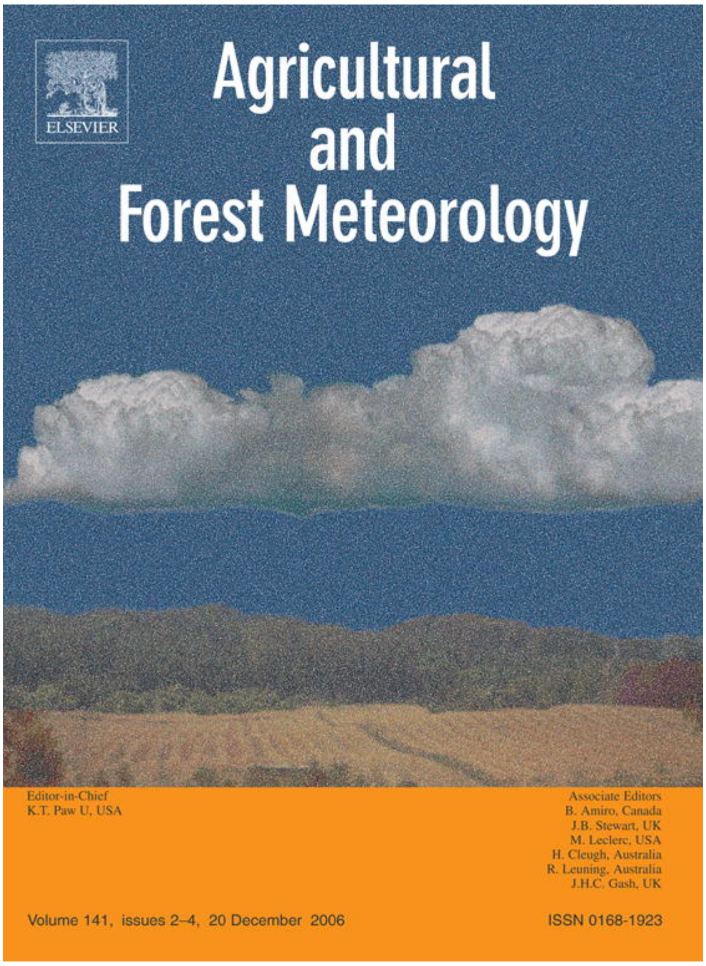
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Long-term trends in solar irradiance in Ireland and their potential effects on gross primary productivity

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Abstract

Long-term trends in total solar irradiance (R_s), diffuse irradiance (R_d) and pan evaporation (E_{pan}), from various sites in Ireland, were examined over the last 20–50 years. This information was used to estimate the impact of changes in R_s and R_d on gross primary productivity (GPP) of forest, arable and grassland ecosystems. Analysis of the data indicated a significant ($P < 0.0001$) reduction in R_s of 19% (27.7 MJ m^{-2} $year^{-1}$) and R_d by 16% (12.2 MJ m^{-2} $year^{-1}$) from 1955 to 1984. However, we show R_s has remained unchanged, or even increased at some sites since the mid-1980s, whilst R_d has continued to decrease. Decreases in measured and calculated (Preistley–Taylor function) E_{pan} between 1955 and 1984 were consistent with the observed changes in R_s. Long-term changes in R_s were associated with variations in atmospheric optical properties, as evident from a change in the slope of the relationship between the diffuse fraction (R_d:R_s) and the clearness index (R_s:R_o). At Dublin Airport an increase in R_s and R_s:R_o since the 1980s was consistent with a decrease in black smoke and sulphate concentrations. We show that combined alterations in R_s and R_d, over the last 50 years, had only a small impact on annual GPP of temperate terrestrial ecosystems (a decrease of 0.5 to 1.7 t C ha^{-1} $decade^{-1}$). These reductions in GPP were larger in arable and grassland systems, where productivity is light-limited and particularly sensitive to changes in R_d:R_s.

Keywords: Global dimming; Gross primary productivity; Light-use efficiency

1. Introduction

Long-term changes in the amount of solar radiation reaching the Earth's surface can have a potentially strong influence on climate (Charlson et al., 2005), hydrological cycles (Roderick and Farquhar, 2002) and ecosystem productivity (Roderick et al., 2001; Farquhar and Roderick, 2003; Gu et al., 2003). A general decrease in global irradiance ('global dimming'), equivalent to 2.7% per decade in the last 50 years, has been reported in a number of studies conducted over a wide range of geographical locations both in the southern and northern hemisphere (for review, see Stanhill and Cohen, 2001). Indirect evidence for a decrease in radiation, at the regional or continental scale, comes from observations of a reduction in pan

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Abbreviations: E_{pan}, pan evaporation; GPP, gross primary productivity; ε_g, apparent light use efficiency; LAI, leaf area index; R_d, diffuse irradiance; R_s, total solar irradiance; R_o, extra terrestrial irradiance; R_d:R_s, diffuse fraction; R_s:R_o, clearness index

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evaporation, despite evidence for recent global warming (Roderick and Farquhar, 2002). The interaction between evaporation and solar irradiance highlights the importance of evaluating the magnitude and future impacts of these changes in relation to greenhouse forcing and ecosystem carbon balance.

The possible causes of global dimming include changes in cloud characteristics, increased loading of anthropogenic aerosols and decreases in atmospheric transmissivity associated, for instance, with volcanic eruptions (Ramanathan et al., 2001; Gu et al., 2003; Power, 2003). Soot particles and sulphates also absorb and reflect incident radiation, and act as nuclei for cloud formation, thereby reducing solar irradiance (R_s). It is uncertain, however, if this global dimming trend has been sustained over the past two decades, at various regional and continental locations. Recent reports suggest that global dimming trends have ceased or even reversed in some locations (Pinker et al., 2005; Wild et al., 2005), possibly due to reductions in the levels of air pollutants (Power, 2003).

The consequences of regional changes in R_s on crop yield, if unaccompanied by other climate-related changes, have been suggested to be small (Stanhill and Cohen, 2001). However, the potential effects of regional changes in irradiance on gross primary productivity (GPP) remains unclear. This would depend on the magnitude of any reduction in R_s as well as the extent of any modifications in the diffuse component (R_d). In turn the outcome of alterations in R_s and R_d on GPP will be related to the characteristics of the crop canopy. Changes in R_s and R_d are also likely to be of greater significance in temperate regions where GPP is often light-limited (Chapin et al., 2002; Turner et al., 2003). Due to the complex interactions between canopy characteristics and the nature of the light field an increase in R_d can lead to an increase in canopy photosynthesis even if this is accompanied by a reduction in R_s (Choudhury, 2001; Roderick et al., 2001; Gu et al., 2003). This suggests that changes in R_d or the diffuse fraction (R_d:R_s) can have a potentially significant impact on GPP independently of any variation in R_s. In a previous study conducted in Ireland, Stanhill (1998) showed that R_d has decreased at a higher rate (R_d; -0.77% year^{-1}) when compared to reductions in R_s (-0.61% year^{-1}), suggesting that R_d:R_s has also declined between 1965 and 1995. A reduction in R_d:R_s, together with a decline in R_s, could have a negative impact on crop productivity.

The aims of this study were firstly to re-assess long-term variations in annual R_s at various sites in Ireland, using a larger data set than that described by Stanhill (1998), with information now available up to the end of 2004 and secondly, to estimate the effects of these changes on GPP of the major land-used types. In 2003, the land cover of Ireland was comprised predominantly of managed grasslands (57%), arable crops (7%, of which 45% was spring barley) and forests (14%). We also assessed if any long-term changes in R_s were associated with variations in pan evaporation and/or aerosol loading.

2. Methods

2.1. Climate and air pollution data

Total daily R_s and R_d data from seven sites across Ireland were obtained from Met Èireann (Irish Meteorological Service, Glasnevin, Dublin). A thermopile pyranometer was used to measure R_s at all sites (McWilliams, 1975; Fitzgerald and Fitzgerald, 2004). A shading ring was used to screen the thermopile sensor from direct irradiance to monitor R_d (McWilliams, 1975). At the Valentia observatory, a pyrheliometer was mounted on a Kipp and Zonen 2AP solar tracker to measure direct irradiance (Fitzgerald and Fitzgerald, 2004). Previous documentation showed that the accuracy of the radiation measurements meet the requirements set by the International Geophysical year (IGY, 1957), with a maximum error of 5% for daily R_s and R_d values, and that the accuracy was similar when estimated 25 years later (WMO, 1983; and see McWilliams, 1975; Stanhill, 1998).

