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ARTICLE

Detection and removal of disturbance trends in tree-ring series for dendroclimatology

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Abstract: Nonclimatic disturbance events are an integral element in the history of forests. Although the identification of the occurrence and duration of such events may help to understand environmental history and landscape change, from a dendroclimatic perspective, disturbance can obscure the climate signal in tree rings. However, existing detrending methods are unable to remove disturbance trends without affecting the retention of long-term climate trends. Here, we address this issue by using a novel method for the detection and removal of disturbance events in tree-ring width data to assess their spatiotemporal occurrence in a network of Scots pine (*Pinus sylvestris* L.) trees from Scotland. Disturbance trends "superimposed" on the tree-ring record are removed before detrending and the climate signals in the precorrection and postcorrection chronologies are evaluated using regional climate data, proxy system model simulations, and maximum latewood density (MXD) data. Analysis of subregional chronologies from the West Highlands and the Cairngorms in the east reveals a higher intensity and more systematic disturbance history in the western subregion, likely a result of extensive timber exploitation. The method improves the climate signal in the two subregional chronologies, particularly in the more disturbed western sites. Our application of this method demonstrates that it is possible to minimise the effects of disturbance in tree-ring width chronologies to enhance the climate signal.

Key words: disturbance, Scotland, proxy system modelling, intervention detection, tree rings.

Résumé : Les événements perturbateurs non climatiques font partie intégrante de l'histoire des forêts. Bien que la détermination de l'occurrence et de la durée de tels événements puisse aider à comprendre l'histoire environnementale et les changements de paysage dans une perspective dendroclimatique, une perturbation peut masquer le signal climatique dans les cernes annuels. Cependant, les méthodes actuelles de suppression des tendances sont incapables d'éliminer les tendances de perturbation sans influencer le maintien des tendances climatiques à long terme. Dans cette étude, nous abordons ce problème en utilisant une nouvelle méthode de détection et de suppression des événements perturbateurs dans les données de largeur de cernes annuels pour estimer leur apparition spatiotemporelle dans un réseau de pins sylvestres (*Pinus sylvestris* L.) en Écosse. Les tendances de perturbation superposées à la chronologie de cernes annuels sont éliminées avant la suppression des tendances, et les signaux climatiques des chronologies avant et après correction sont évalués à l'aide de données climatiques régionales, de simulations avec un modèle basé sur un système de proxy, et de données de densité maximale du bois final (DMX). L'analyse de chronologies sous régionales provenant des West Highlands et des Cairngorms, dans l'est, révèle une plus grande intensité et un historique de perturbations plus systématiques dans la sous-région de l'ouest, probablement liées à une exploitation forestière extensive. La méthode améliore la détection du signal climatique dans les chronologies des deux sous-régions, particulièrement dans le cas des stations plus perturbées de l'ouest. Notre application de cette méthode démontre qu'il est possible de minimiser les effets des perturbations dans les chronologies de largeur de cernes annuels de façon à améliorer la détection du signal climatique. [Traduit par la Rédaction]

Mots-clés : perturbation, Écosse, modélisation basée sur un système de proxy, détection des interventions, cernes de croissance.

1. Introduction

Nonclimatic disturbance events represent an integral element of forest dynamics, and the identification of the occurrence and duration of such events using tree-ring data may serve to help understand environmental history and landscape change. The conceptual linear aggregate model (Cook 1985) of tree growth describes the production of the annual growth increment as the aggregation of multiple factors (eq. 1).

$$G_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t \quad (1)$$

where, for year t, G_t represents total growth, A_t expresses the age-related growth trend, C_t represents the climate trend, $\delta D1_t$ is the endogenous tree-specific disturbance internal to the local stand, $\delta D2_t$ is exogenous disturbance impacting all trees within the stand, and E_t is variance due to random processes. From a dendroclimatic perspective, it is clear that the presence of nonclimatic components such as disturbance could obscure the climate signal in tree-ring data. To achieve an understanding of climatic variability from tree rings, it is necessary to isolate the desired climatic signal extant in tree-ring series while minimising the

