida* (a north-west Pacific kelp), *Mytilopsis leucophaeta* (an Indo–Pacific bivalve), *Eriocheir sinensis* (Chinese mitten crab) and *Tricellaria ornata* (a bryozoan). Some exotics already established will expand independently of climate change while others will benefit from it. Among the latter might be *Sargassum muticum* (a north-west Pacific algae) *Bonamia ostreae* (an eastern Pacific parasite of oysters), *Calyptraea chinensis* (a French snail), *Ficopomatus enigmaticus* (an Indo–Pacific tube worm), *Mytilicola orientalis* (a parasitic copepod introduced from France), *Dreissena polymorpha* (zebra mussel introduced from Britain) and *Styela clava* (Asian sea squirt). Though improved vigilance and sterilisation techniques for ship's ballast water may help limit the arrivals of exotic species, undoubtedly it will not eliminate them as climate conditions render Ireland a more congenial location for them.

Among the most vulnerable sectors of the marine economy is aquaculture. The potential for disruption as a result of climate change related aspects is considerable. Salmon production in Ireland is near the southern range of the species distribution and temperature increases, together with changes in the incidence of algal blooms, pests and diseases, may have considerable commercial impacts requiring further study.

9.3.6 Sea-level rise

Twenty-five per cent of the population of Ireland live in a coastal District Electoral Division and considerable investment in transportation and energy infrastructure has taken place within a few metres of the high water mark in many highly urbanised areas. Exposure of people and facilities to risk as a result of rising sea levels largely depends on their location and the protection offered to them by the make-up of the coast itself. Wave height is largely determined by fetch, the uninterrupted distance over which a wave-forming wind can travel. Off the west coast a 13-m wave may have a return period of about a year, while a similar height off the east coast would represent a once-in-25-year event. Sea-level change impacts, however, are also conditioned by the resistance offered and here the predominantly hard rock of the west coast contrasts greatly with the unconsolidated boulder clay coasts of Leinster.

Sea level at Dublin is currently rising by 0.23 mm per year. Further north, rates are slower due to more marked isostatic rebound, though even at Malin Head falling sea levels appear to have ceased at present. Globally, the best estimate for the end of the present century is just under 0.5 m, though uncertainty in many areas still persists. In any event, increased erosion of soft coastlines will occur in Ireland. Rates of recession for glacial till coasts typically are in the range of 0.2–0.5 m per year.

To assess areas at risk, a range of possible sea level change scenarios was employed in conjunction with a digital elevation model to project probabilities of inundation. A probabilistic approach was considered appropriate to capture errors in input data. The major cities of Dublin, Cork, Limerick and Galway were seen to be most vulnerable from an economic perspective, with the Shannon Estuary and the rias of the south and west coasts also at risk. A sea-level rise of 0.49 m combined with a storm surge of 2.6 m was seen to place approximately 300 km^2 of land in the greater than 50% probability of inundation category, mostly in these vulnerable areas. More definitive identification of areas at risk depends upon higher-quality height data sources and this was demonstrated in a case study of Wexford Harbour using LIDAR data. Such studies are needed to quantify exposure and address where remedial action may be required.

It was concluded that ‘hard’ engineering solutions to problems of sea-level rise in Ireland are inappropriate outside areas with high-value urban property or expensive infrastructure. A policy of planned retreat in some areas, combined with prohibitions on new developments in vulnerable coastal zones offers the best economic solution for most areas in Ireland. Where possible the landward migration of coastal features such as dunes and marshes should be facilitated since these features form an integral part of the coastal defence system. The complexity of the coastal system is, however, only slowly being appreciated and much research remains to be done into the interaction of physical and human systems which climate change is bringing into sharp focus in the coastal zone.

9.4 Policy Implications

9.4.1 The international arena

Many of the climate change impacts identified for Ireland will occur irrespective of policy decisions taken in Ireland or even Europe over the next few decades. Residence times for greenhouse gases are such that only small amounts of mitigation will be possible in the next few decades and cuts in emissions of up to 70% globally would be required to stabilise atmospheric greenhouse gases at twice the pre-industrial level. This does not mean that Ireland should not play its part in efforts to tackle the problem. As the world’s fifth largest emitter of greenhouse gases on a per-capita basis, Ireland has a responsibility to act in concert with its EU partners to ensure that unacceptable impacts are not bequeathed to future generations as a result of inaction in the early 21st century.

The National Climate Change Strategy recognises that in a business-as-usual scenario Ireland would exceed its 1990 emissions by 37% by the Kyoto compliance date, as opposed to the 13% permitted. Were the rest of the world to follow a similar trajectory, the impacts highlighted in this study would be felt almost immediately and be much more acute by mid-century than suggested. Although providing only a first pass at a number of intractable problems, this study clearly justifies the development and enforcement of mitigation policies at international level.

9.4.2 The domestic arena

Climate change considerations have not to date been central in the formulation and development of policy in Ireland. The impact scenarios described here imply that it is appropriate to review this from grass roots level upwards. Decisions about what crops to grow, what landscapes to protect, where to build transport corridors in coastal zones and, perhaps most importantly of all, where to build new residential areas, urgently require to be ‘climate change proofed’. Among the policies and programmes that require an explicit injection of a climate change dimension are:

- The National Spatial Strategy
- The National Development Plan
- Regional Strategic Planning Guidelines
- The Enforcement of EU Directives on Air and Water Quality, Habitats and Biodiversity, Nitrates and Environmental Impact Assessment.

Without seriously incorporating climate change impact assessment into policy, Ireland runs the risk of positioning itself badly to cope with its competitors on the international scale in the years ahead. It also runs the risk of bequeathing to future citizens a landscape and quality of life vastly inferior to what might have been the case if preventative measures had been put in place earlier. The guiding principles of 'no regrets' the 'precautionary principle' and 'inter-generational equity' are touchstones for policy development in this area.

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