Daytime cloud cover (oktas) and daily clear sunshine duration data, measured with a Campbell–Stokes sunshine recorder, were also obtained for all of the sites. At selected sites (Valentia, Dublin Airport and Kilkenny) additional data for mean daily minimum and maximum air temperature, relative humidity, air pressure and monthly class A pan evaporation rates were obtained. These sites were specifically selected on the basis of their geographical locations, covering the most westerly (Valentia) to the most easterly point (Dublin Airport) and a site in the midlands (Kilkenny), as well as the availability of long-term pan evaporation and radiation data. The geographic locations of the measurement sites and the time period of measurement for each site are listed in Table 1. The set up and calibration of the instruments (see Fitzgerald and Fitzgerald, 2004) were in accordance with the World Meteorological Organisation recommendations (WMO, 1983).

Diffuse irradiance measurements commenced after (~10 years) the initiation of R_s measurements at many

Table 1
Long-term means and linear trends for total solar irradiance (R_s) for individual sites in Ireland

Site	Coordinates (N; W)	Period analysed	Mean (S.D.) (GJ m^{-2} $year^{-1}$)	Slope (S.E.) (MJ m^{-2} $year^{-1}$)	r^2	P
All sites		1955–2004	3.47 (0.24)	−12.4 (1.3)	0.31	<0.001
		1955–1984	3.58 (0.27)	−27.7 (2.1)	0.59	<0.001
		1985–2004	3.35 (0.17)	4.9 (2.1)	0.01	0.174
Valentia	51°56′; 10°15′	1955–2004	3.63 (0.26)	−13.0 (1.8)	0.54	<0.001
		1955–1984	3.74 (0.26)	−22.4 (2.1)	0.59	<0.001
		1985–2004	3.47 (0.13)	1.2 (5.6)	0.01	0.864
Kilkenny	52°40′; 7°16′	1969–2004	3.52 (0.26)	−14.8 (3.8)	0.31	0.005
		1969–1984	3.61 (0.28)	−45.2 (10.1)	0.59	0.005
		1985–2004	3.43 (0.22)	−14.7 (9.3)	0.14	0.132
Birr	53°05′; 7°54′	1971–2004	3.39 (0.19)	−9.2 (3.2)	0.19	0.007
		1971–1984	3.49 (0.12)	−33.2 (10.5)	0.45	0.008
		1985–2004	3.32 (0.14)	6.2 (5.9)	0.06	0.132
Dublin Airport	53°26′; 6°14′	1975–2004	3.40 (0.18)	7.5 (4.2)	0.08	0.082
		1975–1984	3.32 (0.20)	0.1 (2.7)	0.01	0.996
		1985–2004	3.46 (0.17)	4.5 (7.6)	0.02	0.552
Clones	54°11′; 7°14′	1981–2004	3.17 (0.13)	−0.8 (4.5)	0.02	0.859
Belmullet	54°14′; 10°00′	1982–2004	3.34 (0.16)	10.7 (4.9)	0.19	0.039
Malin Head	55°22′; 7°20′	1982–2004	3.31 (0.09)	−0.7 (3.2)	0.02	0.812

of the sites (see Tables 1 and 2). In order to complete the R_d data set, which was required to model changes in gross primary productivity since 1955, missing R_d values were calculated. This was based on the inverse linear relationship between the daily diffuse fraction of incident irradiance (R_d:R_s) and the atmospheric clearness index, calculated as the ratio of R_s to the extra terrestrial irradiance at the top of the atmosphere (R_o) according to Roderick (1999);

$$R_d : R_s = m\,R_s : R_o + c \tag{1}$$

where m is the slope and c is the y intercept of the linear relationship and $0.8 > R_s{:}R_o > 0.2$ (Roderick, 1999).

Table 2
Long-term means and linear trends for annual diffuse irradiance (R_d) and the diffuse fraction (R_d:R_s) for individual sites in Ireland

Site	Period analysed	Diffuse irradiance (R_d)			Diffuse fraction (R_d:R_s)		
		Mean (S.D.) (GJ m^{-2} $year^{-1}$)	Slope (S.E.) (MJ m^{-2} $year^{-1}$)	r^2	Mean (S.D.)	Slope (S.E.) over period	r^2
All sites	1965–2004	2.00 (0.14)	−8.8 (1.0)	0.34^{***}	0.59 (0.05)	−0.059 (0.015)	0.31^{***}
	1965–1984	2.09 (0.12)	−12.2 (2.6)	0.33^{***}	0.61 (0.03)	0.017 (0.017)	0.02 ns
	1985–2004	1.97 (0.13)	−10.7 (1.9)	0.20^{***}	0.59 (0.05)	−0.068 (0.013)	0.16^{***}
Valentia	1965–2004	2.07 (0.14)	−9.2 (1.2)	0.61^{***}	0.58 (0.03)	−0.047 (0.016)	0.18^{**}
	1965–1984	2.15 (0.12)	−12.4 (3.3)	0.43^{***}	0.59 (0.03)	−0.005 (0.017)	<0.01 ns
	1985–2004	1.98 (0.09)	−9.5 (3.4)	0.32^{**}	0.57 (0.03)	−0.059 (0.019)	0.21^{*}
Kilkenny	1980–2004	2.05 (0.11)	−9.7 (3.0)	0.33^{**}	0.60 (0.04)	−0.065 (0.024)	0.25^{**}
Birr	1980–2004	2.09 (0.10)	−8.3 (2.6)	0.34^{**}	0.63 (0.03)	−0.078 (0.024)	0.30^{**}
Dublin Airport	1977–2004	1.92 (0.14)	−8.3 (3.0)	0.25^{**}	0.56 (0.05)	−0.121 (0.027)	0.45^{***}
	1977–1984	1.96 (0.14)	1.6 (5.7)	0.02 ns	0.60 (0.03)	−0.021 (0.036)	0.09 ns
	1985–2004	1.98 (0.16)	−14.9 (5.3)	0.33^{**}	0.55 (0.05)	−0.106 (0.034)	0.38^{**}
Clones	1982–2004	1.98 (0.10)	−0.8 (3.6)	<0.01 ns	0.66 (0.04)	−0.015 (0.028)	0.02 ns
Belmullet	1993–2004	1.92 (0.07)	−2.0 (6.2)	0.01 ns	0.56 (0.03)	−0.029 (0.026)	0.13 ns
Malin Head	1982–2004	1.89 (0.10)	−11.4 (2.3)	0.54^{***}	0.57 (0.04)	−0.072 (0.024)	0.31^{**}

Coefficients of determination (r^2) are significant at $^{***}P < 0.001$, $^{**}P < 0.01$ or $^{*}P < 0.05$ or not significant where $P > 0.05$ (ns).

Calculated values for R_d were not used to estimate changes in R_d or R_d:R_s over the time series. Changes in the slope (m) of the relationship between measured R_d:R_s and R_s:R_o were used as an indicator of changes in the optical properties of the atmosphere over time at different sites.

The potential influence of variations in solar irradiance (R_s) on long-term changes in annual class A pan evaporation (E_{pan}), at Valentia and Kilkenny, were calculated using a modified Priestley–Taylor expression for evaporation from a wet surface as described by Roderick and Farquhar (2002);

$$\lambda E_{\mathrm{pan}} = 1.44\left(\frac{s}{s+\gamma}\right)R_s \qquad (2)$$

where λ is the latent heat of vapourisation for water (2.4 MJ kg^{-1}), γ the psychrometric constant (67 Pa K^{-1}) and s is the slope of the saturation vapour pressure–temperature relationship. The ratio $s/(s+\gamma)$ was calculated using the mean air temperature and this varied from 0.48 at 5 °C to 0.7 at 25 °C.

Black smoke and airborne sulphur dioxide (SO_2) concentrations between 1975 and 2004 were obtained from 20 air monitoring stations, located in the Dublin area (see Mc Gettigan et al., 1999). Airborne particulates (>10 μm) were measured according to the standards set by the EU directive 80/779/EEC (CEC, 1980). Assessments of SO_2 concentrations were based on measurements of total-acidity, as in directive 80/799/EEC. Detailed information on the location of the monitoring stations and the methodologies can be obtained from the EPA web site (www.epa.ie).

