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REVIEW ARTICLE

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A review of indicators of climate change for use in Ireland

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Abstract Impact indicators are systems/organisms, the vitality of which alters in response to changes in environmental condition. The indicators assessed in this review fall within the impact category of the driver-pressure-state-impact-response (DPSIR) framework. Instrumental records have shown unequivocal changes in climatic conditions over the past 30 years at a global level but impact indicators allow these changes to be monitored at a finer resolution. Our main aim was to review sets of indicators of climate change currently used in various countries and to make recommendations for their use in the Irish environment. We review a preliminary set of climate change impact indicators in five sectors: agriculture; plant and animal distribution patterns; phenology; palaeoecology and human health. Currently, the most effective impact indicators of climate change have proved to be phenological observations of tree developmental stages. The strongest factor limiting the use of indicators is the lack of long-term data sets from which a climatic signal can be extracted.

Keywords Climate change · Impact indicators · Global warming · Ireland

Introduction

It is now widely accepted that anthropogenically driven climate change is having a significant impact on the environment. The United Nations Framework Convention on Climate Change (1992) defined climate change as "a change of climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The third assessment report of the IPCC (2001) has confirmed that the global average surface temperature has increased by 0.6°C since the mid-nineteenth century and that the 1990s was the warmest decade, with 1998 being the warmest year, since instrumental records began. These changes have been attributed to an increasing concentration of greenhouse gases in the atmosphere, induced by human activity (IPCC 2001). Although the consensus is that climate is changing on a global scale, change on a regional or local scale is often more subtle and variable. Consequently, the search for, and identification of, clear and unambiguous indicators of the impact of global climate change at a regional or local level is of vital importance.

The OECD (1993) has identified a core set of 33 indicators of environmental performance based on the pressure-state-response (PSR) framework for use in the State of the Environment reports published by each of the EU member states. The OECD (1993) defines an indicator as "a parameter, or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value". Indicators therefore provide information about phenomena that are regarded as typical for, and/or critical to, environmental quality and they are used to simplify a complex reality (Smeets and Weterings 1999). While the primary purpose of indicators of climate change is to provide critical information regarding climatic conditions, they also serve as an early warning system by making available observational data that may point to an environmental problem which may be addressed before the situation deteriorates.

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Table 1 Criteria established by the OECD for indicator selection (OECD 1993)

Policy relevance and utility for users
A climate change indicator should
Provide a representative picture of climatic conditions
Be simple, show trends over time and be easily interpreted
Be responsive to change and relate to human activity
Be comparable internationally
Be national in scope or applicable to regional climatic issues
Have a reference value against which comparisons can be made so that users are able to assess the significance of the values associated with it
Analytical soundness
A climate change indicator should
Be theoretically well founded in technical and scientific terms
Be based on international standards
Lend itself to being linked to economic models, forecasting and information systems
Measurability
The data required to support the indicator should
Be readily available at a reasonable cost/benefit ratio
Be of high quality and well documented
Be updated regularly in accordance with reliable procedures

Materials and methods

Theoretical background to climate change indicators

According to the European Environment Agency (EEA) the most important criteria for indicator selection are data availability and policy relevance (EEA 1998). However, other criteria such as spatial representation, transparency, analytical soundness and measurability, and potential inclusion in integrated assessment tools must also be considered (Erhard et al. 2002). The OECD have established a list of criteria for indicator selection (Table 1; OECD 1993). Identifying a set of indicators which fulfil all of these criteria is challenging.

Establishing suitable indicators of climate change impact on the environment presents more challenges than measuring direct meteorological (state) indicators as the effects of climate change are complex and subject to large uncertainty. Whereas most developed countries have had accurate instrumental weather records for more than a century suitable biological data sets tend to be much more recent (Fraser and Smith 2002). One illustration of the difficulty in identifying suitable indicators that fulfil the criteria set out by the OECD was the experience in Wales where of the large number of climate change indicators originally considered by Buse et al. (2002), many were rejected because either a clear climate signal could not be recovered from the data or there were insufficient data available.

The driver-pressure-state-impact-response framework

Indicators are used by the EEA to assess the overall condition of the environment by means of the driver-pressure-state-impact-response (DPSIR) framework (Fig. 1). This causal framework describes the interactions between society and the environment and is an extension of the PSR model developed by the OECD to standardise the use of indicators of environmental performance. The PSR framework describes how human activity exerts pressure on the environment through, for example, the emission of greenhouse gases. Consequently, the state of the environment is altered resulting in a change in, for example, mean temperature or greenhouse gas concentration in the atmosphere. Response, in this case, describes societal response and not ecosystem response and may result in modifications to environmental policy, such as the introduction of taxes, in response to any changes. In addition, the EEA (1999) have extended the PSR framework to include indicators of the drivers of climate change such as consumption of fossil fuel and indicators of the Impact of climate change on ecosystems and human health. The result is the driver-pressure-state-impact-response framework (Fig. 1). Although environmental indicators can be identified for all sectors of the DPSIR framework, the indicators referred to in this paper are associated with the impact sector and their function is to quantify the impacts of climate change on the environment.

The perception and evaluation of impact indicators is of great importance because they will determine societal response to climate change and the effectiveness of this response will be reflected in the drivers of climate change, for example, a reduction in fossil fuel consumption. Another important role of impact indicators is through raising public awareness of environmental issues which can help strengthen public support for policy measures (Smeets and Weterings 1999).

