Rapid report

A relationship between galactic cosmic radiation and tree rings

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Received: *10 July 2009*
Accepted: *14 August 2009*

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New Phytologist (2009) **184**: 545–551
doi: 10.1111/j.1469-8137.2009.03026.x

Key words: diffuse radiation, galactic cosmic rays, Sitka spruce (*Picea sitchensis*), tree rings, volcanic eruptions.

Summary

- Here, we investigated the interannual variation in the growth rings formed by Sitka spruce (*Picea sitchensis*) trees in northern Britain (55°N, 3°W) over the period 1961–2005 in an attempt to disentangle the influence of atmospheric variables acting at different times of year.
- Annual growth rings, measured along the north radius of freshly cut (frozen) tree discs and climatological data recorded at an adjacent site were used in the study. Correlations were based on Pearson product–moment correlation coefficients between the annual growth anomaly and these climatic and atmospheric factors.
- Rather weak correlations between these variables and growth were found. However, there was a consistent and statistically significant relationship between growth of the trees and the flux density of galactic cosmic radiation. Moreover, there was an underlying periodicity in growth, with four minima since 1961, resembling the period cycle of galactic cosmic radiation.
- We discuss the hypotheses that might explain this correlation: the tendency of galactic cosmic radiation to produce cloud condensation nuclei, which in turn increases the diffuse component of solar radiation, and thus increases the photosynthesis of the forest canopy.

Introduction

It is important to understand how forests respond to climatic changes at large temporal scales. Forests belong to the most extensive ecosystems on the planet and are a substantial part of the biosphere, which is one of four interlinked major pools, along with fossil carbon, the oceans and the atmosphere, comprising the global carbon cycle (Schimel, 1995; Byrne & Green, 2004; Grace, 2004). These climatic changes include those that are much-discussed such as temperature, but also those that are less well understood, including changes in cloud cover and atmospheric turbidity. Cloud and turbidity both change over short periods with the weather but also over long periods because of anthropogenic pollution as well as naturally occurring aerosols, such as pollen, dust or materials resulting from volcanic eruptions. By studying how atmospheric conditions, particularly diffuse radiation, affect forest growth, we might understand how forests respond to short-term changes in cloud cover and the longer-term phenomenon of 'global dimming' (Roderick *et al.*, 2001; Stanhill & Cohen, 2001; Roderick, 2006; Mercado *et al.*, 2009) associated with industrial pollution.

Growth conditions change over years and decades, and the annual and periodic growth of needles, shoots and tree rings varies considerably (Spiecker, 1999). Active cell division in the vascular cambium layer produces cells which expand and displace the cambium in an outward direction. In trees from boreal and temperate latitudes, cambial activity is not constant throughout the year. This discontinuity causes the phenomenon of growth rings (Fritts, 1966; Creber, 1977). Yearly tree rings are added to the stem, recording the effect of the respective year's climatic conditions in which they grew.

Dendrochronologists, seeking to reconstruct past climates, have often emphasized the role of temperature in the formation of these rings. By contrast, this study investigates the possible link between growth and a wide range of climatological variables, including diffuse radiation over several decades.

Diffuse radiation is known to stimulate canopy photosynthesis primarily because it penetrates into the canopy more effectively than the direct solar beam (Gu *et al.*, 2003; Suzaki *et al.*, 2003; Urban *et al.*, 2007). There may also be an additional mechanism for this stimulation associated with differences in the spectra of diffuse light vs direct sunlight (Federer & Tanner, 1966; Urban *et al.*, 2007). These shifts in spectral distribution of light , like temperature, also affect stomatal conductance (Morison & Jarvis, 1983). We therefore expect annual growth rates to be significantly stimulated by diffuse light especially when received at high intensity, as occurs during the spring and summer.

Previous work revealed a short-term relationship between CO_2 exchange and diffuse vs direct solar radiation. In the present work we tested the hypothesis that diffuse radiation stimulates growth of the trees over longer (decadal) periods.

