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Biology and Environment: Proceedings of the Royal Irish Academy,
Volume 110B, Number 1, June 2010, pp. 1-16 (Article)

Published by Royal Irish Academy

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CHANGING CLIMATE AND THE IRISH LANDSCAPE

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ABSTRACT

The impacts of current and future changes in climate have been investigated for Irish vegetation. Warming has been observed over the last two decades, with impacts that are also strongly influenced by natural oscillations of the surrounding ocean, seen as fluctuations in the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. Satellite observations show that vegetation greenness increases in warmer years, a feature mirrored by increases in net ecosystem production observed for a grassland and a plantation forest. An ensemble of general circulation model simulations of future climates indicate temperature rises over the twenty-first century ranging from 1°C to 7°C, depending on future scenarios of greenhouse gas emissions. Net primary production is simulated to increase under all scenarios, due to the positive impacts of rising temperature, a modest rise of precipitation and rising carbon dioxide concentrations. In an optimistic scenario of reducing future emissions, CO₂ concentration is simulated to flatten from about 2070, although temperatures continue to increase. Under this scenario Ireland could become a source of carbon, whereas under all other emission scenarios Ireland is a sink for carbon that may increase by up to three-fold over the twenty-first century. A likely and unavoidable impact of changing climate is the arrival of alien plant species, which may disrupt ecosystems and exert negative impacts on native biodiversity. Alien species arrive continually, with about 250 dated arrivals in the twentieth century. A simulation model indicates that this rate of alien arrival may increase by anything between two and ten times, dependent on the future climatic scenario, by 2050. Which alien species may become severely disruptive is, however, not known.

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Cite as follows:
Woodward, F.I.,
Quaife, T. and
Lomas, M.R. 2010
Changing climate
and the Irish
landscape. *Biology
and Environment:
Proceedings of
the Royal Irish
Academy* **110B**,
1–16. DOI: 10.3318/
BIOE.2010.110.1.1.

Received 24
September 2009.
Accepted 9
December 2009.
Published 27 April
2010.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC 2007a) identifies significant global warming over the last two decades and warns of further escalations of temperature and general changes in climate into the future, as there is no evidence of foreseeable reductions in greenhouse gas emissions, the drivers of this change. The IPCC analyses are clearest at the global and continental scales, as defined by the spatial resolution and operation of general circulation models (GCM). For smaller spatial scales, as exemplified by Ireland, these are at or even below the limits of GCM resolution. Identification of future climates at the kilometre scale, for example, can only be realised by various methods of secondary processing (Sweeney and Fealy 2002), perhaps based on current climate. Such downscaling is generally based on one particular GCM, although climate projections can differ significantly between different GCMs (IPCC 2007a). The Community Climate Change Consortium for Ireland (C4I, <http://www.c4i.ie>) provides the most recent simulations of a future climate for Ireland, with

suggested warming of 3°C to 4°C by 2100, with winters and autumns 15% to 25% wetter and summers 10% to 18% drier.

Twenty years of recent warming provides drivers of environmental change, at fine spatial scales, that can supply indicators and pointers of what the future may bring. Sea surface temperatures surrounding Ireland have shown strong warming, particularly since 1994 (Cannaby and Hüsrevoğlu 2009), but with long-term inherent oscillations of the ocean–climate system having strong impacts. Three key oscillations, the Atlantic Multidecadal Oscillation (AMO), the East Atlantic Pattern (EAP) and the North Atlantic Oscillation (NAO) have been shown to exert significant impacts on sea surface temperatures surrounding Ireland (Cannaby and Hüsrevoğlu 2009). It will be of interest to investigate their impacts on the Irish climate.

Jones *et al.* (2006) and Donnelly *et al.* (2006) have shown that the Irish growing season has been extending, particularly in spring, by the order of ten days per decade, with potential increases in vegetation productivity. This change has been driven by increases in temperature over

the last two decades. Increasing carbon dioxide concentrations are one of the drivers of climatic change that impact directly on plant growth. The widespread semi-natural grassland in Ireland has been shown to increase productivity in response to experimental CO₂ enrichment (Byrne and Jones 2002), although species differed in their responses, indicating the potential for changes in species composition and local diversity. By contrast, future warming is projected to have a strongly negative impact on large areas of Irish peatlands (Jones *et al.* 2006).

The differential response of grassland species in Ireland to changing CO₂ (Byrne and Jones 2002) is also likely to be the case in response to changes in climate. Such species-level changes in abundance are likely in all natural and semi-natural vegetation types. In extreme cases, such changes may lead to extinction. The IPCC (2007b) projects that, at the global scale, 20% to 30% of plant species so far assessed are increasingly likely to become extinct when the global temperature rises by more than 2°C to 3°C above the pre-industrial level. Such levels of extinction could also exert severe and negative impacts on vegetation production. However, model simulations by Woodward and Kelly (2008) showed that increasing concentrations of CO₂ may significantly reduce this risk, through enhancing plant Net Primary Production (NPP). However, they also suggest that this could be at a cost of an increasing spread of alien species. Milbau and Stout (2008) have created a database of alien plant species in Ireland. They estimate a total of 716 extant aliens, 369 of which are casual and 347 established in the Irish flora. The number of alien species (84%) is close to the number of native species (Jackson 2007). Significant levels of global scale travel will mean that humans will sample exotic floras and return a fraction to Irish soil. Changing climate and CO₂, alongside continued changes in land use and cover, are likely to enhance the survival and establishment of alien species in the Irish flora, with potentially large but unknown impacts on vegetation composition, diversity and productivity.