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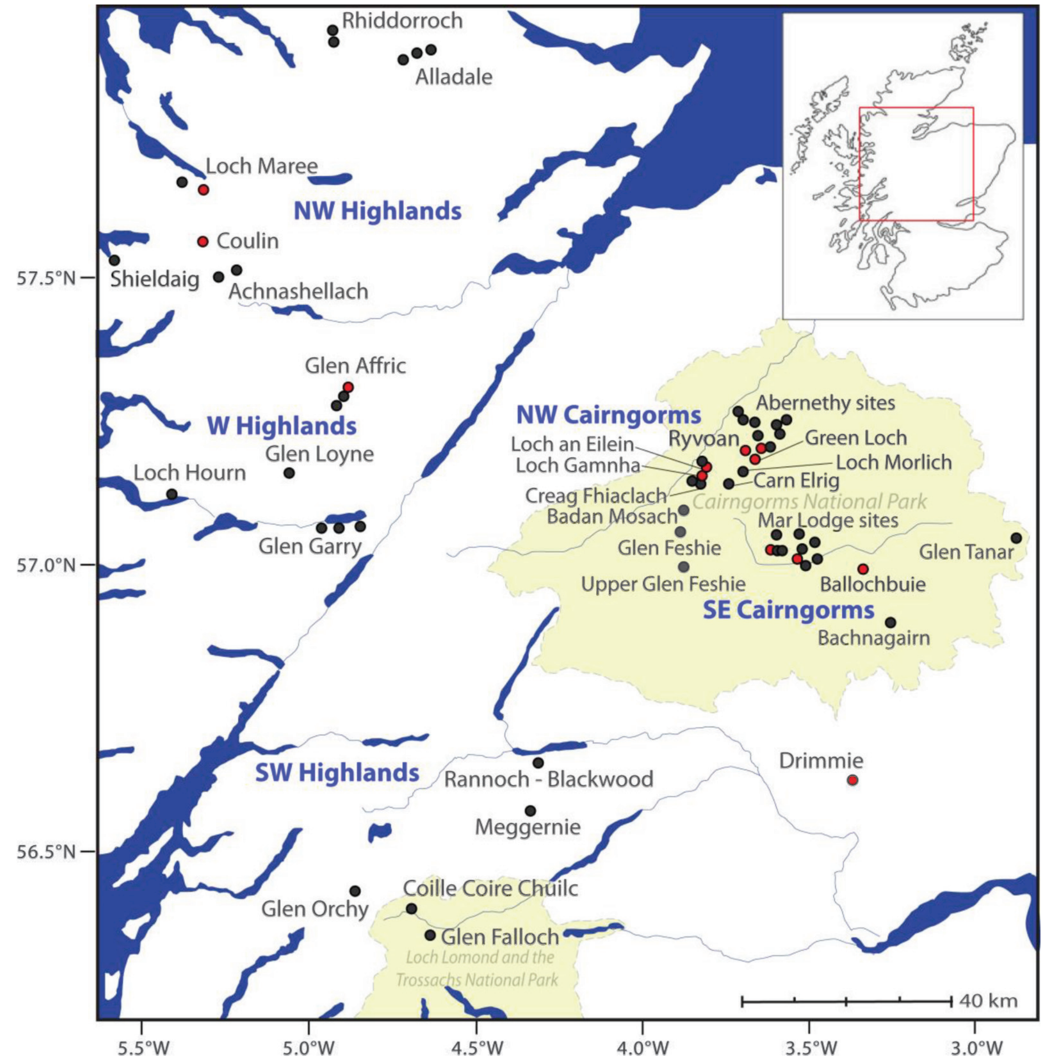
Fig. 1. Map of sampled tree ring site network in Scotland (sites marked in red represent sites for which maximum latewood density (MXD) chronologies have been developed in addition to ring width (RW)). Figure is provided in colour online.

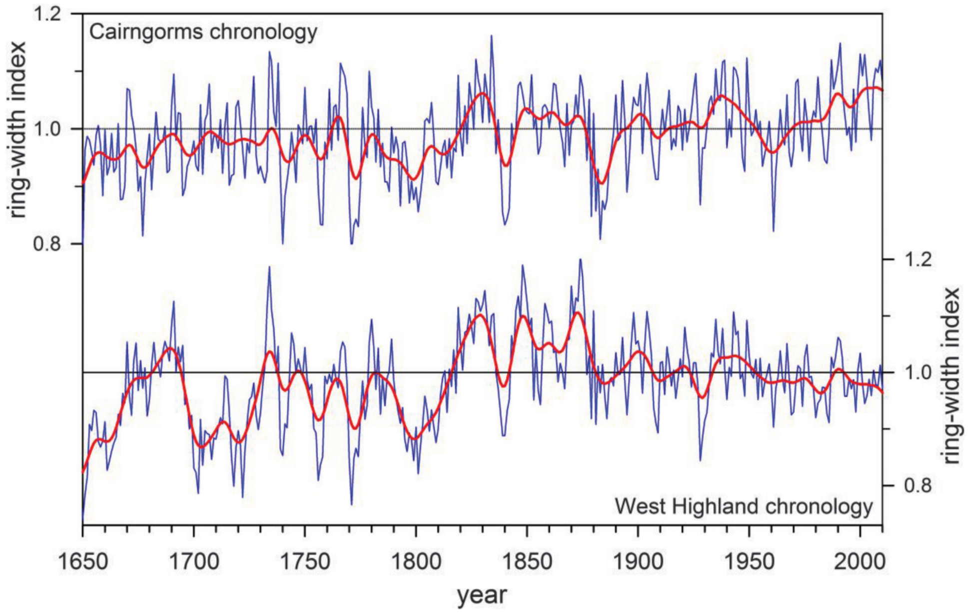


influence of other forcings such as disturbance. The removal of A_t is typically achieved by detrending, and because E_t is presumed to occur randomly in time and between trees in a stand, its influence can be minimised by increasing replication. Endogenous disturbance ($\delta D1_t$) is spatially limited and results from internal stand dynamics, whereas the origin of spatially more extensive exogenous disturbances ($\delta D2_t$) can, for example, include wind, fire, and outbreaks of disease and insects. Removal of endogenous and exogenous components can be complicated as such trends can mimic climatic trends. However, the nonsynchronous nature of endogenous disturbance trends within a stand represents a distinguishing feature that can serve to differentiate them from trends that reflect the wider scale influence of climate (Cook 1985).