2.2. Eddy covariance measurements

Eddy covariance measurements of net ecosystem productivity (NEP) were made on three major land-use classes in Ireland (forest, a cropland sown with spring barley and a managed grassland) between 2002 and 2005 using closed path eddy covariance systems (EdiSol, Edinburgh University), described in detail by Moncrieff et al. (1997). The forest, spring barley and managed grassland sites were located within 30 km of each other, close to the Kilkenny meteorological station, where the 30-year mean annual temperature was 9.3 °C, with a mean annual rainfall of 850 mm. The forest is a Sitka spruce forest, located in Co. Laois in the Irish midlands (52°57′N, 7°15′W, altitude of 260 m), with a leaf area index of 7.8 $\mathrm{m}^2\,\mathrm{m}^{-2}$ in 2003 (Black et al., 2004). The site was previously an unmanaged grassland, planted in 1988 at a density of ca. 2500 stems ha^{-1}. The spring barley and grassland sites are located at the Teagasc Oak Park research station in Co. Carlow (52°52′N, 6°55′W, altitude of 56 m). The arable site has been used for cereal crop production (a spring barley crop (*var* Tavern)), which is normally sown in late March and harvested in mid-August. The grassland was cultivated and replanted with a *Lolium/Trifolium* mixture in 2002. The management of the grassland includes a silage cut in early summer and a period of cattle grazing between July and October.

Fluxes of sensible heat, water vapour, CO_2 and friction velocity (u^*) were calculated for 30 min periods using the EdiRe software (Moncrieff et al., 1997). Automatic weather stations (Campbell Scientific Ltd., Shepshed, England) recorded additional meteorological data at each site including: air temperature, relative humidity, wind speed and direction, net radiation, total incident (I_o) photosynthetically active irradiance (PAR, λ of 400–700 nm) at the top of the canopy, air pressure, soil heat flux, soil moisture, soil temperature and rainfall. The irradiance at the bottom (I_z) of the forest canopy was measured using six PAR sensors randomly located on the forest floor. Tube solarimeters (1 m) were used to measure transmitted light at the bottom of the barley and grassland canopies. Sunshine hours and diffuse irradiance data were recorded using a sunshine sensor (type BF3, Delta-T Devices Ltd., Cambridge, UK).

2.3. Gross primary production

Eddy covariance data were used to calculate GPP as:

$$\mathrm{GPP} = \mathrm{NEP} - R_e \text{ during the day} \qquad (3)$$

where NEP = −NEE (μmol $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$), R_e is the total ecosystem respiration (μmol $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$) which was estimated from the relationships between half hourly night time NEP and air temperature (Lloyd and Taylor, 1994; Falge et al., 2001) for periods when friction velocity was above a threshold value for all of the sites ($u^* > 0.13$; Goulden et al., 1996; Black et al., 2005). The daytime R_e was then calculated using the same temperature relationship (Black et al., 2005).

Half hourly values were integrated to determine daily GPP values, which were then used to assess if canopy gross productivity for the different ecosystems was light limited. Where daily GPP was light limited (crop and grassland ecosystems), a linear light use efficiency model was used to estimate daily GPP (Monteith, 1972):

$$\mathrm{GPP} = \varepsilon_g\, f\, \mathrm{cf}\, R_s \qquad (4)$$

where GPP is measured in mol m^{-2} day^{-1}, ε_g the apparent light use efficiency (mol [CO_2] mol^{-1} [PAR]), f the mean fraction of PAR absorbed by the canopy, cf the conversion factor to convert total irradiance to PAR (2.3 mol [PAR] MJ^{-1}) and R_s is the total solar irradiance (MJ m^{-2} day^{-1}). For the forest ecosystem, a curved function was used to describe the relationship between irradiance and daily GPP (Landsberg and Waring, 1997):

$$\mathrm{GPP} = \frac{\varepsilon_g(f\,\mathrm{cf}\,R_s)\mathrm{GPP}_{\max}}{\varepsilon_g(f\,\mathrm{cf}\,R_s) + \mathrm{GPP}_{\max}} \tag{5}$$

where $\mathrm{GPP}_{\max}$ is the maximal canopy-scale photosynthetic capacity at light saturation, which was derived using a least squares optimisation of the function.

Estimates of radiation extinction coefficients (K) were derived from measured leaf area indices (LAI) and canopy transmittance values for the different canopies over various time intervals. Assuming that canopy reflection was relatively low (see Gower et al., 1999), K was calculated using the following function (Jarvis and Leverenz, 1983):

$$\mathrm{LAI} = \left(\frac{-1}{K}\right)\ln\left(\frac{I_z}{I_o}\right) \tag{6}$$

Values for K were approximated using a least squares optimisation method based on measurements of irradiance from the top (I_o) and bottom (I_z) of the forest and barley canopies when the solar inclination was between 38° and 45° and the diffuse fraction of I_o was greater than 0.8. For the forest site LAI was assumed to be constant through out the year (i.e. 7.8 m^2 m^{-2}, Black et al., 2004) and K was estimated to be 0.56. The LAI of the barley and grassland sites varied with management and stage of crop growth. At these sites, LAI was determined from destructive sampling using measurements of leaf area made with a flat bed scanner and Scion Imaging Software (Beta 4.0.1, Scion Corporation, Maryland, USA) and K estimated to be 0.45 for the barley crop and 0.57 for the grassland. The mean absorbed fraction (f) of PAR for each canopy was then derived as:

$$f = 1 - \left(\frac{I_z}{I_o}\right) \tag{7}$$

where $(I_z/I_o) = e^{(\mathrm{LAI}(-K))}$.

The estimation of a mean f value, under a diffuse light field (when R_d:$R_s > 0.8$), using Eq. (7) does not, however, account for differences in light absorption by the canopy when exposed to different diffuse fractions (R_d:R_s; see Roderick et al., 2001). Instead of using different f values for each diffuse fraction (or a separate relationship for f and R_d:R_s), the influence of changes in the mean daily diffuse fraction on daily ε_g was accounted for using the function described by Roderick et al. (2001):

$$\varepsilon_g = X_s(R_d : R_s) + X_o \tag{8}$$

The slope (X_s) and y intercept (X_o) of this relationship can vary with temperature, and was determined for three to four daily mean temperature classes. The calculated daily ε_g values were then substituted into the daily GPP equations (Eqs. (4) and (5)).

2.4. Modelling long-term changes in GPP

The influence of changes in solar irradiance on annual GPP from the three ecosystems between 1955 and 2004 was assessed using five different scenarios; the combined influence of changes in mean air temperature (T°), daily R_s and R_d:R_s, the combined influence of changes in both R_s and R_d:R_s, and the individual influences of changes in the three variables. Where a variable remained constant, the combined 50-year mean from all of the sites was used. Since these analyses were based on simple light use efficiency and temperature response models, the following implicit assumptions apply:

- The elevated ambient CO_2 concentrations (ca. 30 μmol mol^{-1}) and higher deposition rates of nitrogen between 1955 and 2004 did not influence GPP.
- Any effect on ε_g caused by vapour pressure deficit (VPD) driven changes on stomatal conductance associated with different diffuse fractions were included in the model (Gu et al., 2003; Farquhar and Roderick, 2003).
- The influence of improved crop varieties, superior tree provenances and increased N fertilisation, or different management scenarios, on GPP was ignored and we assume that there was no acclimation to a change in R_s and R_d over time.
- The annual times coarse of changes in LAI for the crop and grassland system were the same for each year of the study.