The continued changes in climate and atmospheric CO₂ concentration are key drivers of Irish vegetation in the future, through direct impacts on productivity and also on diversity. The current potential to address these issues will be investigated through four aspects of the Irish scene:

1. The impacts of ocean and atmosphere on the climate of the Irish landscape over the last 50 years, with associated satellite observations of vegetation;
2. In situ observations of carbon dioxide exchange by Irish grassland and plantation for-

est, in response to recent variations in annual weather;

3. Future projections of carbon exchange by Irish vegetation, in response to climate simulated by an ensemble of GCMs;
4. Potential climatic drivers of changes in alien plant species over the twentieth century and potential future changes.

Although the investigation will clearly not be all inclusive, it aims to show that although Ireland is small in spatial extent, it has and will have a wide range of climatic drivers and vegetation responses, illustrating issues of global relevance.

CLIMATE AND THE IRISH LANDSCAPE

The analysis of climatic controls on Irish waters by Cannaby and Hüsrevoğlu (2009) provides an elegant approach for investigating the controls of climate on land. This approach has been applied, with simplification, to changes in land temperature over the last 50 years (Fig. 1). Monthly climatic data are available at the European Climate and Assessment Dataset site, <http://eca.knmi.nl/indicesextremes/custom-querytimeseriesplots.php>. Air temperature has been variable, but the *c.* 1°C rise over the last 20 years is quite clear and is a feature of all the selected climate recording stations. Observations of soil temperatures, at three climate stations over Ireland indicate very similar trends (García-Suárez and Butler 2006).

The strongly oceanic climate of Ireland indicates that changes in the surrounding Atlantic Ocean will exert strong effects on land. The forcing of winter climate by the NAO is well established (Rodwell *et al.* 1999). The NAO is characterised by a varying strength of air flow and atmospheric pressure difference between Iceland and the Azores, particularly noticeable during winter. This pressure-driven oscillation is further influenced by other climatic oscillations in the Atlantic. The AMO is one such influence and has a long-term effect (Schlesinger and Ramankutty 1994; Dima and Lohmann 2007). The oscillation has a 70-year period that is probably driven by a complex of changes in the thermohaline circulation and the movement of sea ice in the North Atlantic (Dima and Lohmann 2007). The AMO modulates the NAO, as does another pattern of change—the EAP (Cannaby and Hüsrevoğlu 2009). The EAP is like the NAO, with a north-east to southeast pressure gradient over Western Europe but with a multidecadal variability (Cannaby and Hüsrevoğlu 2009).

Fig. 1—Observed (—) and modelled (---) annual temperature anomalies (T) for Ireland (based on meteorological stations at Armagh, Belmullet, Birr, Dublin, Johnstown, Mullinger and Valentia). The mean temperature for the period is 9.85°C. The model regression is: $T = -0.338 - 0.752 \times \text{AMO} + 0.237 \times \text{NAO} + 0.432 \times \text{NHT} + 1.399 \times \text{SST}$, $r^2 = 0.84$. Where AMO is Atlantic Multidecadal Oscillation (<http://www.cdc.noaa.gov/data/climateindices/List/>), NAO is the North Atlantic Oscillation (<http://www.cru.uea.ac.uk/cru/data/nao.htm>), NHT are the northern hemisphere temperature anomalies and SST sea surface temperature anomalies for the area 45°N to 60°N and 5°W to 20°W (<http://www.cru.uea.ac.uk/cru/data/temperature/>).

The different states and dynamics of the three Atlantic Oscillations lead to complex patterns through time, all of which influence Irish weather and climate. A simple analysis using multiple linear regression indicates that the variations and trends in Irish mean annual temperature anomalies (Fig. 1, from 1957 to 2007) are correlated with a number of external forcings: sea surface temperatures to the west of Ireland, the trend in northern hemisphere temperatures, the NAO and the AMO. In combination these different indices are able to predict observed changes in temperature. The trends in monthly temperatures (Fig. 2) also indicate a warming trend in each month but with wide variation and with summer and winter months showing the greatest rates of increase. Regression analysis indicates that the monthly rates of change are dominated by trends in the NAO and sea surface temperatures.

The pattern of annual precipitation anomalies (Fig. 3) indicates three periods of increase—1957 to 1967, 1978 to 1987 and 1992 to 2007—with marked annual variations. Changes in annual precipitation are not correlated with changes in temperature but are correlated with changes in atmospheric pressure and the EAP, which together provide a reasonable projection of the time series of precipitation. Periods of low pressure, in particular, are correlated with increases in precipitation at both the annual and monthly time scales.