As part of the Scottish Pine Project (available from http://www.st-andrews.ac.uk/~rjsw/ScottishPine/), a network of 44 living Scots pine (*Pinus sylvestris* L.) sites were sampled from seminatural pine woodlands throughout northern Scotland (Fig. 1). Through the development of this living tree network, a distinct difference was observed between trends in detrended ring width (RW) chronologies from sites primarily located in the west of the Scottish Highlands and from sites in the Cairngorms. The trend differences are apparent when standard detrending approaches are applied to create subregional composite chronologies (Fig. 2). We hypothesise that these differences are not related to varying climates between the two subregions but, rather, are predominantly related to the influence of growth changes due to disturbance events occurring through time. These disturbance events are most likely related to past anthropogenic woodland exploitation and clearance (Smout et al. 2005; Steven and Carlisle 1959). As Scots pine is a shade-intolerant species (Gaudio et al. 2011), it should be possible to detect growth releases as a result of canopy opening due to felling. Temporary increases in nutrient availability from logging residue (Hyvönen et al. 2000; Palviainen et al. 2004) and decreased competition following the clearance of neighbouring trees (Valinger et al. 2000) may also enhance this effect.

Importantly, although some detrending methods are capable of removing disturbance trends, they cannot do so without affecting the retention of long-term climate trends. For example, standard detrending approaches (e.g., negative exponential or linear functions) commonly used to detrend RW data cannot model and remove shorter term growth releases related to disturbance leading to biases in the final chronologies. Although it may be possible to remove disturbance-related trends from RW series with the use of more flexible detrending approaches such as cubic smoothing splines (e.g., Cook and Peters 1981), this approach will also remove multidecadal and longer term variability, which is undesirable for reconstructing past climate, as such trends may represent climatic variations. As disturbances bias the mid- to low-frequency components of a RW

Fig. 2. Subregional chronologies from the Cairngorms and West Highlands highlighting trend differences between the two composite chronologies developed using a standard (negative exponential or linear) detrending approach (curves in red represent the original chronologies smoothed with a 20 year low-pass Gaussian filter to emphasise decadal variability). Figure provided in colour online.



chronology, the presence of nonclimatic (disturbance) trends needs to be addressed if RW data are to be used for dendroclimatic reconstruction. A possible solution is to identify disturbance in the RW record, quantify the contribution of these events to radial growth, and then attempt to isolate and remove these influences.

1.1. Detecting disturbance

Detection of disturbance signatures in tree-ring data has received considerable attention in the context of a wide range of factors including natural and anthropogenic sources of disturbance such as wind and storm events (e.g., Foster 1988; Nagel et al. 2007; Svoboda et al. 2014), insect and pathogen outbreaks (e.g., Speer et al. 2001; Veblen et al. 1991), forest fires (Swetnam 1993), snow avalanches (Veblen et al. 1994), flooding (Yanosky and Jarrett 2002), forest stand dynamics (Fraver et al. 2009), environmental pollution (e.g., Elling et al. 2009; Rydval and Wilson 2012; Savva and Berninger 2010; Wilson and Elling 2004), timber harvesting, and woodland clearance (Bebber et al. 2004; Nowacki and Abrams 1997). A common approach to disturbance detection is based on the statistical identification of disturbance events manifested as either growth suppression or releases in the RW record with a duration ranging from one or more years to several decades.

In ecological studies, disturbance detection methods have typically relied on the identification of growth changes determined either as absolute changes (Čada et al. 2013; Fraver and White 2005) or, more commonly, as relative (percent) changes (Nowacki and Abrams 1997; Pederson et al. 2008; Svoboda et al. 2014) in growth to identify prolonged periods of growth release or suppression by comparison with periods of growth immediately prior to the initiation of the disturbance event. Increasingly sophisticated approaches include or specify additional detection criteria or data characteristics (e.g., Speer et al. 2001), accounting for a range of variables related to growth release or developing more adaptable release threshold criteria (Black and Abrams 2003). A set of specific growth release criteria were developed by Lorimer and Frelich (1989) and later adapted by Nowacki and Abrams (1997) to permit the detection of multiple events in a single sample. By assessing the percent growth change using 10 year radial growth means prior to and following each year of growth, their approach also attempted to minimise the likelihood of falsely detecting climate-related variability as disturbance releases (Nowacki and Abrams 1997).