Use of indicators of climate change in other countries

Indicators of the impact of climate change on the environment are important tools for providing information on environmental problems, for supporting policy development and for monitoring policy response (Smeets and Weterings 1999). They also indicate if targets are being met and highlight the need for additional measures. Indicators of climate change have been identified for a number of countries. Lists of indicators of climate change, including impact

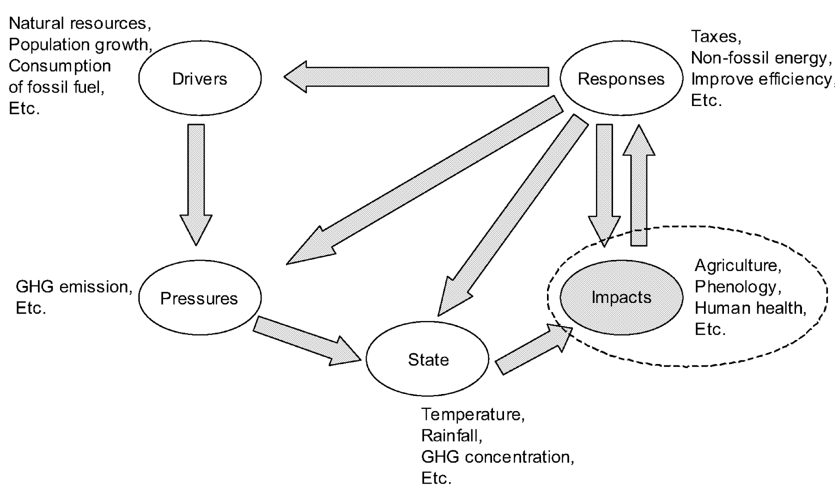

Fig. 1 The DPSIR framework for reporting on environmental change (OECD 1993; Buse et al. 2001) The indicators relevant to this review are concerned with the impact sector of the framework (*dashed line*). *GHG* greenhouse gas

Table 2 List of some indicators which have been suggested could detect climate change in the UK (Cannell et al. 1999), Wales (Buse et al. 2001), British Columbia, Canada (Fraser and Smith 2002) and Nordic countries (Norway, Sweden, Finland, Denmark, Iceland) (Brunvoll et al. 1999). *D* Driving force indicator; *P* pressure indicator; *S* state indicator; *Sp* proposed (but not yet in use) state indicators and *R* response indicator

UK	Wales	British Colombia, Canada	Nordic countries
Dry and wet soil conditions in southern England	Outdoor fires	Change in position of glacier terminus	Annual growth rate of forests (D)
River flows in NE and SW Britain	Heat and cold related mortality and morbidity	Extent of lake and river ice	Hydropower production (D)
Frequency of high and low river flows in NE and SW Britain	Clover flowering	Timing and volume of river-flow	Population size and distribution (D)
Groundwater storage in chalk in SE Britain	Cereal ear emergence	River temperature	Type and reserves of natural resources (D)
Sea level rise	Greenness	Salmon migration	Transport, roads and infrastructure (D)
Risk of tidal flooding in London	Date of insect appearance and activity	Sea level	Economic condition and production (D)
Atmospheric O_3 levels in summer in rural England	Butterfly monitoring scheme	Sea surface temperature	Housing and heating sources (D)
Domestic property insurance claims	Insect abundance	Salmon activity at sea	Energy production and trade (D)
Supply of gas to households	Arrival date of the swallow	Seabird survival	Production, use and trade of wood products (D)
Domestic holiday tourism	Egg-laying of birds	Change in the average annual growing degree days	Energy use (D)
Scottish skiing industry	Flowering time	Range of the mountain pine beetle	Emissions of NO_x (fertiliser) and CH_4 (livestock) (D)
Number of outdoor fires	Bodnaut laburnum	Heating and cooling requirements	Actual emissions of CO_2, CH_4, NO_x, other GHGs (P)
Incidence of lyme disease in humans	Snowdon lily	Human health	Adjusted emissions greenhouse gases (P)
Seasonal pattern of human mortality	Purple saxifrage	Health related illness	Atmospheric concentration of CO_2 (S)
Use of irrigation water for agriculture	Sea level	Respiratory illness	Atmospheric concentration of other GHG's (S)
Proportion of potato crop that is irrigated	Sea temperature	Water contamination	Radiative forcing (S)
Potato yields	Gulf stream	Water-borne disease	Melting of polar ice (Sp)
Warm-weather crops	Coastal water quality	Vector-borne disease	Melting of permafrost (Sp)
Grapes	Upland and lowland river flow	Water related accidents	Rise in ocean level (Sp)
Forage maize	Frogspawn		Decrease or increase of glaciers (Sp)
Late summer grass production			Change in precipitation patterns (Sp)
Date of leaf emergence of trees in spring			Frequency of extreme weather conditions (Sp)
Date of insect appearance and activity			Distribution or occurrence of selected species (Sp)
Insect abundance			Increase in the coniferous timber line (Sp)
Arrival date of the swallow			Change in strength and direction of ocean currents (Sp)
Egg-laying dates of birds			Keeping to goals and agreements (Kyoto) (R)
Small bird population changes			Environmental taxes on GHG emissions (R)
Marine plankton			Use of public transport (R)
Upstream migration of salmon			Alternative fuels and greater efficiency in transport (R)
Appearance of ice on lake Windermere			

indicators, have recently been published for the UK (Cannell et al. 1999), the Nordic countries (Norway, Sweden, Finland, Denmark and Iceland) (Brunvoll et al. 1999), Wales (Buse et al. 2001) and British Columbia, Canada (Fraser and Smith 2002) (Table 2). Many of the indicators listed in Table 2, are unique to a specific country or geographical region, but it is interesting to note that all assessments list phenological observations in one form or another as indicators of the impact of climate change on the environment. These indicators work by reflecting trends over time that can, at least in part, be attributed to changes in climatic characteristics. For example, the arrival date of migratory birds (UK), the flowering time of certain species (Wales), the timing of salmon migration (British Columbia) and the occurrence of selected species (Nordic countries) have been shown to change in relation to increased spring temperature at each location. Birds arrived earlier in the UK (Cannell et al. 1999) and certain species flowered earlier in Wales (Buse et al. 2001) when spring air temperatures were higher than the long-term average. In British Columbia, sockeye salmon migrated later (Fraser and Smith 2002) in the season when ocean temperature was high. This resulted in the salmon reaching their spawning grounds later in the season which can negatively impact on survival rates. The United States Environmental Protection Agency have recently produced a draft report on the environment documenting 181 indicators of environmental quality, although there was no mention of climate change impact indicators (USEPA 2003).