The observed changes in temperature (Fig. 1) and precipitation (Fig. 3) are expected to impact on Irish vegetation. This expectation is realised in comparisons with observations of landscape greenness (Fig. 4), quantified by satellite observations of the Normalised Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR; Sellers *et al.* 1994; Los *et al.* 1994; http://www.neodc.rl.ac.uk/browse/neodc/avhrr_fasir). NDVI provides an indication of the quantity of healthy green vegetation on the Earth's surface. Fluctuations in NDVI are strongly correlated with changes in annual temperatures (Fig. 4), with greater vegetation greenness associated with higher temperatures. A comparison of monthly temperatures and NDVI values (Fig. 5) indicates that years with high NDVI (1983, 1989, 1990, 1995 and 1997) correspond with both warmer spring conditions in February and March and warmer summer months. The years of low NDVI (1986 and 1996) correspond with an opposing pattern of cool spring and summer months. There were no obvious correlations between NDVI and precipitation: in fact one of the driest years in the time series (1989) has a high value of vegetation NDVI. These satellite data also indicate that there will be an increase in vegetation greenness that will continue over a temperature range of 1.7°C.

Fig. 2—Linear decadal trends in monthly temperatures (T) (1957 to 2007): (—) temperature, (.....) Sea Surface Temperatures, (---) North Atlantic Oscillation. Model regression: $T = 0.071 + 0.385 \times \text{NAO} + 0.971 \times \text{SST}$, $r^2 = 0.8$.

Fig. 3—Observed (—) and modelled (---) annual precipitation anomalies (P) for Ireland. The mean annual precipitation is 1026mm. The model regression is : $P = -8.63 + 69.15 \times \text{EAP} - 504.47 \times \text{Pr}$, $r^2 = 0.53$, where EAP is the East Atlantic Pattern (time series from <http://www.cdc.noaa.gov/data/climateindices/List/>) and Pr are pressure anomalies for the Irish meteorological stations indicated in Fig. 1.

CARBON DIOXIDE EXCHANGE BY VEGETATION

Although satellites can record vegetation greenness, via the NDVI index, for example (Figs 4, 5), they can not directly record changes in carbon dioxide exchange by the processes of photosynthesis and respiration. Accurate observations of

the daily fluctuations in vegetation carbon dioxide exchange can be made by measuring rapid changes in CO_2 concentrations in eddies above relatively large areas of vegetation. These eddy flux sites have been established in Ireland at a grassland site (Carlow; Black *et al.* 2006) and in a Sitka spruce (*Picea sitchensis*) plantation (County Laois; Black *et al.* 2007). Although the period of

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Fig. 4—Trends in mean annual temperature (—), (from meteorological stations indicated in Figure 1) and the annual Normalised Difference Vegetation Index (NDVI, - - -), time series data from http://www.neodc.rl.ac.uk/browse/neodc/avhrr_fasir.

cut and harvested. The greater annual uptake rate in 2003 (Table 1) is due primarily to higher rates in the spring, with neither year differing in late summer and autumn. Spring enhancement of net uptake is also seen at the Sitka spruce site (Fig. 7), but for 2008. The wetter and lower radiation fluxes in summer of 2008 reduced rates of uptake compared to 2003.

The perpetually cloudy nature of the climates at the two sites will influence the incoming solar radiation. The responses of grassland (Fig. 8) and forest (Fig. 9) NEP indicate a very wide range of responses to daily photosynthetically active radiation (PAR) in 2003. Days that were essentially cloud-free have been determined by comparing the recorded daily totals of PAR with estimates using a model of clear sky conditions for the sites, using equations presented in Jones (1992). Some clear sky days were identified by this method in 2003 but no such days were identified in 2008.

Table 1—Climatic characteristics of a grassland site (52.9°N, 6.9°W) and a forested (*Picea sitchensis*; 52.95°N, 7.25°W) site in two years.

	Grassland		Forest	
	2003	2008	2003	2008
Air temperature °C	10.09	9.61	9.07	10.08
PAR mol m ⁻² yr ⁻¹	6211	5135	6277	5136
Precipitation mm yr ⁻¹	974	835	966	957
Rain days	230	209	245	234
NEP gC m ⁻² yr ⁻¹	239	151	699	735

PAR = photosynthetically active radiation.

NEP = net ecosystem productivity.

The fitted response curve of NEP to PAR on clear sky days (Figs 8 and 9) indicates that there were many days when NEP was higher during cloudy conditions at the same incoming irradiance. This is accounted for by the enhanced photosynthetic efficiency of diffuse radiation in vegetation canopies (Gu *et al.* 1999; Black *et al.* 2006), where diffuse radiation may penetrate deeply into the canopy, unlike direct radiation, which is very quickly intercepted and absorbed by leaves. Days of low or negative NEP occur primarily during the winter period of the year but may also reflect negative impacts of water logging on vegetation productivity.