Materials and Methods

To investigate the interannual variability in tree growth, discs from sections of mature stems (below 1 m) of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) were used. Thirty discs were provided by Forest Research, the research agency of the Forestry Commission, from the Forest of Ae (Dumfriesshire, Scotland, UK; 55°16′ N; 3°10′ W, 245 m above sea level (a.s.l.)).

The trees had been planted in 1953 and felled in February 2006 (the last complete growth ring being therefore 2005) following felling protocols laid out by Forest Research (Mochan & Gardiner, 2007). Before felling, north and west directions were marked on the bark, and the discs were frozen as soon as they were returned to the Forest Research station.

Discs were scanned on an A3 scanner and rings were counted in their frozen state using WINDENDRO (Version 2003a/b; Regent Instruments Inc., Sainte-Foy, QC, Canada). This method enables an accurate measurement of the actual width; this is often ignored when using dried discs or tree cores, which tend to shrink and crack during the drying process and may be differentially affected by moisture content. None of the discs used in the final analysis showed anomalous growth patterns, such as branch development, injury marks or false rings which might have influenced the growth of the tree on its northern side. The north radius was measured, in order to avoid 'noise' caused by compression wood (east) or downwards slope extension compensation (west) wood. The southern radius was ignored as it may have been influenced by microclimatological variation caused by direct solar irradiance.

Tree rings increase in thickness over the first few years of growth and then decrease steadily towards the bark (Dinwoodie, 1962; Phipps, 1982), assuming no thinning or fertilizer application has interrupted the natural growth. This trend of standard age was factored out by detrending before analysis. This was done by (1) first removing data covering the first few years (the juvenile section), (2) fitting a simple cubic spline to the remaining 45 ring width values. The residuals were taken as representing the effect of climate signals on tree growth (henceforth called the annual growth anomaly).

Meteorological data at Eskdalemuir Observatory, UK (55°12′N; 3°35′W, 350 m a.s.l.) including direct and diffuse solar radiation have been recorded by the British Met-Office (UKMO; Exeter, UK), and were provided by the British Atmospheric Data Centre (BADC; Chilton, UK). Where necessary, gaps were filled by two different methods. Either a simple linear interpolation was applied or, in the case of missing global or diffuse radiation data, the data were replaced by a weighted mean of the same day of the neighbouring year (Aeby, 2007).

Galactic cosmic ray fluxes are known to be dependent on latitude (Svensmark & Friis-Christensen, 1997; Pallé & Butler, 2000; Kirkby, 2007). Monthly corrected galactic cosmic ray flux data recorded at Kiel Neutron Monitor are held by the Christian-Albrechts-Universität zu Kiel and provided by the National Geophysical Data Center, (Boulder, CO, USA; (http://www.ngdc.noaa.gov/stp/SOLAR/ftpcosmicrays.html). Information on the locality and time of volcanic eruptions, as well as on the volcanic explosivity index relevant for this study originate from the Smithsonian Institution, Global Volcanism Program (http://www.volcano.si.edu).

Following the approach of Grace & Norton (1990) we tested the correlation between the annual growth anomaly and the climatological and atmospheric variables, month by month using the Pearson product–moment correlation coefficients. Although the ring width is a time-averaged property, the rings do not form throughout the entire year, and are dependent on stored assimilates. Often the early dendrochronologists found a 'lag effect' whereby the conditions of the previous year influence the growth of the present year (Fritts, 1962; Creber, 1977). We therefore tested the effect of the variables month by month, for the present year and the previous year.

Results

The cubic spline represented the age-related decline in ring width very well ($r^2 = 0.97$), showing a characteristic decline in radial growth as the trees aged (Fig. 1). The residuals suggest distinct periods of anomalous growth, and specific years when growth departed from the average trend. We call these residuals 'annual growth anomaly'.