3. Results

3.1. Long-term trends in annual solar irradiance

Linear regression of the pooled R_s data from all of the seven meteorological stations showed that there was a

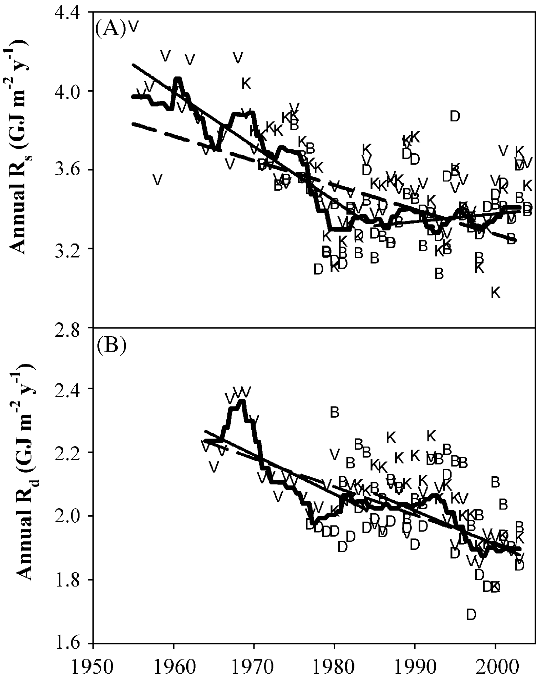

Fig. 1. Long-term variation in total solar (R_s, A) and diffuse (R_d, B) irradiance at Valentia (V), Birr (B), Dublin Airport (D) and Kilkenny (K). The long-term mean for all sites (solid line) was calculated as a 4-year moving average. The broken regressions lines show the linear decline in annual mean irradiance values for all sites over the entire time series. The bold solid regression lines show the linear trends for all sites before and after 1984. The coefficients of determination (r^2) for all linear relationships are significant ($P < 0.05$, see Tables 1 and 2 for details).

significant ($P < 0.001$) reduction of 12.4 ± 1.3 MJ m^{-2} year^{-1}, equivalent to a 17% drop between 1955 and 2004 (Fig. 1A; Table 1). The mean annual reduction in R_s was greater for the periods between 1955 and 1984 (27.7 MJ m^{-2} year^{-1}), when compared to the whole time series (1955–2004, 12.4 MJ m^{-2} year^{-1}). In addition, the r^2 value of the linear regression increased from 0.33, for the 50-year period, to 0.59 for the years 1955–1984. Although there was evidence for a slight increase in R_s (4.9 MJ m^{-2} year^{-1}) from 1984 to 2004, this was not significant, $P = 0.174$ (Fig. 1A; Table 1).

The long-term changes in R_s, based on individual site measurements taken prior to 1984, showed similar trends to those obtained for the pooled data set (Table 1). At three of the four sites, where long-term data were available prior to 1984, there was a significant negative trend in R_s, varying from −22.4 MJ m^{-2} year^{-1}, at Valentia, to −45.2 MJ m^{-2} year^{-1}, at Kilkenny (Table 1). Since the 1980s, there were no significant ($P < 0.05$) changes in R_s, except for Belmullet, where there was a significant increase of 10.7 ± 4.9 MJ m^{-2} year^{-1} (Table 1).

Analysis of linear trends of total monthly R_s data from Valentia suggest that there was a greater decline over the summer months (May, June and July, 10.1 MJ m^{-2} year^{-1}, $r^2 = 0.52$, $P < 0.001$) when compared to the winter months (November, December and January, 5.8 MJ m^{-2} year^{-1}, $r^2 = 0.58$, $P < 0.001$). Similar trends were observed for pooled data from all of the sites and for data obtained for Kilkenny and Birr, but there were no significant monthly trends for the sites, where data were collected after the 1980s.

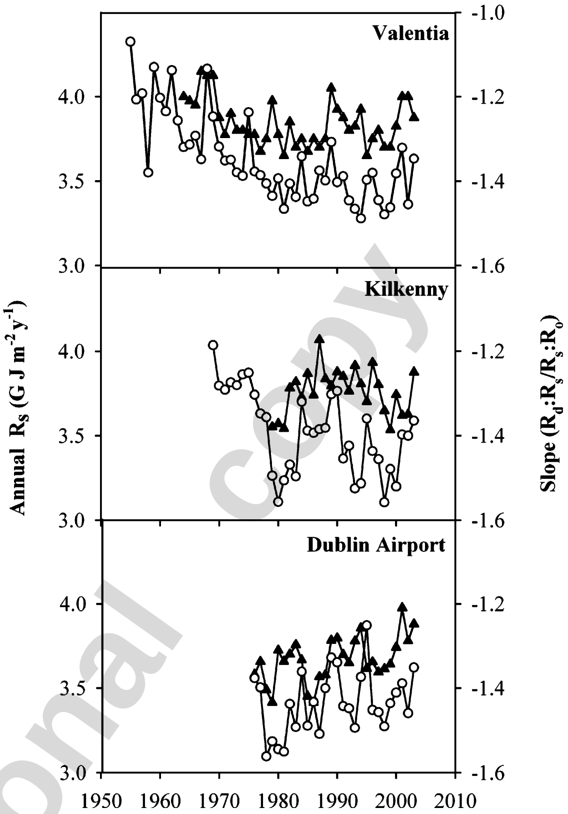

Fig. 2. Long-term trends in total solar irradiance (R_s, white circles) and the slope (black triangles) of the relationship between the diffuse fraction (R_s:R_d) and the atmospheric clearness index (R_s:R_o, see Eq. (1)), at Valentia, Kilkenny and Dublin Airport.

Generally, long-term variations in R_s were associated with changes in the optical properties of the atmosphere, as indicated by alterations in the slope (m) of the relationship between R_s:R_d and R_s:R_o at the major sites (see Eq. (1) and Fig. 2). Although the increase in R_s (7.5 MJ m^{-2} year^{-1}) at Dublin Airport since 1975 was not significant ($P > 0.05$, Table 1), there was a significant increase (7% since 1976, $r^2 = 0.29$, $P = 0.004$) in the slope of R_d:R_s and R_s:R_o (m) over the same time period (Fig. 2). There were no significant changes in m at Valentia ($P > 0.05$, from 1985 to 2004) or at Kilkenny ($P > 0.1$, from 1980 to 2003).

At Valentia, changes in R_s and atmospheric transmission were broadly consistent with variations in annual mean sunshine duration (Fig. 3). However, long-term changes in R_s were not associated with

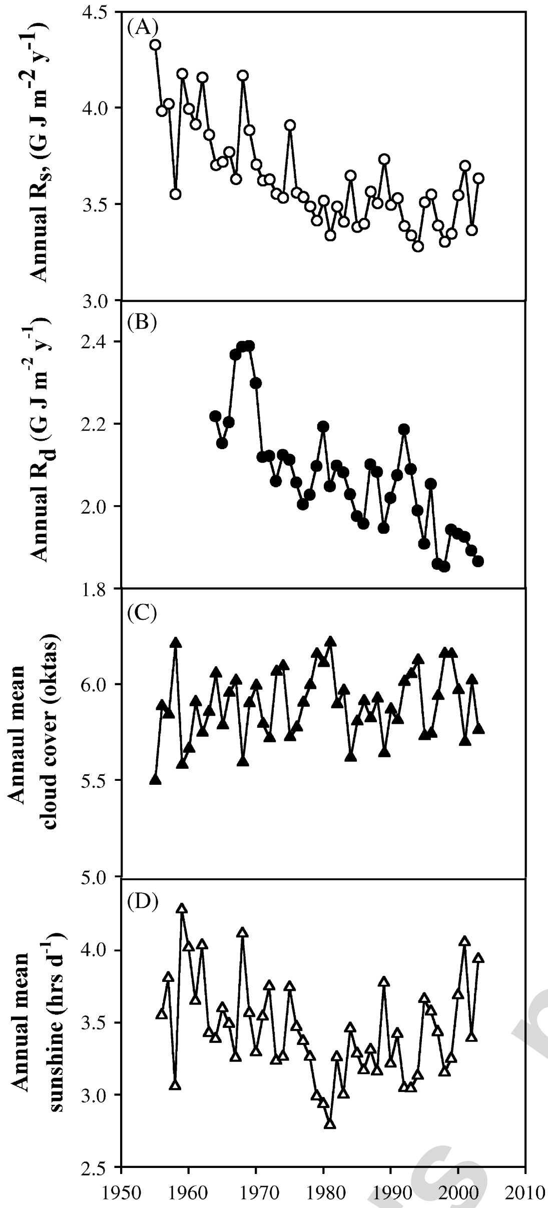

Fig. 3. Long-term trends in total solar irradiance (R_s, A), diffuse irradiance (R_d, B), cloud cover (C) and mean sunshine hour duration (D) at Valentia.

estimates of mean annual cloud cover at Valentia (Fig. 3). Similar results were obtained from an analysis of R_s, cloud cover and sunshine hour data obtained from Kilkenny and Dublin Airport (data not shown).