The remarkably cloudy nature of Irish weather does not generally lead to reduced photosynthetic effectiveness by vegetation canopies, while warmer conditions enhance NEP. The two years selected for investigation indicate that net carbon fixation by Irish vegetation will be stimulated by increased temperatures of at least +1°C, in spite of decreases in PAR receipt due to increases in cloudiness.

FUTURE PROJECTIONS FOR IRISH VEGETATION

Annual observations of net carbon exchange by grassland and forest in Ireland (Table 1) indicate that in this generally wet climate, warming should have a positive impact on carbon fluxes into vegetation and soil. A future of increased carbon dioxide and higher temperatures should therefore lead to increased productivity by Irish vegetation. Semi-natural grassland, typical of much of Ireland, certainly shows positive stimulations of growth with CO₂ enrichment (Byrne

Fig. 6—Net Ecosystem Productivity (NEP) for grassland in 2003 (—) and 2008 (---).

Fig. 7—Net Ecosystem Productivity (NEP) for Sitka spruce plantation forest in 2003 (—) and 2008 (---).

Fig. 8—Net Ecosystem Productivity for grassland in 2003 in relation to photosynthetic active radiation (PAR). ●, days of clear sky, ○, cloudy days. Linear regression for clear days, $NEP = 0.146 \times PAR - 1.151$, $r^2 = 0.85$.

and Jones 2002), enhanced by the addition of fertiliser. Simulating the future responses of Irish vegetation to changes in climate and CO_2 will be investigated with the Sheffield Dynamic Global Vegetation Model (SDGVM; Woodward and Lomas 2004). The model is configured (Sitch *et al.* 2008) to be initialised with a Global Land Cover map of the Earth's surface (GLC2000, Bartholomé and Belward 2005; <http://bioval.jrc.ec.europa.eu/products/glc2000/products.php>). This allows a more accurate representation of the vegetative cover of a landscape than when modelling with potential vegetation, as generally used

in other Dynamic Global Vegetation Models. Quaife *et al.* (2008) showed that the GLC2000 facilitated more accurate carbon flux estimates from the SDGVM than other comparable satellite derived land cover data sets.

The carbon exchange of Irish vegetation was simulated to the year 2100 using a suite of climate scenarios from five different General Circulation Models (HadCM3, ECHam4, PCM, CGCM2, CSIRO2), with details on each GCM available at the following IPCC web site (http://www.ipcc-data.org/sres/gcm_data.html). A range of GCM outputs are used because the models can

Fig. 9—Net Ecosystem Productivity for Sitka spruce forest in 2003 in relation to photosynthetic active radiation (PAR). ●, days of clear sky, ○, cloudy days. Regression for clear days, $NEP = -3.02 + 1/(0.0907 + 1.638 / PAR)$, $r^2 = 0.73$.

differ quite substantially and there is no obvious best model of choice (IPCC 2007a). In addition each GCM has been run with four different future emission scenarios (SRES, Special report on Emissions Scenarios) produced by the IPCC for the Third Assessment Report (<http://sedac.ciesin.columbia.edu/ddc/sres/>). The four different potential emission scenarios are:

1. A1, a world of rapid economic growth, with the global population peaking in mid-century but with cleaner technologies developing;
2. A2, with a continual increase in global population;
3. B1 the same population growth as A1 but greater use of clean technologies;
4. B2 with an increasing global population, but less than A2, and with local solutions to environmental issues. Of closer relevance to simulating the land carbon budget are the trends in atmospheric CO_2 that have been simulated for the four SRES scenarios (Fig. 10).

The A1 and A2 scenarios show the most rapid increases in CO_2 , while the B1 scenario shows a slight decline in CO_2 concentration by 2100.

The different GCMs also differ significantly in their simulated trends in temperature (Fig. 11). ECHam4 simulates the greatest temperature changes, from a 7°C temperature rise between 2000 and 2100 under the A1 scenario to a 2.5°C rise for the B2 scenario. The other GCMs show closer agreement in the global mean changes in temperature, ranging from 2.5°C from 2000 to

2100 for the A1 scenario to 1.5°C for the B2 scenario. The simulations for precipitation are not shown, but when averaged, all cases show a small linear increase from 0.7mm yr⁻¹ for the B1 case to 0.98mm yr⁻¹ for the A1 case.

The underlying map of land cover is defined at the 0.5° resolution (Fig. 12). GLC2000 classifies Irish vegetation as dominated by grassland with small fractions of deciduous broadleaf woodland and crops. Evergreen needle-leaf trees are rather more frequent in the west of Ireland and indicate significant planting of the exotic coniferous species, Sitka spruce. The GCL 2000 map of Ireland is very coarse, with only four types of vegetation cover: grassland, covering 89% of Ireland; evergreen trees, 4%; deciduous broadleaf trees, 1.7%; and crops, 2%. These proportions are similar to those described by Cruickshank *et al.* (2000), using the finer scale of mapping resolution provided by the CORINE land-cover mapping of Ireland. The GCL 2000 category of grassland includes a number of different land cover types in CORINE, including grasslands, pasture, moors and heathland, sparse vegetation and peat bogs. Peat bogs cover about 12% of Ireland (Cruickshank *et al.* 2000) with relatively small amounts of carbon stored in the vegetation. However, carbon stored in peat is very substantial and estimated at about 1233Mt C (Cruickshank *et al.* 1998; Tomlinson 2005) for Ireland. The fate of this carbon is not modelled in these simulations but presents a serious potential source of carbon to the atmosphere should future

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Fig. 10—Time series of atmospheric carbon dioxide concentration for four SRES emission scenarios.