The use of boundary-line release criteria offers a more flexible and adaptive method for the establishment of disturbance-related growth release thresholds by scaling releases according to the maximum physiological potential as determined by previous growth rates, which are species specific and may also vary regionally or locally (Black and Abrams 2003). Although the possibility of applying more unified release criteria to a range of species to facilitate both cross-species and between-site comparisons was proposed by Black and Abrams (2004), the development of species-specific boundary-line functions is normally necessary, although a single (universal) boundary line can be developed and applied over the range of some species (Nagel et al. 2007). A detailed comparative review of disturbance detection methods was presented by Rubino and McCarthy (2004). Although such methods are capable of identifying growth release events with varying success, they all lack the ability to remove disturbance trends from tree-ring records.

1.2. The combined step and trend method

Druckenbrod (2005) and Druckenbrod et al. (2013) developed a robust procedure to detect disturbances called combined step and trend intervention detection (CST), which accounts for temporal autocorrelation and age-related growth trends in ring-width data. The CST method employs a time series analysis approach for the identification of "interventions" (i.e., external forcings that affect a time series and that can be detected as outliers from a model of that time series) manifested as either step outliers or trend changes. The method has been shown to successfully identify instances of known disturbance, and the potential application of intervention detection to a range of species and growth environments has been proposed (Druckenbrod 2005; Druckenbrod et al. 2013). Intervention detection methods offer the capability to not only identify and assess the timing, duration, and magnitude of growth attributable to disturbance, but also quantify the contribution of these events to the RW record and remove their influence from the time series.

Druckenbrod et al. (2013) suggested that the removal of disturbance signals from RW series using an intervention detection approach could be applied to enhance the climate signal. Here, for the first time, we apply intervention detection in this manner. The application of this approach to RW chronologies from the Scottish Highlands offers an opportunity to evaluate its performance on an extensive network of sites without detailed a priori knowledge of the history of past disturbance but in a region where substantial timber extraction has taken place over the last five centuries. We use a variant of the CST method to detect and remove the disturbance "noise" superimposed on the climate signal and evaluate the spatiotemporal occurrence of disturbance events in RW chronologies from the Scottish pine network. We assess the climate signal in the pre- and post-correction chronologies using both simulated chronologies from the VS-Lite (Tolwinski-Ward et al. 2011) proxy system model and regional instrumental temperature data. We further evaluate differences between the corrected and uncorrected RW chronologies by comparison with a maximum latewood density (MXD) composite chronology from multiple sites across northern Scotland, which should represent a purer summer temperature signal that is not significantly affected by disturbances.

2. Materials and methods

2.1. Sampling sites and tree-ring data

The entire network of 44 RW Scots pine chronologies from the Scottish Highlands was utilised in this study (Fig. 1). Seven of these chronologies were supplemented with RW data from the International Tree-Ring Data Bank (ITRDB) originally used in Hughes et al. (1984) to reconstruct Edinburgh summer temperatures (Grissino-Mayer and Fritts 1997; ITRDB 2014). The Scottish regional MXD chronology was developed from 12 individual site chronologies (seven of which included MXD data archived in the ITRDB). A summary of individual site and chronology information is listed in Table 1. Two subregional clusters were defined for the Cairngorms National Park (including the southeast Highland site "Drimmie", hereafter referred to as "Cairngorms") and the sites stretching from the southwestern to the northwestern Highlands (hereafter referred to as "West"). For RW measurement, following standard dendrochronological practice (Stokes and Smiley 1968), samples were air-dried, mounted, sanded, and visually crossdated before measurement. Samples were measured to a precision of 0.001 mm with either a Velmex traversing measuring stage or CooRecorder (Larsson 2014) from scanned sample images. With the exception of the "older" ITRDB archived data, measurement of MXD followed the procedures described in Rydval et al. (2014). Crossdating was statistically validated using COFECHA (Holmes 1983) and CDendro (Larsson 2014).

2.2. Intervention detection and disturbance correction

The procedure employed for disturbance identification and correction follows Druckenbrod et al. (2013) and is briefly outlined below. Before detrending, power transformation (Cook and Peters 1997) of the measurements was performed to reduce heteroscedasticity in the RW series (or, in other words, to limit the increase in spread of the data with increasing level). The transformed measurement series were then detrended by fitting either negative exponential or linear regression functions. Negative exponential curves are fitted iteratively from the beginning of the transformed measurement series, and the curve length with the lowest mean squared error was selected to approximate A_t. This detrending approach removes the age trend for a RW series that would otherwise fail to fit a negative exponential curve due to a release event later in that RW series. The order (p) of the autoregressive (AR) model, which best fits each series, and AR model parameters were determined according to the maximum entropy "Burg" method (Barnard 1975). A residual time series from the AR model estimates and the detrended series were calculated. Inverse modelling was applied for the first "p" indices to permit the calculation of residuals for the full length of the series. Values of years with missing rings were estimated using one-step ahead AR model predictions. Running means of the residual series with varying window lengths (between 9 and 30 years) were used for outlier detection. As the distribution of these running means should approach a Gaussian distribution, it is possible to identify residual means beyond a specified threshold as outliers from this distribution. Tukey's biweight mean and scale (robust equivalent of standard deviation) were used to give more robust measures, as some distributions may only approximate a Gaussian distribution. A sequence of residuals was identified as an outlier when it exceeded a scale of 3.29 from the biweight mean. From all sets of detected outliers using a range of window lengths, the largest outlier was used to determine the first year of the intervention and also the window length that can be used to best characterise it. The disturbance trend was then removed, the AR model redetermined, and the entire process was iteratively repeated until no outliers were detected. In the CST method, removal of the disturbance trend is performed by fitting a linear regression to the outlier period. Additional details pertaining to the CST approach are described in Druckenbrod et al. (2013).