Most variables were only weakly correlated with the annual growth anomaly: total solar radiation was never statistically significantly correlated with the growth anomaly but diffuse radiation was significantly correlated in some months (Fig. 2). When considering the diffuse radiation received over the spring and summer months, we observed a statistically significant correlation: the amount of diffuse radiation received over the spring and summer (March–August) period was statistically positively correlated with the annual growth anomaly, with a correlation coefficient of +0.29 ($P = 0.05$; $n = 45$).

Temperature was negatively correlated with growth in the months of June and September, and precipitation was negatively correlated with growth in February and October. There were correlations between the annual growth anomaly and both the water vapour pressure deficit (VPD) and the calculated height of the most frequently occurring cloud base.

The galactic cosmic ray (GCR) flux shows a well-known periodicity that is anticorrelated with the sunspot number, with four maxima in the period 1961–2005 (Fig. 3). Surprisingly, the tree ring data show a similar periodicity although it is possible to identify particular years where the relationship is broken by instances of extreme weather: for example 1995 was an especially warm and dry year in Scotland as in much of Europe, and under these conditions the tree rings were reduced in size. The probability of such a good relationship between the annual growth anomaly and galactic cosmic ray flux occurring by chance alone is 0.008 ($n = 45$, $r = 0.39$) (see the inset of Fig. 3). Of all the variables investigated, it is by far the one most correlated with the annual growth anomaly.

Diffuse radiation is associated with periods of high volcanism. When the fraction of the incoming solar radiation that is received as diffuse radiation is examined in relation to the occurrence of volcanoes with a volcanic explosivity index (VEI) of 3 and higher which have erupted upwind (to the west of the UK) it appears that the fraction of diffuse radiation is often less in periods where there are few volcanoes (Fig. 4).

Discussion

There were correlations between annual growth anomaly and both the water vapour pressure deficit (VPD) and the

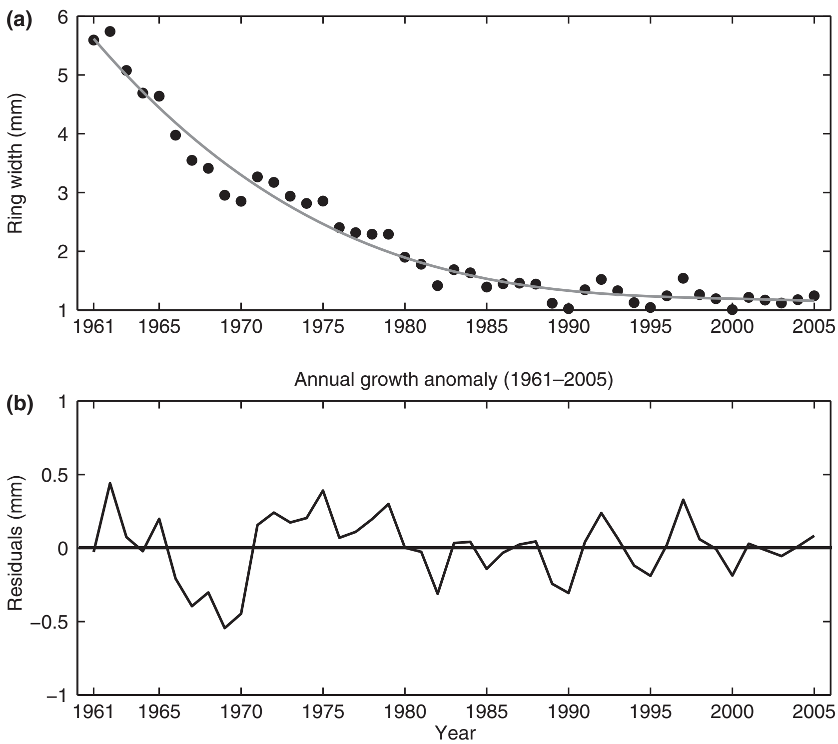

Fig. 1 Distribution of the mean tree ring width (a) and the resulting annual growth anomaly (b) after applying the de-trending method.