Fig. 11—Simulations of mean annual temperatures for Ireland for four SRES scenarios and produced by five different GCM scenarios.

Fig. 12—Land cover (%) of four functional vegetation types in Ireland (from GLC2000).

warming, for example, lead to drying out of the peat surface and a drop in the water table (Ise *et al.* 2008).

The simulated map of NPP shows a relatively uniform pattern across Ireland at 500gC to $700\text{gC m}^{-2}\text{ yr}^{-1}$, averaged for the period from 1991 to 2000 (Fig. 13). These values are in line with NPP calculated at around $700\text{gC m}^{-2}\text{ yr}^{-1}$ for relatively old-growth Sitka spruce plantation (Black *et al.* 2009). This is expected as SDGVM does not account for the timing of planting for plantation forest and assumes mature forest. Gilmanov *et al.* (2007) indicate NPP for Czech and German grasslands at between 600gC and $700\text{gC m}^{-2}\text{ yr}^{-1}$, similar to those simulated (Fig. 13). For the Irish landscape as a whole (Fig. 14), NPP is stimulated up to the end of the century, with climate from the ECHam4 GCM leading to the largest increases in NPP for the A1 and B1 scenarios, similar to the CSIRO2 simulations for the A2 and B2 scenarios. It is notable that NPP saturates from about 2050 in all of the B1 scenarios, indicating a direct response to a levelling of the CO_2 trend (Fig. 10). Nitrogen supply constrains productivity in many ecosystems (LeBauer and Treseder 2008), and this is also expected for Irish ecosystems. However, the trends in NPP simulated by SDGVM (Fig. 14) account for the

supply and uptake of nitrogen from the soil and so the trends in NPP are smaller than would be the case without nitrogen limitation. Changes in the deposition of pollutant nitrogen into the future are not considered but would be expected to stimulate productivity.

NPP is that production by vegetation, above and below ground that is immediately available for harvest. Over any period of time, loss of plant

Fig. 13—Simulation of vegetation Net Primary Production averaged over the period from 1991 to 2000.

material by decay removes available NPP and after the conversion back to released CO_2 reduces the vegetation's sink capacity. Over the current century there will be a growing interest in the sink capacity of vegetation (Woodward and Lomas 2004), and so it is crucial in these terms to consider the whole carbon budget of vegetation, which is defined as Net Biome Production (NBP). NBP is NEP less losses through fire and other biomass removal, such as crop harvesting, but is essentially equal to NEP for the twentieth century. This assumption of equality may be in error if losses of dissolved inorganic and organic carbon (which are rarely measured) are significant, reducing NBP (Siemens 2003). At the end of the twentieth century, SDGVM predicts relatively little change in vegetation and so NBP is small, in the range of 5gC to $30\text{gC m}^{-2} \text{yr}^{-1}$, which is in the lowest 20% of observations for European grasslands (Gilmanov *et al.* 2007) and rather closer to blanket bog (Sottocornola and Kiely 2005).

The large future changes in temperature and CO_2 , associated with more modest changes in precipitation, are expected to significantly impact on carbon fluxes by vegetation and therefore NBP is also expected to change. Simulations of NBP for Ireland are shown and averaged for 2091

to 2100 and for the four SRES scenarios (Fig. 15). The four SRES scenarios and the five GCM simulations are shown to provide an indication of the simulated range of future NBP over Ireland. No particular scenario is of necessity any better than any other, and providing an average result is not instructive. Areas of positive NBP indicate that the joint stimulation of NPP by CO_2 and temperature stimulation exceed the losses of carbon by ecosystem respiration.

The high emission A1 and A2 scenarios lead to somewhat similar patterns of NBP using the climatic simulations of the five GCMs. The highest temperature predictions from the ECHam4 GCM also lead to the greatest simulations of NBP, which follows from the responses of NPP (Fig. 10). The NPP simulations from PCM and CSIRO2 climates produce the smallest changes in NPP (Fig. 14), and the smallest NBP over the Irish landscape under the A1 and A2 scenarios. This indicates that the Irish landscape is close to carbon neutral (Table 2), in terms of net CO_2 fluxes, a feature that could by this time of higher temperatures be strongly influenced by losses of carbon from the large peat stores.

The effect of CO_2 saturation for the B1 scenario is clear to see, with areas of the Irish landscape turning to a CO_2 source by the end of the century.