3.2. Diffuse irradiance and the diffuse fraction

Linear regression analysis of R_d data from all sites, showed a significant mean annual reduction of 8.8 ± 1.0 MJ m^{-2} year^{-1} (Fig. 1B; Table 2). Mean annual R_d continued to decline at a similar rate after 1985 (10.7 ± 1.9 MJ m^{-2} year^{-1}) unlike R_s, where there was no change between 1985 and 2004 (Fig. 1B; Table 2). This was consistent with a significant decrease in R_d:R_s from 1985 to 2004 (Table 2). Data from individual sites showed the same trends as those observed for the pooled data (Table 2).

Based on an analysis of the climatic data from Valentia, the observed long-term variation in R_d could not be explained by changes in cloud cover (Fig. 3). At Valentia, these long-term reductions in annual R_d and R_d:R_s were consistent with a decrease in the mean slope of the relationship between the diffuse fraction and m, from −1.21, in the 1960/1970s, to −1.34, between 1984 and 2000 (Figs. 2 and 3).

3.3. Other factors influencing incident solar irradiance

For the years prior to 1984, mean annual R_s was lowest at Dublin Airport (Table 1). However, since the 1980s, the mean annual R_s at Dublin Airport has increased to a level comparable with other sites. Over the corresponding period, the annual SO_2 concentrations, measured from 20 sites across the Dublin area, decreased ca. 10-fold (Fig. 4). There has also been a significant decrease in black smoke concentrations in the Dublin area, particularly since the introduction of smoke control legislation in 1990 (Fig. 4). The observed changes in black smoke and SO_2 concentrations may explain the increase in R_s, as well as the reductions in R_d (10.8%, $P = 0.031$), and the altered in the optical properties of the atmosphere in the Dublin area between 1977 and 2004, as indicated by the less negative slope of the relationship between R_d:R_s and R_s:R_o (Figs. 2 and 4).

3.4. Coupling of pan evaporation and R_s

There was significant correlation between the observed and calculated E_{pan} values, as determined using the Priestley–Taylor equation, for Valentia

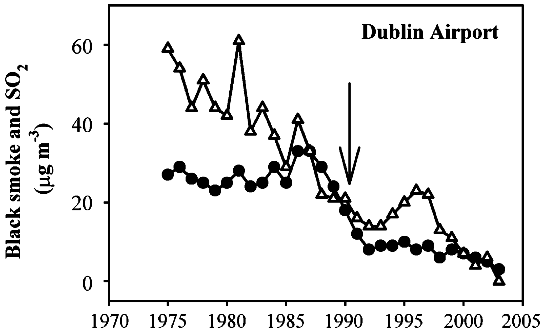

Fig. 4. Changes in mean annual black smoke (black circles) and sulphate (white triangles) concentrations for the Dublin area from 1977 to 2004. The arrow indicates when local pollution control legislation was implemented in 1990.

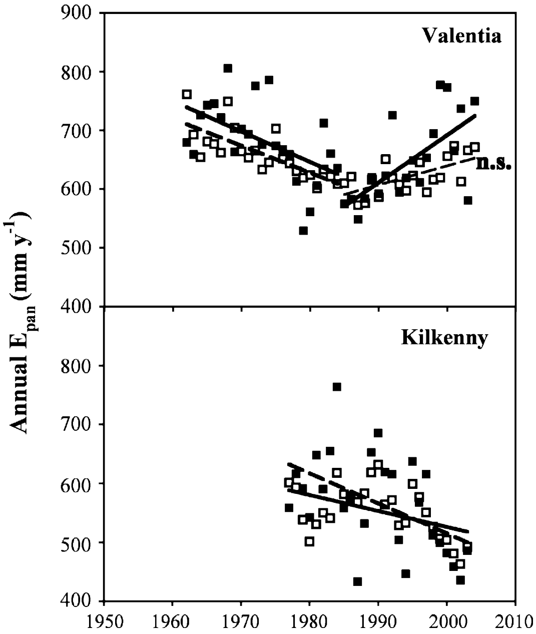

Fig. 5. Measured (black squares), calculated (white squares) pan evaporation (E_{pan}) for Valentia (1964–2004) and Kilkenny (1976–2004). Estimated E_{pan}, associated with R_s (white squares), was calculated using the Priestley–Taylor equation. The slope ($P < 0.05$) of the linear relationships were: *Valentia* 1960–1984; −5.2 mm year^{-1} for measured E_{pan} (bold solid line) and −4.5 mm year^{-1} for predicted E_{pan} (bold broken line). *Valentia* 1984–2004; 7.5 mm year^{-1} for measured E_{pan} (bold solid line). *Kilkenny* 1976–2004; −5.1 mm year^{-1} for measured E_{pan} (bold solid line) and −2.9 mm year^{-1} for predicted E_{pan} (bold broken line).

($r^2 = 0.39, P < 0.01$) and Kilkenny ($r^2 = 0.48, P < 0.01$). There was no significant change in either the mean maximum and minimum daily air temperature or the mean daytime vapour pressure deficit at both sites (data not shown). At Valentia, the decrease in E_{pan} (−5.2 mm year^{-1}), between 1964 and 1984, was consistent with a reduction in R_s (−22.8 MJ m^{-2} year^{-1}) 1) and the calculated change in E_{pan} (−4.5 mm year^{-1}) over the same time period (Fig. 5). Although there was no significant change in R_s and the estimated E_{pan} at Valentia post 1984 (Table 1) the measured E_{pan} increased significantly (3.2 mm year^{-1}) over the corresponding time period (Fig. 5).

Whilst E_{pan} data were only available for Kilkenny from 1976, our analysis also suggests that decreases in R_s between 1976 and 2004 (Figs. 1 and 2) were consistent with significant changes in both the observed and estimated variations in E_{pan} over the same time period (Fig. 5).

3.5. Daily GPP and ε_g for the three crops

The relationship between daily GPP and absorbed irradiance varied considerably between sites. Fig. 6 shows the daily GPP–light response relationships for the three crops (grassland, barley and forest), for a temperature range of 10–15 °C, from April to August 2003. For the spring barley crop, absorbed radiation was calculated using the green leaf area index to minimise the influence of alterations in phenology (such as during grain filling and leaf senescence) on daily light use efficiency (ε_g). Approximately 90% of the canopy in the grassland site comprised of photosynthetic tissue, except after the silage cut, when very little photosynthetic tissue remained. The calculation of ε_g for the forest site was based on the total LAI, including absorption of light by non-photosynthetic tissue

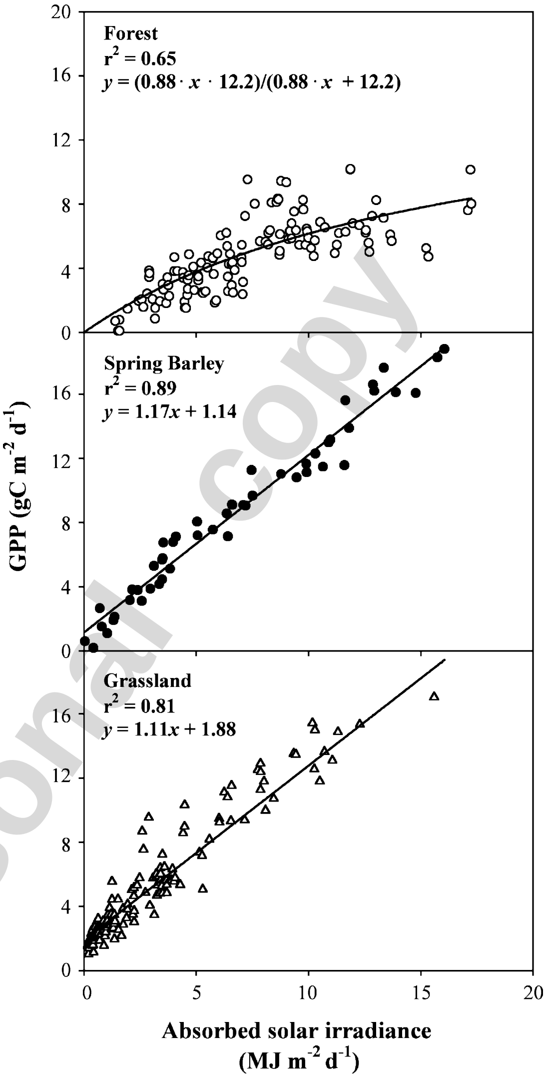

Fig. 6. The relationship between gross primary productivity (GPP) and absorbed irradiance* for the forest, barley and grassland canopies. The analysis was performed using irradiance and GPP data obtained between April and August 2003, when air temperatures ranged between 10 and 15 °C (see Table 3 for the complete temperature response data). *Corrected for absorbed irradiance by the canopy, but this does not account for the effect of diffuse fraction on light absorption (see Section 2).