On occasion, the CST method may produce negative measurement values in parts of series when they are expressed in original measurement units after disturbance correction. Because negative measurements are illogical, all such values are treated as if no growth occurs (i.e., zero growth). This leads to a possible loss of information and also creates a potential problem when attempting to detrend series corrected with CST. For example, ARSTAN (Cook and Holmes 1986) is widely used for detrending tree-ring measurement data. However, the programme does not permit fitting a detrending function to measurements if this function were to be negative at any point. Even with power transformed series, this issue can occur with series which approach or reach "zero" measurement values. Although it is possible to utilise the transformed and detrended versions of the CST-corrected series for further analysis without the need to re-express these in original measurement units, this would prevent the application of alternative detrending approaches (which may be of particular importance for dendroclimatological analysis) other than the one currently integrated within the CST procedure as described above. Although it is possible to remove series that exhibit such characteristics (i.e., containing a series of zero measurement values), this would not be desirable as ~5%–10% of series may typically be affected and their exclusion would therefore lead to further removal of valuable information. As an alternative approach, a constant of 1 mm was added to all measurements prior to commencing the disturbance detection procedure to avoid the above-mentioned issues. Although this "shift" results in a variance reduction of the detrended chronologies, there is little difference between the transformed and untransformed chronologies, with the overall trends remaining unaffected (Rydval 2015). The shifted versions of both the precorrection (preCST) and postcorrection (postCST) chronologies were used in all subsequent analyses.

For this study, a modified version of the CST method was therefore utilised. Previous versions of CST used a two-step process to remove disturbance trends and would on occasion introduce an artificial trend if only the first step was performed, which could ultimately affect the overall structure and trends in a site chronology and would certainly affect attempts to develop, for example, a regional standardisation curve (Briffa and Melvin 2011). Unlike those earlier versions, the modified method used here features an improved curve-based disturbance trend removal mechanism (Warren 1980), which we use to remove disturbance release events in a single step. This adjusted version is referred to here as curve intervention detection (CID). CID resolves the two-step disturbance trend removal issue altogether by correcting for the growth release in a single step using indices with a mean of 1. After correction, the time-series data are re-expressed as raw

Table 1. Summary information for sites and site chronologies from the Scottish Highlands.