Fig. 14—Time series of simulated Net Primary Production for four SRES scenarios and in response to climate simulated by five different GCMs.

Fig. 15—Net Biome Production (gC m⁻² yr⁻¹) over the Irish landscape, Y-axis latitude (north), X-axis longitude (west), averaged for the period 2091–2100.

Table 2—Simulated Net Biome Production (MtC yr⁻¹) for Ireland averaged for the period from 2091 to 2100, using the climate simulations from five General Circulation Models (GCMs). Net Biome Production for the period 1991 to 2000 was 0.732 MtC. Positive values indicate that Ireland is a carbon sink, negative values a source.

<i>SRES</i>	<i>CGCM2</i>	<i>CSIRO2</i>	<i>ECHam4</i>	<i>HadCM3</i>	<i>PCM</i>
A1	1.465	0.752	2.495	2.323	0.116
A2	1.798	1.125	2.504	2.449	1.117
B1	0.117	-0.712	0.004	0.089	-0.329
B2	0.831	0.083	0.518	0.816	0.243

The NBP of Ireland as a whole (Table 2) shows that the climate from two GCM simulations (CSIRO2 and PCM) leads to simulations of an Irish source of carbon, under the B1 scenario. Areas of Ireland are also turning out to be a source under some of the B2 scenarios, where the rate of increase in atmospheric CO₂ is slowing. An important feature of the B1 and B2 scenarios is that although CO₂ concentrations are slowing or stabilised (Fig. 10), temperatures are expected to continue rising (Fig. 11). Therefore any stimulation of vegetation productivity due to rising CO₂ concentrations will be minimal, while the stimulation of respiration by increasing temperatures will continue—a combination that will lead to a change to an Irish source of carbon to the atmosphere.

ALIEN PLANT SPECIES

Simulations of the Irish carbon cycle responses to potential climate futures indicate large changes in potential productivity (Fig. 14), which also vary spatially (Fig. 15). The expectation is, therefore, that there will be quite substantial changes in vegetation characteristics, in particular productivity and soil and vegetation water status, with different geographical patterns emerging, such as mirrored by NBP (Fig. 15). These differential changes, alongside changes in the geographical patterns of temperature precipitation will provide different and potentially novel habitats for the plant species that constitute vegetation. The significant and extensive management of the Irish landscape through human activities also creates new areas that are initially vegetation free. In combination these factors, plus the capacity of humans to move seeds around the world with extensive travel (Westphal *et al.* 2008), indicates that the landscape is and will be increasingly susceptible to the arrival and naturalisation of alien plant (and animal) species. Perhaps the majority of alien species will have minor impacts on the existing vegetation. However, some may flourish, leading both to reductions in natural diversity

(Asner *et al.* 2008) and disruptions of vegetation productivity and hydrology (Pejchar and Mooney 2009).

An investigation of the future Irish landscape should, therefore, also consider and attempt to provide some idea about the potential future of alien species spread. Both warming and increasing CO₂ concentrations have been a feature of the twentieth century in Ireland (Figs 1, 2). These changes, in combination with increasing human modifications of the landscape up to the present and into the future (Araújo *et al.* 2008) provide abundant opportunities for the arrival and naturalisation of alien species.

The expectation of a rise in alien species arrivals in Ireland can be assessed using the database of alien plants of Ireland (<http://www.biochange.ie/alienplants>) created by Milbau and Stott (2008). The database has been used to determine the rate of alien species invasions into Ireland during the twentieth century, based on the dates of first record (Fig. 16). Close to 250 new documented arrivals occurred during the twentieth century, with an increasing rate of recording since the 1960s. Woodward and Kelly (2008) demonstrated that at the global scale, NPP was highly correlated with plant species diversity, after land area is taken into account. They demonstrated that the rate of increase in NPP was also a good predictor of the rate of alien species arrival for different regional scale locations (Fig. 17). When the area of Ireland is taken into account then the predicted rate of alien species arrival in the twentieth century is close to that observed.

The same model, accounting for the area of Ireland and the rate of increase in NPP can be applied to the future scenarios of changing NPP (Fig. 14). Using the HadCM3 GCM projection, the model predicts a range of rates of alien species arrival by 2050, depending on the SRES scenario. The rates are 22 species/year for A1, 17 species/year for A2, 7 species/year for B1 and 5 species/year for B2. The model clearly simulates increasing rates of arrival of alien species, with potential to interact negatively with the native

Fig. 16—Cumulative curve of first dated record of alien plant species in Ireland.

Fig. 17—Observed and predicted rates of alien species invasions for different location (from Woodward and Kelly 2008) and now including Ireland.

flora. What is not known, but is clearly crucial, is the identities of the species that will flourish and adversely affect ecosystem services and diversity.