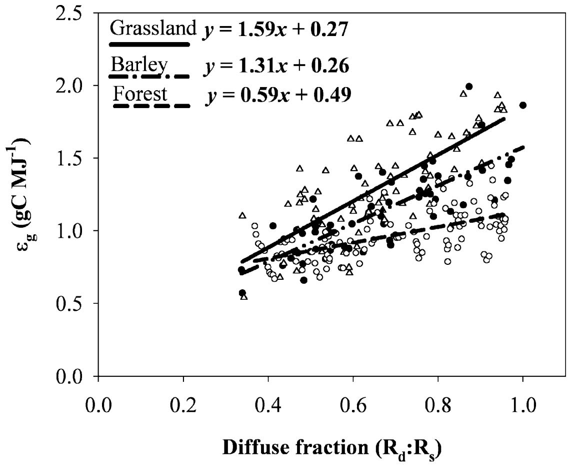

Fig. 7. Relationship between apparent light use efficiency (ε_g)* and the diffuse fraction of irradiance (R_d:R_s) for the grassland, barley and forest canopies. Data were used between April and August 2003, when the air temperature ranged between 5 and 10 °C. All linear relationships were significant at $P < 0.05$. *ε_g is based on absorbed irradiance by the canopy, but this does not account for the effect of diffuse fraction on light absorption (see Section 2).

(ca. 25% of total area). For the grassland and barley crops, daily GPP was light-limited and the linear light use efficiency model gave a good fit with a high r^2 value. The forest canopy was less light-limited than the barley and grassland canopies and a non-linear response gave the best fit with a higher r^2 value (Fig. 6). Daily ε_g was generally higher in the barley crop and grassland, compared to the Sitka spruce forest (Fig. 7; Table 3).

The lower maximal daily GPP at the forest (Fig. 6), compared to the other sites may be associated with higher proportional respiratory loss, as evident from the ratio of daytime R_e to GPP, calculated over the same time period and temperature range. Between April and August 2003, when air temperatures were between 10 and 15 °C, the mean daytime R_e:GPP was higher at the at the forest (0.53), compared to the grassland and (0.43) and barley (0.41) sites.

Daily ε_g, for the different ecosystems varied depending on air temperature (Table 3) and R_d:R_s (Fig. 7). The highest daily ε_g, for all three ecosystems occurred for the temperature range 5–10 °C. The lower daily ε_g values were recorded for the highest and lowest temperature ranges (Table 3).

Variations in daily ε_g, within a particular temperature range, were primarily associated with changes in R_d:R_s (Fig. 7). There was a positive relationship between GPP and R_d:R_s, over the temperature range of 5–10 °C, with a somewhat lower slope for the forest (0.59), compared to the barley (1.31) and grassland sites (1.59; Fig. 6).

Table 3
Apparent light use efficiency (ε_g)[a] of the three crop canopies over different temperature ranges

Temperature range (°C)	ε_g (g C MJ^{-1})		
	Forest	Spring Barley	Grassland
<0	0.48 (0.21)		0.32 (0.14)
0–5	0.88 (0.28)	–	0.86 (0.34)
5–10	0.98 (0.31)	1.38 (0.58)	1.56 (0.60)
10–15	0.89 (0.22)	1.17 (0.31)	1.11 (0.56)
>15	0.48 (0.20)	–	0.75 (0.28)
April–August 2003	0.71 (0.26)	1.28 (0.38)	1.33 (0.28)

The values for ε_g are means and standard deviation (in parenthesis), based on the slope of daily gross primary productivity (g C m^{-2} day^{-1}) vs. absorbed solar radiation (MJ m^{-2} day^{-1}).

[a] ε_g is based on absorbed irradiance by the canopy, but this does not account for the effect of diffuse fraction on light absorption (see Section 2).

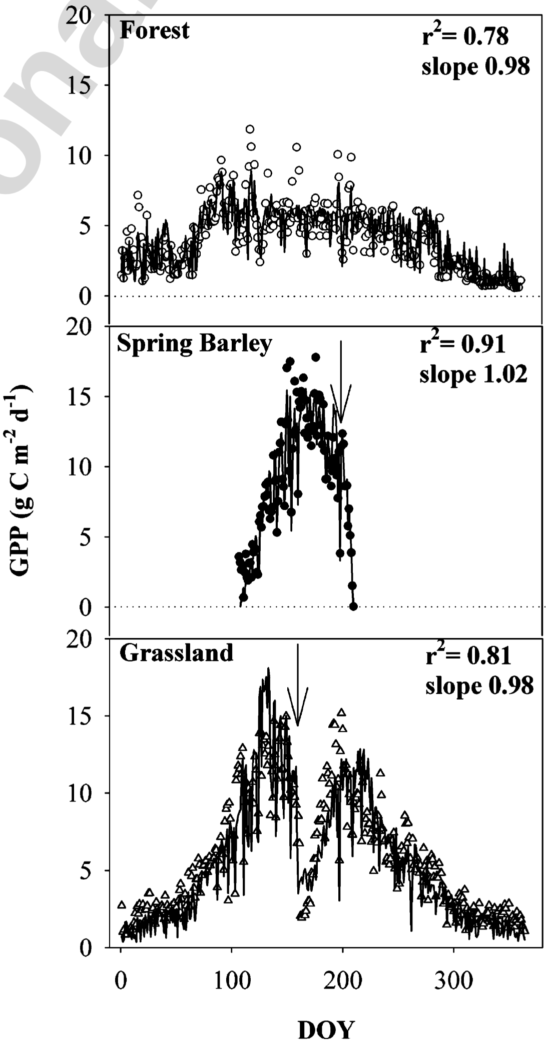

Fig. 8. Predicted (solid lines) and measured (symbols) daily gross primary productivity (GPP) for the three crop canopies during 2003. The arrows indicate the onset of senescence for the barley canopy and where the silage cut occurred at the grassland site.

3.6. Annual GPP estimates

There was good agreement (r^2 = 0.78–0.91) between the estimated (Eqs. (4) and (5)) and predicted daily and annual GPP values for all of the three land-use types (Fig. 8). Seasonal patterns of GPP tracked seasonal trends in R_s (Fig. 8). There was a net uptake of C by the grassland and forest canopy throughout the year, whilst the spring barley crop only took up C after 10–20 days following crop planting, until leaf senescence, equivalent to a total of 78 and 94 days for 2003 and 2004, respectively.

The maximum daily GPP was somewhat lower for the forest (12 gC m^{-2} day^{-1}), compared to the barley crop (17 gC m^{-2} day^{-1}) or the grassland (14 gC m^{-2} day^{-1}, Fig. 8). For the grassland and barley sites, GPP was highest at the maximum LAI, prior to the silage cut in June and grain filling in mid-July (Fig. 8). LAI varied between 0.54 and 8.4 m^2 m^{-2} for the grassland and 0–7.9 m^2 m^{-2} for the spring barley crop in 2003.

Annual GPP, between 2002 and 2004, was generally higher for the grassland (1999–2124 gC m^{-2} year^{-1}), compared to the forest (1870–1727 gC m^{-2} year^{-1}) or barley crop (967–715 t gC m^{-2} year^{-1}). However, 60–70% of the assimilated C was lost via respiration in the grassland, compared to ca. 45% for the barley and forest ecosystems (data not shown). Inter-annual variations (2002–2005) in GPP for the grassland and forest sites were less than 100 gC m^{-2} year^{-1} (or <5% of the mean value). The annual GPP for the barley site was lower in 2004 (715 t gC m^{-2} year^{-1}), compared to 2003 (967 gC m^{-2} year^{-1}). This was associated with lower than normal rainfall before anthesis (<16 mm between 5 May and 18 June) and resulted in a 13% drop in grain yield in 2004, compared to 2003 (unpublished data).

3.7. Effects of global dimming on GPP

Fig. 9 shows the estimated influence of reductions in R_s and R_d:R_s on ecosystem GPP, for three time periods with five irradiance/temperature scenarios. The significance ($P < 0.05$) of any changes in GPP in response to variations in irradiance or temperature was based on the linear regression of annual GPP over the corresponding time periods (i.e. the r^2 and the t-value for coefficients of determination were significant). The errors of estimation for the annual change in GPP were estimated as the standard deviation at 95% confidence levels for the slope of the linear relationship between estimated annual GPP over different time periods (i.e. 1955–2004, 1964–1984 or 1984–2004).