Our main purpose is to review indicators of the impact of climate change on the environment, which are currently in use in various countries and to make recommendations on their suitability for use in Ireland. Indicators relating to impacts of climate change on the economy such as changes in tourism, energy consumption, insurance claims, etc. have been omitted as it was impossible to identify a climate impact from the available data. However, because impacts on these sectors have been demonstrated elsewhere by Cannell et al. (1999), Brunvoll et al. (1999) and Fraser and Smith (2002) (Table 2) they have been included in the list of recommendations for Ireland (Table 4) as more research in this area could reveal suitable climate change indicators.

Results and discussion

Potential indicators of climate change in Ireland

The indicators have been grouped into five sectors: agriculture, plant and animal distribution patterns, phenology, palaeoecology and human health. In turn each sector is subdivided into various sub-groups as necessary. The indicators presented here are those which best fit the criteria proposed by the OECD outlined in Table 1 and from which a climate signal could be established.

Agriculture

It is difficult to isolate climate change effects on crop production and performance because factors such as changes in crop management, the introduction of new varieties, the fertilising effect of increasing concentrations of atmospheric CO_2 may have an overriding influence. In this section changes in farming practices and crop yields that may indicate changes in temperature and rainfall are examined.

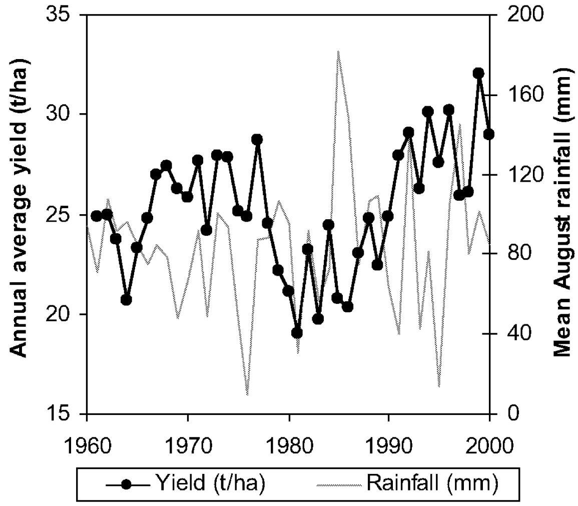

Fig. 2 Annual average potato yields (t/ha) in relation to mean August rainfall (mm). Data were taken from the Central Statistics Office Annual Reports

Crop yields

Grass. Most Irish agricultural production is grass based. Using both empirical data and model simulations, Jones and Jongen (1997) and Jones and Brereton (1992), predicted increased yields of agricultural grasses in Ireland as a result of increasing concentrations of atmospheric CO_2 coupled with increasing temperatures. They also pointed out that the interactions between water supply and other environmental variables such as temperature and CO_2 are complex and it is therefore difficult to predict future responses to climate changes. Nevertheless, it is likely that data on both early and late summer grass production have potential for use as indicators of climate change impacts in Ireland. According to Holden and Brereton (2003) model predictions for 2055 and 2075 suggest that both early and late harvesting of grass and other crops could become difficult due to increased winter precipitation which prevents the use of heavy machinery because of the risk of soil damage. They also show that grass yields will be lower than at present, mainly in the east of the country, due to drought. Results from a long-term grass experiment at Rothamsted (UK) have shown that in years when the summer temperatures are high and soil moisture is low a 1°C increase in July to August temperature can result in a loss of 0.33 ton per hectare (Sparks and Potts 1999). Conversely, if both rainfall and temperature increase, production could also increase. The time of the first silage cut was considered for inclusion in the Welsh list of indicators but was omitted as no climate signal was detected (Buse et al. 2001).

Potato. Potato is a shallow rooting plant with a high water requirement for sufficient tuber filling to occur. This makes it particularly vulnerable to drought stress. In England and Wales, potato yields are strongly correlated with August rainfall and they can be reduced by as much as 25% during dry summers (Lister and Subak 1999b). However, in Ireland there is a poor correlation (R^2=0.04) between main-crop potato yield and August rainfall (Fig. 2). Furthermore, it is likely to be difficult to identify a long-term trend in these data, as newly introduced varieties and improved crop management clearly help to increase yields and counteract the limitation imposed by lack of rainfall.

Use of irrigation in agriculture

Irrigation systems are not generally associated with Irish agricultural activity, as rainfall is not a limiting factor for most agricultural production. However, declining summer precipitation and increasing summer temperatures may give rise to soil moisture deficits which adversely affect the yield of crops such as potato. Consequently, during the past 6–8 years, possibly instigated by the 1995 drought, large sprinkler systems have been used in Ireland to irrigate the potato crop and an "experienced guess" would suggest that 15% of the total main-crop (i.e. not including early maturing varieties) is currently being irrigated (Burke, personal communication). Within the next 50 years, Holden and Brereton (2003) suggest that the potato crop will no-longer be commercially viable unless irrigation is widely used.