Site name	Site code	Latitude (N)	Longitude (W)	Elevation (m.a.s.l.)	First year	Last year	No. of series	Period covered by ≥10 series
North Highlands region								
Alladale	ALD/UAL	57°52′	4°42′	280–380	1626	2012	52	1743–2012
Rhidorroch	RHD	57°53′	4°59′	180–230	1708	2012	24	1762–2012
NW Highlands region								
Achnashellach East	ACE	57°29′	5°15′	100–130	1711	2009	28	1750–2009
Achnashellach West	ACW	57°28′	5°18′	100–120	1767	2009	21	1865–2009
Coulin	COU	57°32′	5°21′	250	1636	2009	67	1702–2009
Coulin (MXD)	COU	57°32′	5°21′	250	1671	1978	21	1793–1978
Glen Grudie	GRD	57°38′	5°25′	70–120	1634	2009	30	1728–2009
Loch Maree	LM	57°37′	5°21′	100	1621	2009	70	1748–2009
Loch Maree (MXD)	LM	57°37′	5°21′	100	1756	1978	16	1846–1978
Shieldaig	SHG	57°30′	5°37′	10–100	1801	2011	45	1866–2011
West Highlands region								
Glen Affric	GAF	57°17′	4°55′	300	1693	2013	189	1713–2013
Glen Affric (MXD)	GAF	57°17′	4°55′	300	1728	2013	50	1758–2013
Glen Garry	GLG	57°03′	4°56′	190	1747	2009	41	1799–2009
Loch Hourn	HOU	57°07′	5°27′	90–240	1802	2007	10	1859–2007
Glen Loyne	LOY	57°09′	5°05′	240–370	1458	2007	57	1559–2003
SW Highlands region								
Coille Coire Chuilc	CCC	56°25′	4°42′	210–280	1686	2011	20	1828–2011
Glen Falloch	GLF	56°22′	4°39′	160–200	1508	2011	98	1600–2011
Glen Orchy	GOS	56°27′	4°53′	200–210	1710	2009	22	1833–2009
Meggernie	MEG	56°34′	4°20′	325	1742	2011	20	1854–2011
Rannoch	RANN	56°40′	4°19′	320	1703	2010	81	1784–2010
NW Cairngorms region								
Abernethy East	ABE	57°13′	3°34′	340–450	1634	2009	68	1747–2009
Abernethy North	ABN	57°14′	3°41′	240–340	1859	2009	84	1863–2009
Abernethy West	ABW	57°12′	3°38′	350–420	1735	2009	80	1783–2009
Abernethy West (MXD)	ABW	57°12′	3°38′	350–420	1691	2013	13	1864–2013
Badan Mosach	BAM	57°03′	3°53′	370–420	1763	2008	25	1845–2008
Creag Fhiaclach	CRF	57°08′	3°49′	500–550	1690	2009	61	1769–2009
Carn Eilrig	CRNE	57°08′	3°46′	480–540	1735	2008	23	1824–2008
Glen Feshie	GF	57°05′	3°52′	480–540	1811	2006	24	1849–2006
Green Loch	GRN	57°10′	3°39′	370–480	1607	2013	141	1721–2013
Green Loch (MXD)	GRN	57°10′	3°39′	370–480	1734	2013	10	1876–1909
Loch an Eilein	LE	57°09′	3°49′	260	1755	2013	173	1841–2013
Loch an Eilein (MXD)	LE	57°09′	3°49′	260	1828	2013	18	1871–2013
Loch Gamnha	LG	57°08′	3°50′	275	1694	2010	36	1775–2010
Loch Gamnha (MXD)	LG	57°08′	3°50′	275	1763	2013	20	1851–2013
Morlich	MOR	57°09′	3°41′	410–450	1740	2009	26	1782–2006
Ryvoan	RYO	57°10′	3°39′	420–480	1778	2011	25	1794–2011
Ryvoan (MXD)	RYO	57°10′	3°39′	420–480	1769	2011	17	1828–2011
Upper Glen Feshie	UGF	56°59′	3°52′	400–520	1718	2010	90	1754–2010
SE Cairngorms region								
Derry East	GDE	57°01′	3°34′	480–530	1629	2008	54	1741–2008
Derry East (MXD)	GDE	57°01′	3°34′	480–530	1773	1978	26	1806–1978
Derry North	GDN	57°03′	3°35′	530–600	1477	2010	71	1617–2010
Derry West	GDW	57°01′	3°35′	450–520	1739	2008	18	1773–2008
Ghleann East	GLE	57°02′	3°28′	490–540	1697	2008	31	1760–2008
Ghleann West	GLW	57°03′	3°31′	480–550	1744	2008	24	1764–2008
Glen Tanar	GTA	57°01′	2°50′	306–379	1699	2012	25	1822–2012
Inverey	INV	57°00′	3°31′	500–550	1706	2011	55	1720–2011
Inverey (MXD)	INV	57°00′	3°31′	500–550	1706	1976	24	1731–1976
Luibeg	LUI	57°01′	3°36′	460–540	1657	2008	31	1711–2008
Mar Lodge	MAL	56°59′	3°30′	350	1828	2008	26	1837–2008
Upper Punch Bowl	PNB	57°00′	3°28′	450–550	1681	2008	22	1839–2008
Quoich	QUO	57°01′	3°31′	430–500	1657	2011	43	1707–2011
South Cairngorms region								
Bachnagairn	BAG	56°54′	3°14′	500–560	1833	2008	20	1847–2008
Ballochbuie	BAL	56°58′	3°19′	300–500	1589	2011	86	1677–2011
Ballochbuie (MXD)	BAL	56°58′	3°19′	300–500	1675	2011	44	1729–2011
Drimmie	DRIM	56°38′	3°21′	215	1824	2010	38	1832–2010
Drimmie (MXD)	DRIM	56°38′	3°21′	215	1828	1976	22	1843–1976

Note: Chronologies that include data archived in the ITRDB are underlined. m a.s.l, m above sea level; MXD, maximum latewood density.

(nondetrended) measurements after the original growth trends are added to the disturbance-corrected data. In this way, a range of detrending approaches can be applied to both the pre- and post-CID corrected measurement series using commonly utilised detrending packages (e.g., ARSTAN; Cook and Holmes 1986).

It should be noted that the initiation of disturbance-related growth releases as they are detected may not reflect the actual initiation year precisely (Druckenbrod et al. 2013). Also, the timing of the response to a disturbance event may differ between individual trees as some may react earlier than others. For these reasons and also in the interest of simplifying interpretation, rather than presenting detected disturbance events on an annual scale, disturbance initiation years are grouped and presented according to the decade in which they were detected.