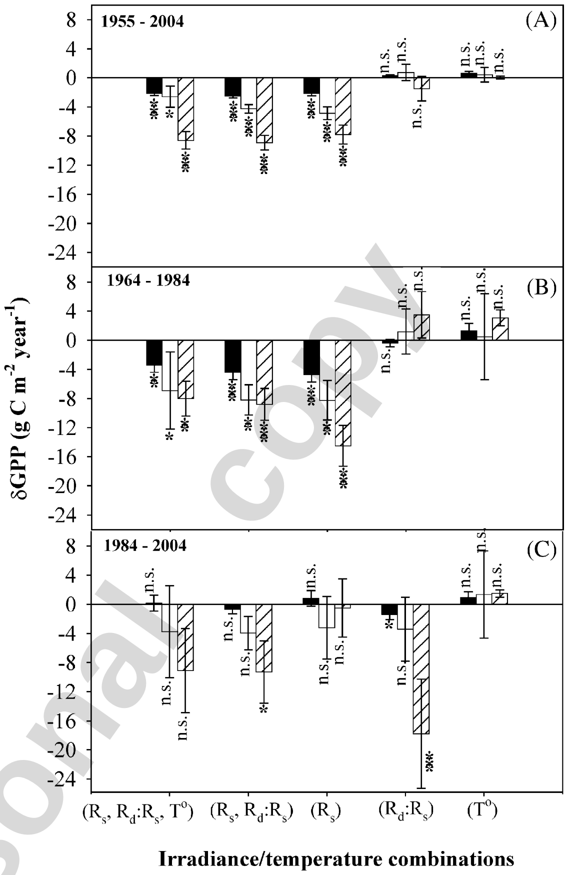

Fig. 9. The predicted influence of five different irradiance–temperature combinations variations in annual gross primary productivity (δGPP) between 1955 and 2004 (A), 1964 and 1984 (B), and over the last 20 years (C). The five different scenarios includes; the combined influence of changes in mean air temperature (T°), daily R_s and R_d:R_s (R_s, R_d:R_s, T°), the combined influence of both R_s and R_d:R_s (R_s, R_d:R_s) and the individual influences of changes in the three variables (R_s), (R_d:R_s) or (T°). The δGPP values (histograms ± S.E. bars) for the forest (black histograms), barley crop (white histograms) and grassland (hatched histograms) were significant at $^{***}P < 0.001$, $^{**}P < 0.001$ and $^{*}P < 0.05$; n.s.: not significant.

Generally, the increase in mean annual minimum (0.02 °C year^{-1}) and maximum temperatures (0.01 °C year^{-1}), between 1955 and 2004, had no effect on grassland, cropland or forest ecosystem GPP over the 50-year period. The small temperature-related increase in forest GPP, under this scenario, was consistent with the increase in GPP$_{\max}$ as temperature increased (data not shown) and the higher ε_g over the 5–10 °C, compared to the 0–5 °C temperature range (Table 3).

The decrease in R_s, between 1955 and 2004, resulted in a significant decrease in calculated GPP, varying from 2.5 to 7.8 gC m^{-2} year^{-1}, or 1.25 to 3.9 t C ha^{-1} over the 50-year period (Fig. 9). This would be equivalent to a reduction in GPP of 7%, for the forest, to 17%, for the grassland site, since 1955. For the time series between

1964 and 1984, where the decrease in R_s was ca. 21.1 MJ m^{-2} year^{-1}, GPP is predicted to decrease from 4.7 to 14.5 gC m^{-2} year^{-1}, or 0.98–2.9 t C over the 20-year period. The reductions in ecosystem GPP for all sites, prior to 1984, were greater when data were simulated using the scenario where only R_s was changed. Larger reductions in the R_s-related decline of GPP at the grassland and barley site, prior to 1985, were associated with a higher ε_g and a linear response of GPP to irradiance (Table 3; Fig. 5).

No significant R_s-related changes in GPP were observed between 1985 and 2004 (Figs. 1 and 9). Over the same time period, the observed decrease in R_d:R_s resulted in a significant reduction in GPP for the forest (1.4 gC m^{-2} year^{-1}) and grassland (17.8 gC m^{-2} year^{-1}) sites. The greater reduction in grassland GPP, under this scenario, was consistent with the larger response of ε_g to variations in R_d:R_s (Fig. 7).

4. Discussion

The decrease in solar irradiance in Ireland since the 1950s, reported here, is consistent with the results obtained from an earlier study (Stanhill, 1998) and with global pyranometer measurements recorded at a range of geographic locations (Stanhill and Cohen, 2001). However, our study now provides evidence that a decline in R_s has ceased, or reversed at some sites in Ireland, since the mid-1980s. This is consistent increase in daily bright sunshine duration and may also have been associated with alterations in the optical properties of the atmosphere as indicated by changes in the slope of the relationship between R_d:R_s and R_s:R_o. Recent reports have suggested a widespread cessation of global dimming or even an increase in R_s since the late 1980s (Wild et al., 2005). In contrast, other studies report a continuing decline in localised R_s in Central Europe, Australia and Thailand until the present with no abrupt changes in the 1980s (Pinker et al., 2005; Philipona et al., 2004; Roderick and Farquhar, 2004; Tebakari et al., 2005).

Although recent reports do not provide consistent evidence for a uniform change in global R_s, indirect evidence for a discontinuation of global dimming comes from recent satellite data, which shows that the reflectance of radiation from the Earth's atmosphere has decreased since the 1990s (Pallé et al., 2004; Charlson et al., 2005). Indirect evidence from pan evaporation studies, again, provides conflicting results (Fig. 5; Roderick and Farquhar, 2002). We show that changes in both E_{pan} and R_s were consistent with the reported association between these two variables (Roderick and Farquhar, 2002). Even in Ireland the response was not uniform. Since the 1980s, E_{pan} increased at Valentia whilst it decreased at the Kilkenny site. The increase in E_{pan} after 1985 could not be attributed to an increase in R_s (Fig. 5). However, indirect assessments of R_s, based on E_{pan} observations, may only be valid if there are no changes in VPD or wind speed over the same period (Roderick and Farquhar, 2002). It is plausible, therefore, that changes in evaporation may be influenced by other factors, such as the North Atlantic Oscillation, particularly in western coastal areas, such as Valentia. At the Kilkenny site, the decline in both the observed and calculated E_{pan} was consistent with a slight but insignificant decrease in R_s between 1976 and 2003 (Fig. 5).

Although other studies (Zhang et al., 2004), including the previous Irish study (Stanhill, 1998), showed a linear decline in R_s over the last four to five decades, we suggest that these long-term trends can be interpreted differently, with two distinct phases, as indicated in Fig. 1. Such an interpretation is supported by a higher r^2 value for the linear decline in mean annual R_s, between 1950 and 1980, when compared to the entire 50-year data series (Table 1; Fig. 1). This interpretation also suggests a more rapid decrease in R_s up to the 1980s than previously suggested (Stanhill, 1998; Stanhill and Cohen, 2001; Zhang et al., 2004).

The effects of the absorption or scattering of light by aerosols and clouds on R_s are difficult to quantify because of their different effects on R_s (Stanhill and Cohen, 2001) that are confounded by historical, natural or climatic anomalies. Changes in the optical characteristics of the atmosphere at any given site, as indicated by the change in the slope of the relationship between R_s:R_d and R_s:R_o, is determined by the optical air mass which in turn is a function of numerous factors including turbidity, albedo and absorption (Monteith and Unsworth, 1990; Roderick, 1999). Whilst it has been reported that the slope of the relationship between R_d:R_s and R_s:R_o is relatively constant at different latitudes (Roderick, 1999), we show that there were site-specific changes in the slope of this relationship, particularly at Dublin Airport over the last 20 years, where the slope (m) has increased significantly. These results are consistent with more recent reports (Wild et al., 2005), suggesting that the clearness index of the atmosphere has increased since 1984, probably due to a decrease in aerosol loading. Long-term variations in annual R_s were not associated with changes in cloud cover (Fig. 3), measured as a total percentage of the sky or oktas. This suggests that differences in the optical properties of particular cloud types, such as variations in geometrical depth or water content, rather than cloud cover per se, has a major impact on both R_s and R_d (Stanhill and Cohen, 2001). It has been suggested that anthropogenic sulphate aerosols may only account for less than one-fifth of the observed reduction in global radiation over the last 50 years (Harvey, 2000). Therefore, reduced sulphate emissions (Power, 2003) may only partially explain the decrease in global dimming, particularly in non-urban areas. In contrast, localised reductions in the levels of pollutants, such as sulphate aerosols and black particles, may have a larger influence on both R_s and R_d in urban areas. We suggest that the increase in R_s at Dublin Airport, since the mid-1980s, may have been primarily associated with a decrease in absorbing black particles, whilst the continued decline in R_d:R_s could be due to a reduction in atmospheric scattering associated with a decrease in sulphate particles and/or sulphate cloud-forming nuclei.