In the UK, nearly 50% of the potato-growing areas have provision for irrigation (Palutikof and Lister 1999). Irrigation has been introduced to potato-growing in England and Wales both because of consumer demand for a high quality product and the increased risk of summer drought (Palutikof and Lister 1999). Two indicators of the impact of climate change used in the UK are the percentage of the potato crop that is irrigated and the annual amount of water used in the irrigation of crops. However, in Wales the water required for irrigation was not considered to be a suitable indicator of climate change as the amount used was very small and the requirements changed with the crop type (Buse et al. 2001). In Ireland, we suggest that the percentage of the main crop that is irrigated and the amount of water used in irrigation systems are potential indicators of the impact of climate change.

Introduction of warm weather crops

In future, farming in Ireland may include expansion of the production area of warm weather crops such as maize and soybean. Forage maize has been grown in Ireland since the early 1990s and demand is expected to increase in order to supplement the declining amount of grass fodder for livestock. The introduction of maize is mainly attributed to the breeding of cold-tolerant strains that are able to survive our cool temperate climate and as a consequence the area under forage maize has increased steadily from 1992 to 2003 (Fig. 3). Maize yields in 1995, 1997 and 2000 were higher as a result of warmer summers and according to Lister and Subak (1999a) maize yields in

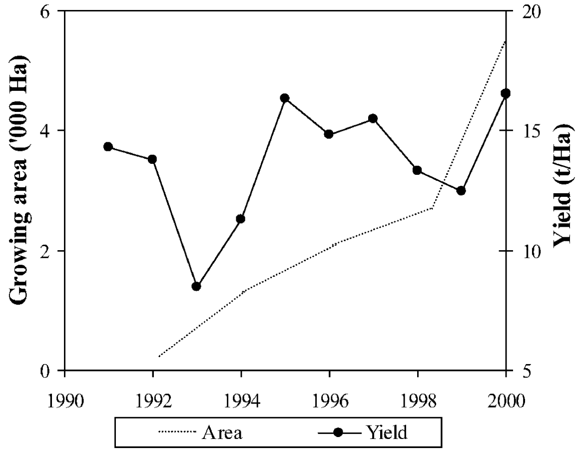

Fig. 3 Area and yield of forage maize in Ireland (data from Teagasc, Oak Park, Carlow). Note highest yields in 1995, 1997 and 2000

the UK will continue to increase as temperatures rise. However, if soil moisture is reduced the benefit of increased temperatures will be lost as the crop is not commercially valuable enough to justify the use of irrigation. In Ireland, the area under maize production is expected to expand and yields are expected to increase if temperatures increase and rainfall during the growing season does not fall below 400 mm (Holden and Brereton 2003). Both the area sown and yield could be used as indicators of the impact of climate change on this warm weather crop. Furthermore, Holden and Brereton (2003) suggest that in the longer term soybean could replace maize as a marginal crop if temperatures rise as predicted. Therefore it is proposed that soybean yields and area under production are used as climate change indicators for Ireland.

Cereal development

As phenological development of plants, and especially spring phenology, is strongly reliant on temperature (see below), any change in spring temperature would be expected to impact on the rate of crop development. Holden and Brereton (2003) predict an earlier harvest by up to 1 week for spring barley, maize and other crops. Consequently, changes in the timing of phenological stages such as terminal spikelet development, anthesis and final harvest in cereal crops (see Tottman and Broad 1987) could prove useful as impact indicators of climate change.

Plant and animal distribution patterns

An increase in temperature and/or a change in rainfall pattern could have important implications for the survival of plants and animals, particularly those living at the limits of their range. Some species may be expected to increase their range whereas others could become more restricted. In this section the possibility of using changes in distribution patterns of some plants and animals to indicate changes in climate are examined.

Plants

Ireland's native flora contains species of both arctic/alpine and Mediterranean origin (Webb et al. 1996) and changes in temperature and rainfall may be expected to impact on their distribution. We suggest that changes such as the reduced distribution and loss of arctic/alpine plant species and increase in the distribution of Mediterranean species as the climate warms should be monitored to assess their usefulness as impact indicators of climate change. Arctic/alpine plants such as *Dryas octopetala*, *Alchemilla alpina* and *Salix herbacea* currently have very restricted distribution patterns and given an increase in temperature it might be expected that their distribution and range would become further reduced. On the other hand, more Mediterranean species, such as *Euphorbia hyberna*, *Rubia peregrina* and *Saxifraga spathularis*, with a strong south-west distribution at present, may extend their range in a north-east direction across Ireland as temperature increases.

Insects

Because many species of butterfly in Ireland and Britain are at the limit of their European range they are very vulnerable to small changes in environmental conditions. As such, their distribution may be sensitive indicators of changes in climate (Asher et al. 2001). In recent years in the UK, the date of appearance of many butterflies has become earlier coupled with longer flight times (Roy and Sparks 2000). In Wales the timing of peak abundance of meadow brown butterfly is considered a good indicator of climate change (Buse et al. 2001). Currently in Britain, the date of appearance and abundance of aphids, the abundance and peak flight times of the orange tip butterfly and the abundance and timing of the activity of the common footman moth are all being used as indicators of climate change (Sparks and Woiwod 1999).

Birds

The East Coast Bird Reports for Ireland (Cooney and Madden 1980–1999) have shown that since the 1980s several bird species such as the little egret (*Egretta garzetta*), the pied flycatcher (*Ficedula hypoleuca*) and the goosander (*Mergus merganser*) that were not previously recorded in Ireland, are now found to be nesting here. The little egret, which is a Mediterranean species, has been nesting in Co. Cork since 1997. Consequently, sightings of arctic birds such as species of golden-eye (*Bucephala clangula*), eider (*Somateria mollissima*) and the black-throated diver (*Gavia arctica*) may be expected to decrease in warmer winters (Cooney, personal communication).