CONCLUSION

Praeger (1950) considered that 'prophecy is a seductive though dangerous pastime' when contemplating the future of Irish natural history. At that time he was, nevertheless able to prophecy that Ireland will be 'subject to no tendencies threatening unduly to disturb the rural influences which prevail on her green countryside'. The research presented here generally supports the latter statement. Simulations of vegetation responses to a wide range of future climatic scenarios (Figs

10 and 11) indicate rather limited changes in vegetation activity (Fig. 15), with rather uniform increases in NPP (Fig. 14). The very oceanic nature of Irish climate ensures a continued supply of precipitation that is expected to maintain the green countryside. However variations in vegetation greenness (Figs 4 and 5) will occur as a result of the inherent climatic oscillations of the surrounding ocean (Figs 1, 2 and 3).

In situ observations of Net Ecosystem Productivity of grassland and plantation forest (Figs 6 and 7) indicate that both ecosystems respond positively to increases in temperature (Table 1) and that the perpetually cloudy nature of Irish weather does not generally limit growing season carbon fixation (Figs 8 and 9) because the enhanced fraction of diffuse radiation readily

penetrates to depth in vegetation canopies (Gu *et al.* 1999; Mercado *et al.* 2009).

Praeger (1950) in the *Natural History of Ireland* was particularly exercised by the poorer species richness of Ireland compared with Britain, noting 'British animals and plants absent from Ireland, without any apparent climatic or similar cause for their absence' and ascribing the Irish paucity as being to 'a considerable extent the result of the existing barrier of the sea' (between Britain and Ireland). Although aware of a relevance, in some way, to the differences in land area, this was not considered of central importance, in spite of existing work, at that time, on species-area relationships (Rosenzweig 1995). Praeger's concern with dispersal barriers is much less of an issue at the present, with heavy and widespread movement of humans and plant propagules subjecting all landscapes of the world to new alien species. The last century saw the recording of large numbers of alien species and a simulation model indicates at least a doubling of alien arrivals (with a maximum of ten times under the A1 scenario) by 2050, in the most modest future climates. Although the Irish landscape may remain green, one can expect its species composition to change markedly, particularly where humans are modifying the landscape.

ACKNOWLEDGMENTS

We are pleased to acknowledge funding from the NERC (UK) in support of the work presented here. Thanks are due to M.B. Jones and B. Osborne for permission to use their flux data for 2003 and 2008 and particular thanks to M. Saunders for providing the flux and associated climatic data, in useable form.

REFERENCES

- Araújo, M.B., Nogués-Bravo, D., Reginster, I., Rounsevell, M. and Whittaker, R.J. 2008 Exposure of European diversity to changes in human-induced pressures. *Environmental Science and Policy* **11**, 38–45.
- Asner, G.P., Hughes, R.F., Vitousek, P.M., Knapp, D.E., Kenndey-Bowdoin, T., Boardman, J., Martin, R.E., Eastwood, M. and Green, R.O. 2008 Invasive plants transform the three-dimensional structure of rain forests. *Proceedings of the National Academy of Sciences* **105**, 4519–23.
- Bartholomé, E. and Belward, A. 2005 GLC2000: a new approach to global land cover mapping from Earth observation data. *International Journal of Remote Sensing* **26**, 1959–77.
- Black, K., Davis, P., Lynch, P., Jones, M., McGettigan, M. and Osborne, B. 2006 Long-term trends in solar irradiance in Ireland and their potential effects on gross primary productivity. *Agricultural and Forest Meteorology* **141**, 118–32.
- Black, K., Bolger, T., Davis, P., Nieuwenhuis, M., Reidy, B., Saiz, G., Tobin, B. and Osborne, B. 2007 Inventory and eddy covariance-based estimates of annual carbon sequestration in a Sitka spruce (*Picea sitchensis* (Bong.) Carr.) forest ecosystem. *European Journal of Forest Research* **126**, 167–78.
- Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B., Bolger, T., Saiz, G., Green, C., Farrell, E.T., Osborne, B. 2009 Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. *Forestry* **82**, 255–72.
- Byrne, C. and Jones, M.B. 2002 Effects of elevated CO₂ and nitrogen fertiliser on biomass productivity, community structure and species diversity of a semi-natural grassland in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* **102**, 141–50.
- Cannaby, H. and Hüsrevoğlu, Y.S. 2009 The influence of low-frequency variability and long-term trends in North Atlantic sea surface temperature on Irish waters. *ICES Journal of Marine Science* **66**, 1480–9.
- Cruickshank, M.N., Tomlinson, R.W., Devine, P.M. and Milne, R. 1998 Carbon in the vegetation and soils of Northern Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* **98B**, 9–21.
- Cruickshank, M.M., Tomlinson, R.W. and Trew, S. 2000 Application of CORINE land-cover mapping to estimate carbon stored in the vegetation of Ireland. *Journal of Environmental Management* **58**, 269–87.
- Dima, M. and Lohmann, G. 2007 A hemispheric mechanism for the Atlantic Multidecadal Oscillation. *Journal of Climate* **20**, 2706–19.
- Donnelly, A., Jones, M.B. and Salamin, N. 2006 Changes in tree phenology: an indicator of spring warming in Ireland? *Biology and Environment: Proceedings of the Royal Irish Academy* **106B**, 47–55.
- García-Suárez, A.M. and Butler, C.J. 2006 Soil temperatures at Armagh Observatory, Northern Ireland, from 1904 to 2002. *International Journal of Climatology* **26**, 1075–89.
- Gilmanov, T.G., Soussana, J.F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C.L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B.O.M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A.F.G., Jones, M.B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, Nagy, Z., Pilegaard, Pinter, K., Pio, C., Rashci,