It has been proposed that a decrease in R_s over the past 50 years is generally associated with an increase in R_d:R_s (Farquhar and Roderick, 2003). The consequences of an increase in the proportion of diffuse light is likely to have a positive affect on plant productivity particularly for canopies with a large LAI (Roderick et al., 2001; Gu et al., 2003). In contrast to previous reports (Farquhar and Roderick, 2003), we show that there has been no change in R_d:R_s prior to the mid-1980s, but this subsequently declined even though R_s remained unchanged. Based on our eddy covariance estimates of GPP for the three land-use categories, daily light use efficiency (ε_g) is significantly reduced as R_d:R_s decreases (Fig. 7). These findings are in agreement with the hypothesis that the decrease in ε_g is associated largely with a decreased absorption by the canopy. Concomitantly, this will be associated with an increased stomatal limitation on C gain due to higher vapour pressure deficits, under clearer sky conditions (Roderick et al., 2001; Gu et al., 2003). The results presented in this study suggest that the impact of changes in R_d:R_s on ε_g are primarily associated with variations in light absorption by the canopy, because GPP of crop and grassland canopies are largely unresponsive to VPD (Jarvis and Mc Naughton, 1986). Similarly, eddy covariance based evaluations of GPP of forests have also indicated a small response to VPD (Baldocchi et al., 1987).

We suggest that differences in the ε_g response to R_d:R_s by the three vegetation types (Fig. 7) may be related to leaf orientation, canopy structure and the proportion of photosynthetic to non-photosynthetic surfaces. For example, conifer forests are effective in distributing light throughout the canopy due to needle clumping and the uniform angular distribution of needles and shoots (Norman and Jarvis, 1974; Chapin et al., 2002) so that they may be less responsive to variations in R_d:R_s. These features, together with a high proportion of light being absorbed by non-photosynthetic tissues, may reduce the impact of changes in R_d:R_s on ε_g, when compared to grassland or arable crop canopies. A modelling study also reported a larger response of ε_g to variations in R_d:R_s in cereal crops ($n = 31$), compared to forest canopies ($n = 34$; Choudhury, 2001).

Canopy specific characteristics of the GPP response to absorbed irradiance may also be a function of canopy structure and/or inherent photosynthetic differences (Fig. 7; also see Turner et al., 2003). Needle clumping, together with a higher proportion of non-photosynthetic tissue and the relatively low photosynthetic capacity of conifers (Woodward and Smith, 1994) would lead to light saturation and the observed non-linear relationship between GPP and absorbed irradiance (Fig. 7; Jarvis and Leverenz, 1983; Turner et al., 2003). In the crop and grassland canopies, the higher ε_g (Fig. 8) may also be associated with a higher availability of nitrogen, due to fertilisation (Chapin et al., 2002; Turner et al., 2003).

The predicted decline in GPP (50–90 gC m^{-2} $decade^{-1}$), associated with a reduction of 17% in R_s, since 1955, was greatest for the grassland and crop systems because of the higher ε_g and the light-limited nature of GPP. The smaller predicted decline in GPP of the barley crop, compared to the grassland site was possibly due to the short crop rotation cycle (ca. 100 days). It is important to note that the decline in GPP in all sites was primarily related to changes in R_s and not R_d:R_s, up to 1984. Most theoretical and experimental studies suggest that small decreases in R_s, along with an increase in R_d:R_s may result in an increase in GPP (Liepert, 1997; Stanhill and Ianetz, 1997; Roderick et al., 2001; Farquhar and Roderick, 2003). We suggest that changes in R_d:R_s may have a larger influence on GPP of canopies in the future, but the sign or magnitude of the impact would depend on geographical location, climate or atmospheric conditions. Intercomparisons between modelling and experimentally based assessments of the influence of global dimming on photosynthetic performance are, however, difficult because of problems associated with both methodologies. Experimental approaches generally involve the use of shading treatments with reductions in irradiance that are far greater than those observed due to global dimming (Singh and Gopal, 1970). In addition, shading treatments are likely to create a more diffuse radiation field and a lower VPD, thereby confounding the interpretation of the results. Modelling approaches, on the other hand, are inherently oversimplified and do not include the effects of genetic plasticity and acclimation to high or low irradiance (this study; Monteith, 1977; Landau et al., 1998). However, it is generally accepted that the intrinsic light use efficiency of crop varieties have not changed over the past 50 years (Evans, 1993; Hafner, 2003; Chloupek et al., 2004), so it is plausible that changes in GPP may be due to alteration in the amount and nature of solar irradiance.

Whilst it can be argued that the use of an over simplified integrated daily GPP–light response model may not reflect the short-time scale photosynthetic processes and that ε_g may not be a linear function of irradiance over short time scales, we opted to use the daily GPP model because of the original format of the long-term radiation data. The integrated daily or even annual GPP approach has, however, been used in numerous modelling studies (e.g. Choudhury, 2001; Roderick et al., 2001).

Although we do show there were significant reductions in GPP in response to changes in R_s and R_d since 1955, these represent very small annual changes in crop yield. For example, an annual decline in GPP of 14 g C m^{-2} $year^{-1}$ would be equivalent to the mean maximal daily GPP for the three different sites. The evidence presented here as well as reports from studies suggest that a 10–20% reduction in global irradiance, if accompanied by no other climate changes, would have a minor effect on either crop yield or plant productivity. For example, the 0.4 t C ha^{-1} $decade^{-1}$ (4 gC m^{-2} $year^{-1}$, Fig. 9A) decrease in GPP for the barley crop, since 1955, would be equivalent to a grain yield reduction of ca. 0.2 t d.wt ha^{-1} $decade^{-1}$ or 2.8% per decade. This is based on a respiratory cost of 46% (Choudhury, 2001), a biomass C content and harvest index of 50% (unpublished data) and a mean grain yield of 7 t ha $year^{-1}$ (Chloupek et al., 2004). These changes are small in comparison to the large increase in crop yield associated with fertilisation, the introduction of improved varieties and more efficient management practices over the last 50 years (Hafner, 2003; Chloupek et al., 2004). The potential decrease in silage yield, due to a reduction in both R_s and R_d:R_s, at the grassland site would be slightly higher (9% per decade), based on an annual silage yield of 9 t d.wt ha^{-1} $year^{-1}$ and a C content of 40% (unpublished data). Although we have not assessed the consequences of a reduction in R_s for different aged forests, the potential reduction in timber yield at the forest site, which is due for the first thinning cycle, would be equivalent to 0.28 m^3 ha^{-1} $decade^{-1}$ or 1.4% per decade, based on a mean timber yield of 20 m^3 ha^{-1} $year^{-1}$, a biomass expansion factor of 2.2 t t^{-1} (total biomass to timber ratio), a timber density of 0.4 t m^{-3} and a mean C content of 50% (Black et al., 2004). Therefore, the predicted change in productivity associated with global dimming for each of the land-use types are small, in comparison with the large increase in yield (20–60%) due to nitrogen deposition in European forests (Nabuurs et al., 2002) or the increased use of fertilizers on arable crops over the past 50 years (Hafner, 2003; Chloupek et al., 2004).

5. Conclusion

We provide direct and indirect evidence of a cessation of the previously reported decline in solar radiation across various sites in Ireland. These localised changes and associated variations in atmospheric optical properties may, in part, be due to alterations in cloud optical properties and reductions in pollutants, such as black particles, sulphate particles and/or sulphate cloud-forming nuclei. We suggest that the predicted changes in productivity associated with the observed long-term reduction in global irradiance for each of the land-use types are small. However, the continued decline in the R_s:R_d may have larger influence in GPP and crop productivity in the future.

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