Salmon

There is strong evidence that the number of salmon returning to Irish rivers has been declining in recent years (McGinnity, personal communication). Initially it was thought that this resulted from a decline in the stock but when the data for the whole of Europe were examined it transpired that the number of salmon returning to rivers in Norway, and other Scandinavian countries was increasing. It has now been hypothesised that changes in water temperature are affecting the distribution of salmon in Europe, although other influences such as water pollution, fish farming and forestry practices may also be involved. Consequently, the upstream migration of salmon is used in both the UK (Georg 1999) and Canada (Fraser and Smith 2002) as an impact indicator of climate change.

Animal and plant phenology

Phenology is the study of the timing of recurring developmental stages in plants and animals such as the arrival date of migratory birds or the date of bud-burst on trees. Many of these developmental stages in the life cycle of plants and animals are triggered by environmental signals such as temperature and light. Consequently, any change in temperature could impact on the developmental stages of both plants and animals. We also know that the phenological stages of different species are often interdependent; e.g. insect abundance and chick survival in birds, and as a result, any disruption to this synchronisation brought about by climate change could impact on entire ecosystems. Changes in the phenology of plants and animals have increasingly been considered to be robust impact indicators of climate change in many countries (Cannell et al. 1999; Buse et al. 2001; Fraser and Smith 2002).

Bird phenology

Egg-laying dates of both migratory and resident birds can be used as an indicator of climate change. Spring temperature has a strong influence on egg-laying dates with higher temperatures resulting in earlier laying dates (Crick 1999) but unfortunately there are no long-term data available on egg-laying dates of birds in Ireland.

The arrival of the swallow (*Hirundo rustica*) is certainly an indication of the arrival of spring for many people in Ireland. The spring arrival of the swallow and other common birds such as the cuckoo (*Cuculus canorus*), the swift (*Apus apus*) and the house martin (*Delichon urbica*) are frequently recorded across Europe as they are easily identified (Sparks 1999a). Sparks (1999a), and Buse et al. (2001) have clearly shown that an

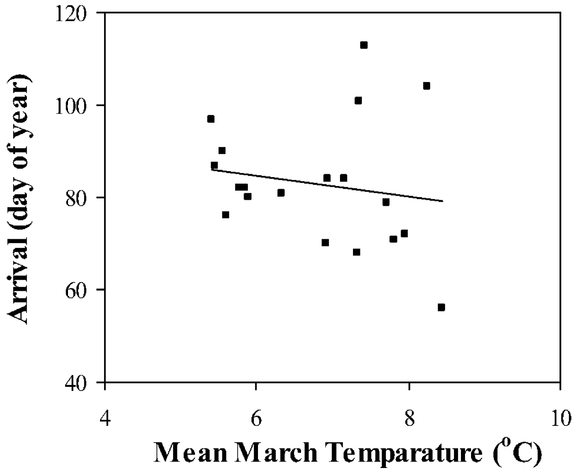

Fig. 4 Arrival date of the swallow to the east coast of Ireland and mean March temperatures. Data were taken from the Irish East Coast Bird Reports (Cooney and Madden 1980–1999)

earlier arrival of spring migrants in the UK in recent decades is strongly associated with higher temperatures. Many of these migratory birds are insectivorous and therefore they arrive when insect numbers increase and leave when their numbers decline (Sparks 1999a).

In Ireland the arrival dates of the swallow on the east coast has been recorded since 1980 (Cooney and Madden 1980–1999), providing a valuable data-set for monitoring the possible impact of climate change. When these arrival dates are plotted against mean March temperature, regression analysis shows that the data indicate a 2-day earlier arrival of the swallow for every 1°C increase in temperature (Fig. 4). This observation is similar to that made in the UK which shows that with a 1°C increase in temperature the arrival date of the swallow is expected to be 2–3 days earlier (Sparks and Loxton 1999).

Tree phenology

Spring phenophases in trees such as bud-burst, leaf unfolding and flowering are known to be strongly correlated with spring air temperatures (Sparks and Manning 2000; Sparks et al. 2000; Chmielewski and Rötzer 2001; Menzel 2000; Beaubien and Freeland 2000; Ahas 1999; Sparks 1999b). Also in autumn, cooler temperatures trigger leaf fall. Long-term phenological observations of trees, such as the dates of leaf unfolding, flowering, leaf discolouration and leaf fall, provide an historical record which may indicate how plants have responded to changes in climatic conditions. As growth is strongly influenced by climatic conditions, changes in growth rate, crown density and timber production are other possible indicators of climate change.

We have carried out an analysis of 31 years of phenological data (1970–2000) collected for four Irish sites located at Valentia Observatory, Co. Kerry, John F. Kennedy Arboretum, Co. Wexford, Johnstown Castle, Co. Wexford and the National Botanic Gardens in Dublin (Sweeney et al. 2002). The data have been collated by Met Éireann, and archived at the International Phenological Gardens (IPG) centre, at Humboldt Universität in Berlin. The IPG network was established in 1959 to collect phenological data from sites across Europe (Chmielewski and Rötzer 2001) and the Irish sites have formed part of this network. At the initiation of the project, vegetatively propagated trees and shrubs were planted at each site in order to assure genotypic uniformity. Here we have used data collected from lime (*Tilia cordata*), one of the species planted in Ireland, to establish the observed relationship between climate and phenology. Lime was chosen as it was present at all sites and had the longest data sets available. The phenological stages recorded for lime were the beginning of leaf unfolding (which is considered to be the beginning of the growing season, BGS) and leaf fall (which is considered to be the end of the growing season, EGS). The length of the growing season (LGS) is the number of days between BGS and EGS. Although the records were not continuous at all sites over the 31-year period sufficient data was available to establish trends over time (Fig. 5).