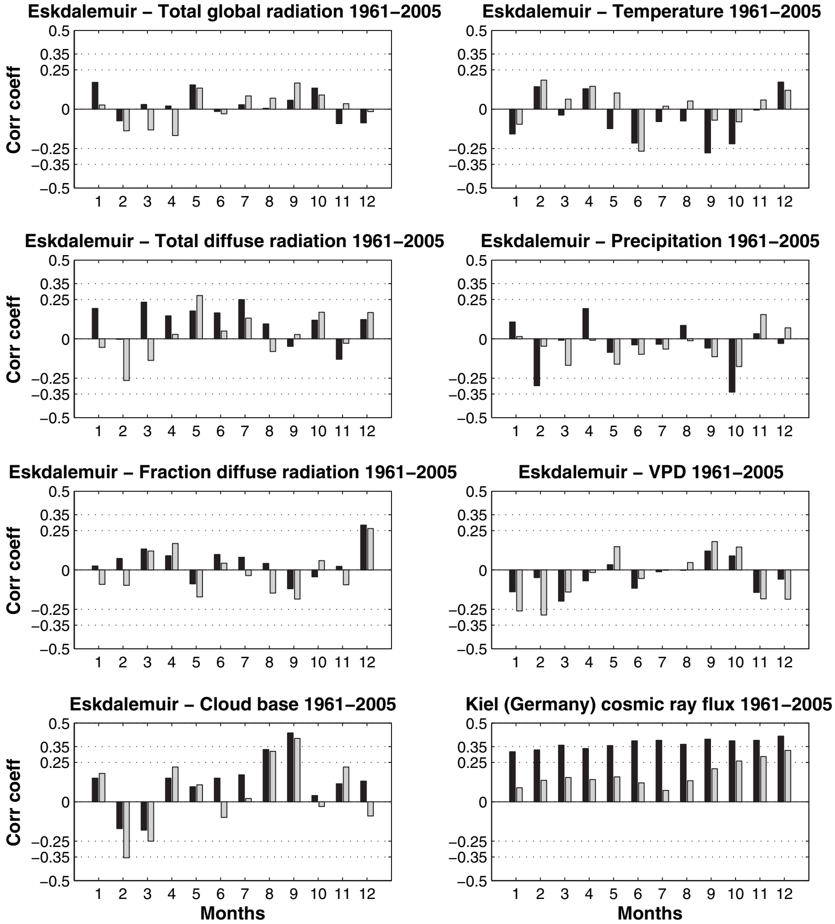

Fig. 2 Pearson correlation coefficients between climatic variables recorded in Eskdalemuir (Scotland, UK) between 1961 and 2005, and the annual growth anomaly. The histograms show the correlations, month by month, for the respective (closed bars) and the previous year (tinted bars; see main text for a full explanation). Correlation coefficient values of 0.25 and 0.35 respectively correspond to the ± 0.1 and ± 0.02 significance level.

height of the most frequently occurring cloud base. The VPD has long been known to influence photosynthesis for the reason that the stomata close when the air is dry, especially in this species (Grace *et al.*, 1975; Neilson & Jarvis, 1975). Cloudiness *per se* may be expected to reduce plant growth through a reduction in solar insolation, although Williams *et al.* (2008) have found that the effect of cloud cover on tree growth, and thus ring width, may vary depending on the type of cloud, the time of day, and the time of year.

We were surprised to see that the GCR flux (Kiel Neutron Monitor, 54°34′ N; 10°12′ E, 54 m a.s.l.) was statistically significantly correlated with the annual growth anomaly in all months, and the first presumption is that GCRs create aerosols and thus change the radiation field. However, processes other than GCR flux are involved in aerosol production and may also modify the radiation field, and thus mask any effect of galactic cosmic radiation.