2.3. Chronology development

All series (pre- and post-CID) were detrended using signal free (SF) detrending (Melvin and Briffa 2008), which was developed with the intention to limit chronology trend distortion resulting from commonly applied standardisation procedures. Essentially, the procedure removes the common (climatic) signal, which may otherwise bias the fitting of the detrending functions. SF detrending was performed by fitting negative exponential or negative linear functions to the series. Indices were calculated as ratios by division, and variance stabilisation (Osborn et al. 1997) of the time series was performed to minimise artificial variance changes in chronology variance primarily as a result of changing sample size, particularly when the sample size is low. Tukey's robust biweight mean was used to limit the influence of outliers on the final mean index calculation (Cook and Kairiukstis 1990). An alternative, nonSF detrending approach was also explored using the more conventional negative exponential or linear functions with negative slope (NX) in ARSTAN (Cook and Holmes 1986), with indices calculated as residuals after power transformation. Analysis using NX chronologies produced broadly similar though generally weaker results (results not shown).

2.4. Assessing CID correction

To assess chronology changes resulting from disturbance trend removal and more specifically to ascertain whether improvement of the RW chronology climate signal had occurred, three separate approaches were utilised.

2.4.1. Correlation with instrumental data

Following the procedure in Rydval et al. (2014), mean monthly surface temperatures for Scotland (SMT) by Jones and Lister (2004) were extended to 2009 using CRU TS3.10 mean monthly gridded temperature data (Harris et al. 2014) covering the Scottish Highlands. The extended SMT data are hereafter referred to as the ESMT dataset. The correlation between ESMT temperatures for the January through August (January–August) season (for which both subregions show a consistently strong response) and subregional or individual site chronologies is used to assess the climate signal in the pre- and post-CID chronologies.

2.4.2. VS-Lite growth modelling

The application of growth simulation modelling can provide insight into observed growth by the production of a synthetic record of expected growth behaviour based on climatic forcing alone (Evans et al. 2013). Derived from the Vaganov–Shashkin (VS) model (Vaganov et al. 2006), VS-Lite (Tolwinski-Ward et al. 2011) is a streamlined, monthly resolution process-based proxy system model of tree-ring growth. The model allows for nonlinear and nonstationary climate influences on tree growth and, therefore, permits greater complexity than linear empirical statistical approaches to growth modelling (Tolwinski-Ward et al. 2011; Tolwinski-Ward 2012). The model requires monthly precipitation and temperature data, and its relative simplicity offers the potential for extensive application. VS-Lite utilises only 12 model parameters compared to over 40 parameters for the full VS model.

Table 2. VS-Lite model parameters.

Temperature response parameters		
Threshold temperature for $g_T > 0$	T_1	∈[0 °C, 8.5 °C]
Threshold temperature for $g_T = 1$	T_2	∈[9 °C, 20 °C]
Moisture response parameters		
Threshold soil moisture for $g_M > 0$	M_1	∈[0.01, 0.03] *v*/*v*
Threshold soil moisture for $g_M = 1$	M_2	∈[0.1, 0.5] *v*/*v*
Soil moisture parameters		
Runoff parameter 1	α	0.093 month^{-1}
Runoff parameter 2	μ	5.8
Runoff parameter 3	m	4.886
Maximum moisture held by soil	W_{max}	0.76 *v*/*v*
Minimum moisture held by soil	W_{min}	0.01 *v*/*v*
Root (bucket) depth	d_r	1000 mm
Integration window parameters		
Integration start month	I_0	−2 (pNovember)
Integration end month	I_f	12 (December)

Note: g_T and g_M represents growth response function due to temperature and moisture, respectively (adapted from table 1 in Tolwinsi-Ward et al. (2011)). pNovember, previous November.

The model has been validated over a wide range of species, climate regimes, and biomes (Tolwinski-Ward et al. 2011, 2013, 2014). Analysis of differences between actual and modelled RW data has distinct advantages over evaluating chronology performance by its response to instrumental climate data. Specifically, simulated growth is controlled by the climatic variable (temperature or precipitation, which determines moisture availability) that is the most limiting for a particular year's annual growth. The growth response of RW data simulated by VS-Lite need not be constrained to reflect a particular seasonal window, as the integration of annual growth is primarily driven by input climate data and the length of the growth season, and the contribution to annual growth from individual months can vary between years.