There was a strong positive correlation between LGS and the average annual temperature at all sites except Johnstown Castle (Table 3). BGS was negatively correlated with spring air temperature (average monthly temperature from February to April) at all sites (Table 3) and this suggests that if on average, spring temperatures increase by 1°C BGS will start 6 days earlier. Sparks (1999b) also reported a 6-day advancement in leafing of oak (*Quercus robur*) with an increase of 1°C in spring temperature in Surrey, England. There was no correlation

Table 3 Correlation between average air temperatures and LGS (days), BGS and EGS (day of year), at the four phenological gardens in Ireland. Significant correlations (P<0.05) in bold. Average values for LGS, BGS and EGS with corresponding standard errors for each data set. Regression slopes refer to changes over time and those printed in bold are significantly different from zero, *n.s.* not significant

	Valentia island	JFK Arboretum	Johnstown Castle	Botanic gardens
LGS vs annual air temperature	**0.47**	**0.32**	**–0.16**	**0.36**
BGS vs spring air temperature	**–0.58**	**–0.54**	**–0.37**	**–0.35**
EGS vs season air temperature	n.s.	n.s.	n.s.	n.s.
Length of growing season (LGS)	182±4.6	183±1.4	196±3.3	190±0.8
Regression slope	**3.49**	–0.32	0.99	0.47
Beginning of growing season (BGS)	108±1.9	116±1.2	108±2.1	126±0.9
Regression slope	**–0.85**	0.19	**–0.95**	–0.18
End of growing season (EGS)	286±2.9	302±1.4	302±2.3	316±0.5
Regression slope	**2.07**	–0.30	0.07	0.12

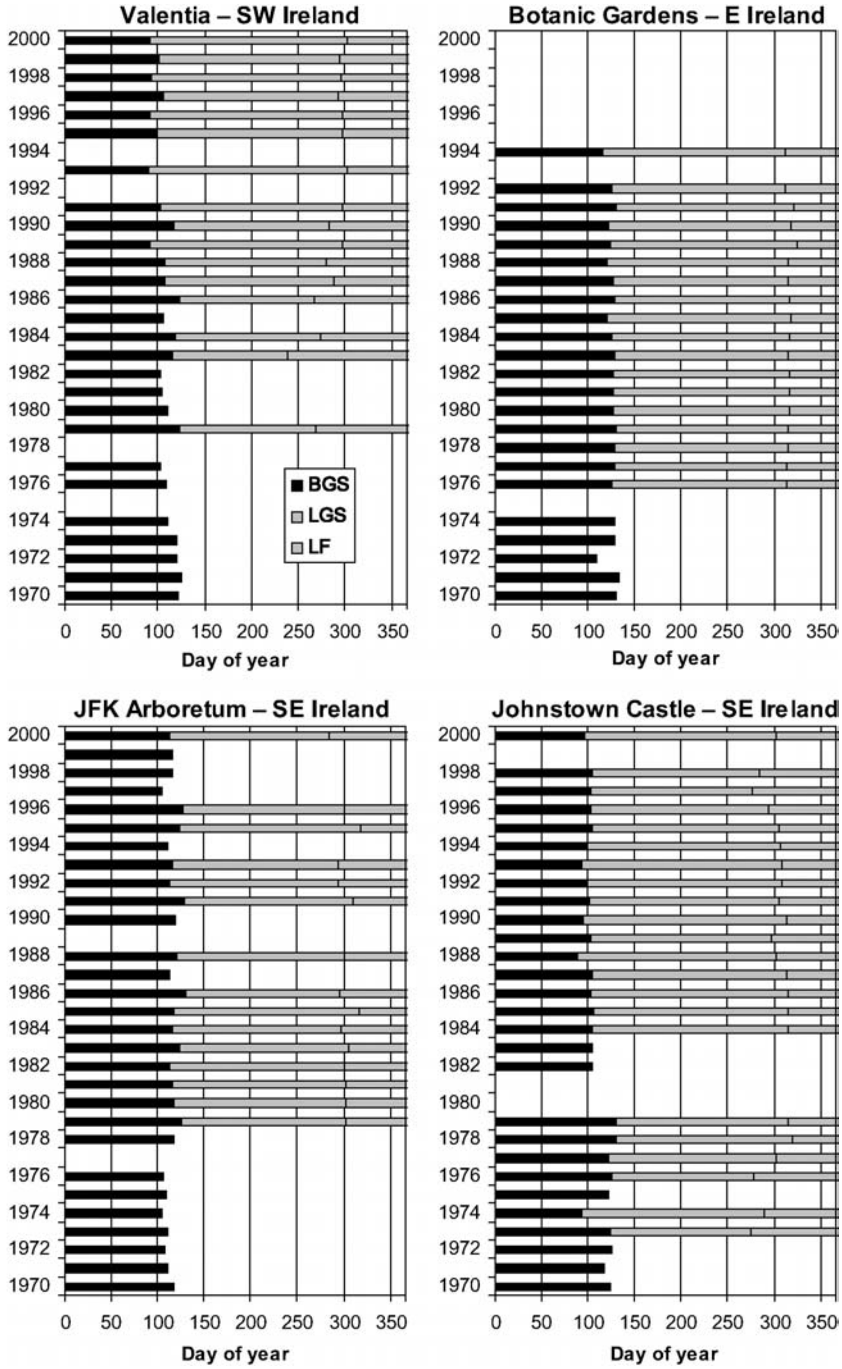

Fig. 5 Beginning of growing season (*BGS*), length of growing season (*LGS*) and end of growing season (*EGS*) for *Tilia cordata* at each of the four phenological gardens

between air temperature during the growing season and EGS at any of the sites.