First, volcanic eruptions affect the flux of diffuse radiation received at the Earth's surface even when they are many thousands of miles away. While sulphur aerosols are capable of remaining in the atmosphere over 1–3 yr and ashes only a few months, aerosols resulting from GCRs have a much shorter lifespan. According to Yu & Turco (2000); Kristjansson *et al.* (2002) these aerosols have a lifespan of only a few days, so cloud formation and any consequent impact on photosynthesis should take place within this short time. Second, local aerosol production by coniferous forests has been observed (Kulmala *et al.*, 2001, 2007), and may be expected to modify the diffuse radiation flux, possibly at a regional scale in highly forested areas.

It has been observed that GCR cycles are correlated with cloud cover (Svensmark & Friis-Christensen, 1997; Marsh & Svensmark, 2000; Pallé & Butler, 2000). Moreover, a description of this process is presented by Yu & Turco (2000) and Harrison & Carslaw (2003). Substantial ionizing radiation is also produced from radioactive decay of elements below the surface of the soil (Kotaka & Krueger, 1978) and released to the atmosphere according to soil depth and moisture, but does not vary in cycles as we see in GCRs. The correlative studies linking GCRs to cloud formation have, however, been challenged (Kristjansson *et al.*, 2002; Laut, 2003).

The following casual link between GCRs, and the formation of clouds has been proposed: GCRs stimulate ionization, which leads to more nucleation and thus more aerosol

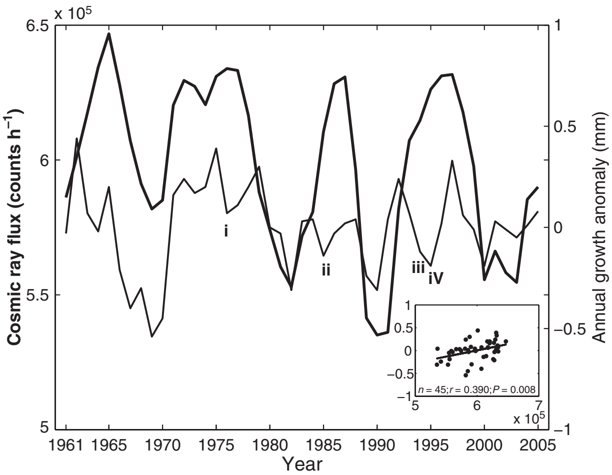

Fig. 3 Cosmic ray flux (bold line) and the growth anomaly (thin line) of Sitka spruce. A distinct periodicity is visible with four distinctive maxima over the period 1961–2005. The inserted (lower right) graph shows the correlation (n = 45, r = 0.39, P = 0.008) between the galactic cosmic ray flux and the annual growth anomaly. Instances of extreme weather are noted as follows: (I) in 1976 most parts of the UK experienced severe drought (Morren, 1980; Jarvis & Mullins, 1987; Kay, 2004), (II) Eskdalemuir recorded snow in June 1985 (Burt, 1985), (III) extreme cold and wet weather occurred in 1994 (UK MetOffice, 2008a,b) and (IV) 1995 was an especially warm and dry year in Scotland (Buckland *et al.*, 1997; UK MetOffice, 2003), as in much of Europe. If anomalous years are excluded the correlation coefficient increases from 0.39 to 0.64 (r^2 = 0.41).