- A., Rogiers, N., Sanz, M.J., Stefani, P., Sutton, M., Tuba, Z., Valentini, R., Williamns, M.L. and Wohlfahrt, G. 2007 Partitioning European grassland net ecosystem CO₂ exchange into gross primary productivity and ecosystem respiration using light response function analysis. *Agriculture, Ecosystems and Environment* **121**, 93–120.
- Gu, L.H., Fuentes, J.D., Shugart, H.H., Staebler, R.M. and Black, T.A. 1999 Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: results from two North American deciduous forests. *Journal of Geophysical Research—Atmospheres* **104** (D24), 31421–34.
- IPCC 2007a Summary for Policymakers. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds), *Climate Change 2007: the physical sciences. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge. Cambridge University Press.
- IPCC 2007b Summary for Policymakers. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds), *Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge. Cambridge University Press.
- Ise, T., Dunn, A.L., Wofsy, S.C. and Moorcroft, P.R. 2008 High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience* **1**, 763–6.
- Jones, H.G. 1992 *Plants and microclimate a quantitative approach to environmental plant physiology*, 2nd edn. Cambridge. Cambridge University Press.
- Jones, M.B., Donnelly, A. and Albanito, F. 2006 Responses of Irish vegetation to future climate change. *Biology and Environment: Proceedings of the Royal Irish Academy* **106B**, 323–34.
- LeBauer, D.S. and Treseder, K.K. 2008 Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology* **89**, 371–9.
- Los, S.O., Justice, C.O. and Tucker, C.J. 1994 A global 1 by 1 degree NDVI data set for climate studies derived from the GIMMS continental NDVI data. *International Journal of Remote Sensing* **15**, 3493–518.
- Mercado, L.M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M. and Cox, P.M. 2009 Impact of changes in diffuse radiation on the global land carbon sink. *Nature* **458**, 1014–7.
- Milbau, A. and Stout, J.C. 2008 Factors associated with alien plants transitioning from casual, to naturalized, to invasive. *Conservation Biology* **22**, 308–17.
- Pejchar, L. and Mooney, H.A. 2009 Invasive species, ecosystem services and human well-being. *Trends in Ecology and Evolution* **24**, 497–504.
- Praeger, R.L. 1950 *Natural history of Ireland: a sketch of its flora & fauna*. London. Collins.
- Quaife, T., Quegan, S., Disney, M., Lewis, P., Lomas, M. and Woodward, F.I. 2008 Impact of land cover uncertainties on estimates of biospheric carbon fluxes. *Global Biogeochemical Cycles* **22**, GB4016. doi:10.1029/2007GB003097.
- Rodwell, M.J., Rowell, D.P. and Folland, C.K. 1999 Oceanic forcing of the wintertime North Atlantic Oscillation and the European Climate. *Nature* **398**, 320–3.
- Rosenzweig, M.L. 1995 *Species Diversity in Space and Time*. Cambridge. Cambridge University Press.
- Schlesinger, M.E. and Ramankutty, N. 1994 An oscillation in the global climate system of period 65–70 years. *Nature* **367**, 723–6.
- Sellers, P.J., Los, S.O., Tucker, C.J., Justice, C.O., Dazlich, D.A., Collatz, G.J. and Randall, D.A. 1994 A global 1×1 degree NDVI data set for climate studies. Part 2: The generation of global fields of terrestrial biophysical parameters from the NDVI. *International Journal of Remote Sensing* **15**, 3519–45.
- Siemens, J. 2003 The European carbon budget: a gap. *Science* **302**, 1681.
- Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C. and Woodward, F.I. 2008 Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using 5 Dynamic Global Vegetation Models (DGVMs). *Global Change Biology* **14**, 2015–39.
- Sottocornola, M. and Kiely, G. 2005 An Atlantic blanket bog is a modest CO₂ sink. *Geophysical Research Letters* **32**, L23804.
- Sweeney, J. and Fealy, R. 2002 A preliminary investigation of future climate scenarios for Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* **102B**, 121–8.
- Tomlinson, R.W. 2005 Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management* **76**, 77–93.
- Westphal, M.I., Browne, M., MacKinnon, K. and Noble, I. 2008 The link between international trade and the global distribution of invasive plant species. *Biological Invasions* **10**, 391–8.
- Woodward, F.I. and Kelly, C.K. 2008 Responses of global plant diversity capacity to changes in carbon dioxide concentration and climate. *Ecology Letters* **11**, 1229–37.
- Woodward, F.I. and Lomas, M.R. 2004 Vegetation dynamics—simulating responses to climatic change. *Biological Reviews* **79**, 643–70.