When the trends of phenological phases over time were examined, only at Valentia was there evidence that the growing season became significantly longer (Fig. 5 and Table 3). The increase in LGS at Valentia since 1970 appears to be due to a combination of an earlier BGS and a later EGS. At Johnstown Castle, BGS occurred earlier but this had no effect on LGS. There was no significant variation in any of the phenological phases over time at the other two sites over the 31 years of observation. In conclusion, therefore, it is apparent that on the basis of observed changes in the timing of phenological phases of *Tilia cordata* at the Valentia and Johnstown Castle sites, a warming of the climate has occurred since 1970 but the absence of trends at the other sites suggests that they have experienced no significant change in climate over the same time period.

Palaeoecological records

The use of palaeoecological records to reconstruct past climates is well established and events such as the Little

Ice Age (1530–1700 in Britain, Lamb 1985) and the Medieval Warm Period (1150–1300 in Britain, Lamb 1985) can be identified in both pollen records and tree-ring analysis (Briffa et al. 1988a,b).

Bogs: pollen records

Cole and Mitchell (2003) carried out a palaeoecological study to investigate evidence for recent (over the last 1,200 years) climate change using peat cores collected from three bogs in Ireland: Liffey Head Bog, All Saint's Bog and Ballygisheen Bog. Regional pollen records reflected mass clearance of trees from the landscape, the introduction of agricultural and exotic species and the Great Famine (1840–1845). However, there was little evidence provided by the regional pollen record of changed climate during the time of the Medieval Warm Period or the Little Ice Age, in Britain. There was some evidence from local pollen records and fungal spores to suggest an increase in dry conditions in the twentieth century but this may simply reflect drainage of the bogs or peat cutting. Unfortunately, much of the palaeoecological record lacks the temporal resolution necessary to detect changes in climate over centuries or decades (Cole and Mitchell 2003). Also it is likely that anthropogenic influences, such as disturbance and drainage of the bogs, have dominated the regional pollen records in the past 1,200 years, and this probably renders it impossible to distinguish any recent climatic change.

Dendroclimatological data

It has been recognised for many years that annual tree-ring widths reflect current climatic conditions (Briffa et al. 1988a,b). The time-scale over which environmental change may be detected from changes in tree-ring width ranges from annual to millennial (Briffa et al. 1988a,b; Baillie and Brown 1995). Summer temperatures are the most important determinant of tree growth at mid to high latitudes; and as most models predict an increase in summer temperatures, growth responses may be expected. *Arbutus unedo* (strawberry tree) is a species that is living at the extreme of its European range in Ireland and analysis of its tree rings could reveal some indications of recent changes in climate. However, climate is not the only factor affecting tree-ring widths. Growth of different trees in the same stand may be influenced to varying degrees by competition, soil conditions, micro-climate and genetic make-up (Briffa et al. 1988a,b). Consequently, isolating a climate signal can be difficult.

A tree-ring chronology for Irish oak has been extended back 7,000 years (Baillie and Brown 1995), and shows some notable downturns in growth relating to catastrophic environmental events (Baillie 1999). The authors concluded that any possible recent increases in temperature are not evident in the Irish oak chronology as the events have not been severe enough or of long enough duration.

Stalagmites and stalactites

Stalagmites and stalactites form, respectively, on the floors and roofs of caves, as seeping water deposits layers of calcite. These structures develop over thousands of years and provide a chronology of past temperatures recorded in the ratio of the oxygen isotopes ^{16}O:^{18}O contained in the calcite deposits (McDermott et al. 2001). In theory, it is possible to detect a fraction of a degree change in groundwater temperature reflected in the ^{18}O concentration of the calcite. For example, analysis of the calcite layers in stalagmites from Crag Cave in Co. Kerry revealed evidence of a sudden and abrupt 40-year-long cooling period that occurred about 8,200 years ago (McDermott et al. 2001). However, to date there have been no studies in Ireland of the recent calcite deposits to confirm whether or not recent climate change could be detected. Analysis of more recent speleothem deposits are currently underway and these may prove to be useful indicators of recent climate change (McDermott et al. 2001).

Human health

Climate change may affect human health directly through more frequent exposure to extreme weather events such as storms or floods or periods of very hot or cold weather. It has been shown in the UK that for every 1°C increase in January temperature, 30 fewer deaths each day are expected (Subak 1999b). Indirect effects may also occur through increased atmospheric pollutants or increased frequency of food and water-borne diseases (Fraser and Smith 2002). Instances of lyme disease (spread by ticks) have been positively correlated with higher summer temperatures in the UK, with a greater number being reported in south-western regions than in northern areas (Subak 1999a).

Another indicator of the impact of climate change on human health may be the increased incidences of skin cancers, on both the face and exposed limbs at higher summer temperatures. This is because, as the summer temperatures increase, more people will spend long periods out of doors exposing their skin to the sun and so increase the risk of contracting melanomas. Although an increase in the incidences of skin cancer may be used as an indicator of climate change on human health Buse et al. (2001), in their review for Wales, did not consider skin cancer or eye damage to be useful indicators because of the large effect of other variables on these conditions.

Recommendations for Ireland

Obviously many indicators proposed for the UK (Table 1) can be adopted for Ireland because of similarities in climatic and environmental condition. On the other hand, some of the indicators proposed for Canada and the Nordic countries, such as those relating to snow cover and glaciers, would obviously not be applicable to Ireland.