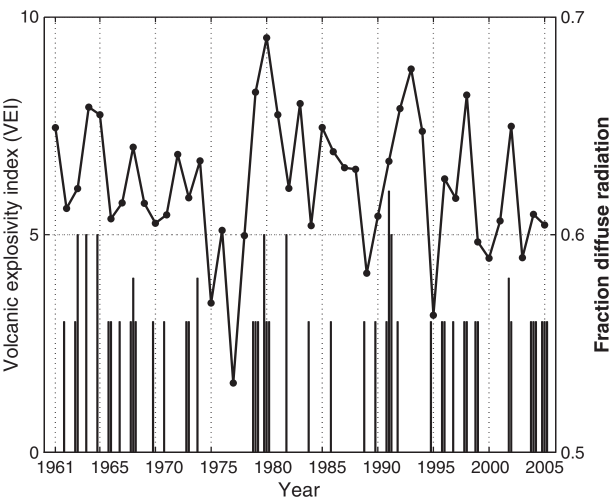

Fig. 4 The fraction of diffuse radiation received at Eskdalemuir (Scotland, UK) over the period 1961–2005 and volcanoes erupted upwind with an explosivity index of ≥ 3 (tephra volume > 0.01 km^3). The volcanic explosivity index (VEI) is a logarithmic scale indicating the magnitude and intensity (volume of produced ash, height of eruption cloud and the duration) of eruption.

particles; these particles serve as cloud condensation nuclei and thus enhance cloud formation (Carslaw *et al.*, 2002; Harrison & Carslaw, 2003; Curtius *et al.*, 2006). At present, the debate regarding the link between GCRs, aerosols, clouds and diffuse radiation continues (Carslaw, 2009; Kerr, 2009). Recent models (Pierce & Adams, 2009) show only small effects of GCRs on clouds but do not rule out the possibility of such a link.

We propose the possible hypotheses to account for the strong link between GCR flux and the annual growth anomaly. We call this hypothesis the radiation-scattering effect. To explain the link between GCRs and the annual growth anomaly we propose that the forest 'sees' a radiation field that is to some extent modified by scattering of radiation by the aerosol particles derived from the flux of GCRs (Kulmala *et al.*, 2001; Harrison & Stephenson, 2006). This modification may not be seen readily by traditional broad-band radiation sensors, especially against a 'noisy' background of synoptic weather patterns and spectral distribution of sky light. In this hypothesis the resulting increase in diffuse radiation stimulates photosynthetic production via the mechanisms demonstrated by Urban *et al.* (2007).

We cannot, however, rule out the possibility of a direct stimulatory effect of GCR on the growth of trees, as beneficial effects have sometimes been demonstrated in biological materials exposed to GCR in space (Hammond *et al.*, 1996), despite the prevalence of chromosomal aberrations in such materials (Nevzgodina, 1999).

Dendrochronogists have sometimes reported cyclic phenomena in long time-series of tree-rings but they have rarely offered an explanation (Douglass, 1927; Siren & Hari, 1971; Briffa, 1994; Rigozo *et al.*, 2007). For example, in a study of 305 tree-ring chronologies from North America, periods of 18.6 yr and 10.5 yr were found in 286 and 244 instances (Currie, 1991), respectively. These observations have been largely ignored, perhaps because no underlying mechanism could be found to explain the intriguing results.

Acknowledgements

We thank Dr Barry A. Gardiner and Dr Mike Perks from Forest Research, Northern Station (Roslin, Scotland, UK) for providing us with freshly cut tree discs used in the current study, for information on Forest of Ae and the initial help with the analysis of tree ring data with WINDENDRO. Furthermore, the authors would like to thank the British Atmospheric Data Centre (BADC) for the provision of meteorological data (UK MetOffice) for Eskdalemuir. Galactic cosmic ray flux data recorded at Kiel Neutron Monitor are held by the department of Extraterrestrial Physics, Institute for Experimental and Applied Physics, Christian-Albrechts-Universität zu Kiel and provided by the National Geophysical Data Center, Boulder, Colorado (USA) (http://www.ngdc.noaa.gov/stp/SOLAR/ftpcosmicrays.html). Information on the locality and time of volcanic eruptions, as well as on the Volcanic Explosivity

Index relevant for this study originate from the Smithsonian Institution, Global Volcanism Program (http://www.volcano.si.edu). Prof. Alan Blyth kindly commented on the manuscript. SD was funded by the Torrance Bequest.

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