Table 4 Recommendations for the use of Impact indicators of climate change and their expected response to climate change, in Ireland

Proposed climate change indicator	Recommendation			Expected response to climate change
	Yes	Potential	No	
Agriculture				
First silage cut in spring		✓		Earlier silage may result from increased temperature. Water stress not likely in spring
Grass production in late summer		✓		Expect an increase or decrease depending on temperature and rainfall pattern
Potato yields		✓		Trend influenced more by husbandry than climate change. More data required
Use of irrigation in agriculture		✓		Increase in number of irrigation systems and water used is expected. More data required
Warm weather crop production and new varieties		✓		Increase in production and more varieties expected. More data required
Plant and animal distribution				
Changes in the range of plant species		✓		Expect range of key plant species to change. More analysis and data required
Change in distribution pattern of insect		✓		Increase in range and abundance expected. More data required
Bat hibernation and distribution activity			✓	Difficult to find trends at present, few data available. Expect increase in range
Bird distribution and range		✓		Expect gains of some species and losses of others. More data required
Salmon run		✓		A decrease in the upstream migration of salmon may be expected. More data required
Fish stocks		✓		An increase in warm-water fish and decrease in cold-water fish expected. More data
Phenology				
Phenological stages of agricultural crops	✓			Expect trends to be influenced by variations in temperature. More data required
Arrival date of migratory birds	✓			Earlier arrival trend expected to continue. More species and analysis required
Tree phenology				
Length of growing season	✓			Expect growing season length to continue to increase in future
Beginning of growing season	✓			Expect earlier start of growing season to continue in future
End of growing season	✓			Expect end of growing season to advance at a greater rate in future
Palaeoecology				
Dendroclimatological data		✓		Not detectable at present. Key species could reveal an increasing trend in future
Pollen records			✓	Recent climate change not detectable as too great an influence of disturbance
Peat humification analysis			✓	Recent climate change not detectable as recent deposits overestimate degree of wetness
Speleothem data		✓		No evidence to date. Current analyses could reveal trend in future
Human health				
Seasonal pattern of mortality		✓		No clear trend at present. More data required. Expect decrease in winter
Skin cancers		✓		Might expect an increase in a specifically outdoors population. No data at present
Economy				
Domestic holidays			✓	No clear trend evident. Trend influenced more by foreign travel
Changes in energy consumption		✓		Requires more analyses and data. Expect an increase in summer and decrease in winter
Insurance claims from storm damage		✓		Data not available at present. An increase in claims expected

Table 4 is a list of possible indicators of the impact of climate change on the Irish environment, based on the current review. These indicators are categorised into "yes", "potential" and "no" signifying (I) recommended for use (ii) has potential and (iii) not recommended. Indicators in the "potential" category could become recommended if more data is available or a stronger link to changes in climate is demonstrated in the future.

There is evidence to suggest that climate change could be inferred from both tree-ring analysis and speleothem deposits. Particular species of tree and suitable speleothem deposits that are sensitive to changes in climate need to be identified. However, it is unlikely that bog pollen records are sensitive enough to become a useful indicator of climate change impacts over the relevant time scales due primarily to the overwhelming influence of human activity.

Identifying suitable indicators of climate change impacts on aspects of human health is challenging due to the influence of factors other than climate acting upon these parameters and the lack of long-term records. However, indicators of climate change impacts on human health, such as seasonal mortality and morbidity have been successfully established in Wales (Buse et al. 2001) and England (Subak 1999b). Given the proven sensitivity of these indicators to climate change it is wholly possible to identify similar indicators for Ireland.

We suggest that the most reliable indicators of climate change are associated with the phenological responses of both plants and animals. This is primarily because of the availability of relatively long-term data sets (e.g. in excess of 30 years, for the IPG network) and the geographical spread of sites across the country. The use of phenological data as an indicator of climate change on the Irish environment could clearly be a sensitive tool. However, it should be recognised that these observations are site specific and extrapolation to larger areas is problematic. The results from lime suggest a spring warming at some sites (Valentia and Johnstown Castle) but not at others. From the information currently available we can conclude that the LGS has increased in Valentia over the last 31 years but there has been no change in either JFK Arboretum, Johnstown Castle or in Dublin. This variation between sites presumably indicates that the increase in temperature has not been uniform across the whole country.

This review has clearly shown the importance of phenological recording of both plant and animal behaviour to indicate the impact of climate change on the environment and consequently should be encouraged throughout the country. These simple observations can easily be recorded by school children and the general public if appropriate definitions of the different stages are made available. This could be an effective way of collecting data suitable for demonstrating the impact of climate change on the local environment. By encouraging people from the local community to get involved in recording, a greater awareness of the effect of global environmental problems on everyday life could also be demonstrated. The main disadvantage is that subjective observations are prone to observer error. However, these data once collected may be subjected to stringent “quality control” procedures to minimise this type of error. The data from the phenological gardens (IPG Network) have clearly highlighted the usefulness of the day to day observation of the natural environment to help quantify effects of anthropogenically driven changes to the climate.

This review has highlighted the complexity associated with identifying indicators of climate change which fulfil all the criteria established by the OECD. However, the indicators presented here form a comprehensive list of indicators of the impact of climate change on various aspects of the Irish environment. The primary use of these indicators is to illustrate how climate change is impacting on the environment at a local level. This will in turn, provide evidence to the policy makers by which they can judge the seriousness of the change and respond accordingly through implementation of environmental policy. Furthermore, the targets established by the policy can be examined through continued monitoring of the indicators.

Conclusions

Appropriate and sensitive indicators of the impact of climate change on the environment can provide an early warning mechanism of possible effects—both positive and negative. These indicators are required for effective policy development aimed at minimising these effects, primarily through reduced greenhouse gas emissions, the main driver of climate change. Effective indicators should provide the tools which measure progress in mitigating policies and/or adaptation measures taken by the policy makers. Although there appear to be numerous possibilities for indicators of the impact of climate change on the Irish environment this review has highlighted the difficulties involved in identifying an unambiguous set. The main problems relate to the absence of existing long-term data sets which can be extended into the future and from which trends can be observed. In addition, the overwhelming influence of factors other than climate change on particular indicator can reduce their significance and value. Currently, the most effective impact indicator of climate change in Ireland appears to be phenological observations on tree developmental stages. In future, it is hoped to add to this list of indicators as additional data and more data sets become available which will cover a wider range of environmental variables.

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