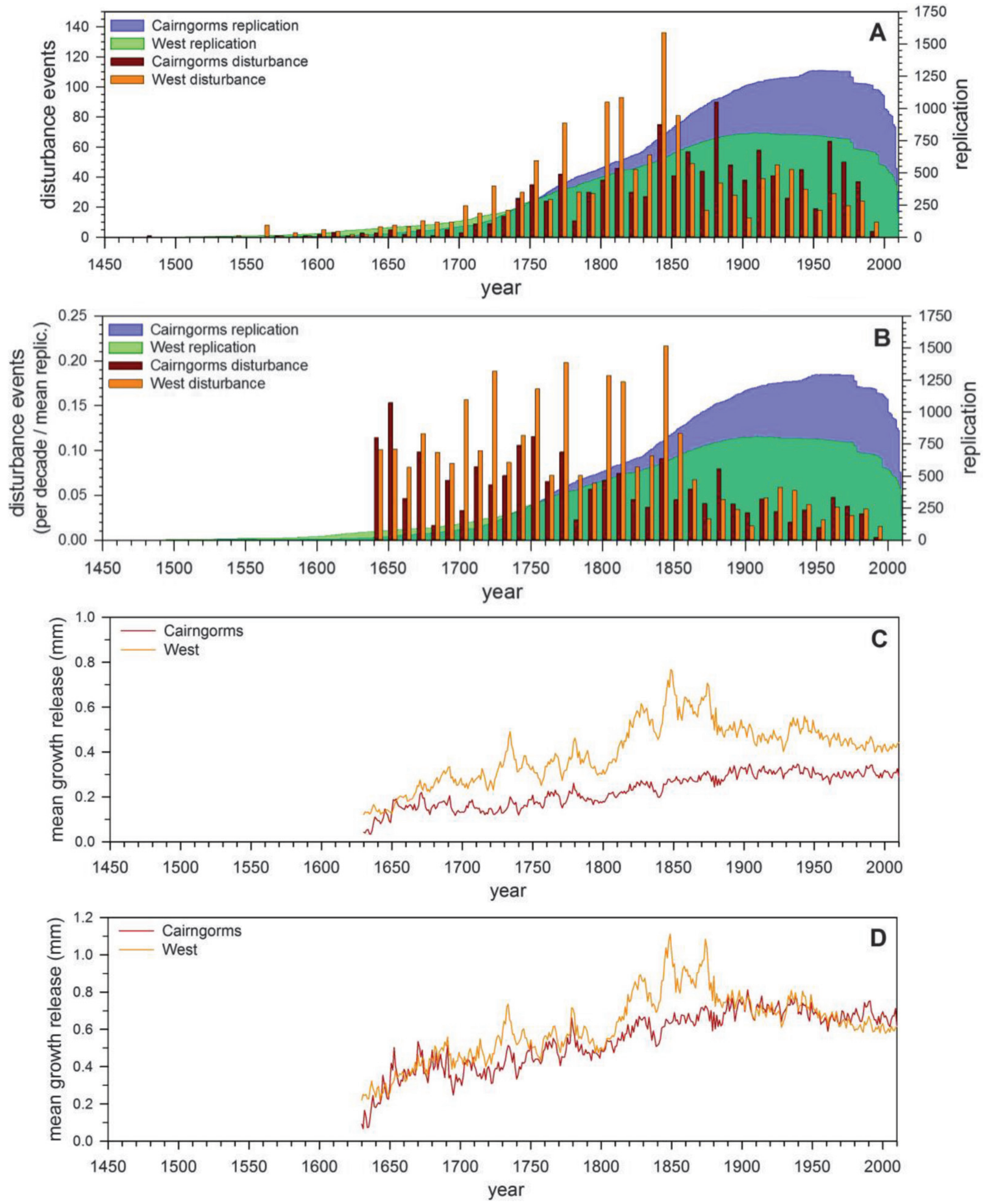
Using VS-Lite, simulated chronologies were generated for the 1901–2009 period for each site using site latitude and mean monthly CRU TS3.10 gridded 0.5° temperature and precipitation data (Harris et al. 2014) overlapping with the location of each site. Gridded temperature data were adjusted for site elevation (Ian Harris, personal communication, 2013). Two subregional composite chronologies “Cairngorms” and “West”, were also compared against VS-Lite simulations developed using a mean of the gridded climate data covering each of the subregions. The mean of the locations of all sites within each subregion was used to determine the input latitude for the subregional models.

Model parameters and their settings used in this analysis are listed in Table 2, and a detailed description is available in Tolwinski-Ward et al. (2011), which also includes a general overview of VS-Lite functionality. Monte Carlo simulations (2500 iterations) were carried out by incrementally varying the VS-Lite minimum and optimal growth parameters for temperature (T_1, T_2) and soil moisture (M_1, M_2) within the parameter range provided in Table 2. The optimal or “best” models were selected based on highest correlation with individual site or subregional chronologies.

2.4.3. Comparison with MXD chronology

The previous two methods do not provide any assessment of the pre- and post-CID chronologies before 1866 and 1901, respectively. As individual MXD site chronologies possess a consistently stronger climate signal and are less variable between sites, it is therefore assumed that they are either not affected at all by disturbance or are at least systematically less affected than RW. Therefore, as an additional assessment of the RW chronologies, the correlation between each pre- and post-CID chronology is calculated (for

Fig. 3. Disturbance event timeline of pulse releases and total replication for the Cairngorms and West Highlands. Disturbance events are grouped according to the decade in which the disturbances were initiated. Results are displayed as (A) the absolute number of events (bars) including replication over time for both subregions (shaded area), (B) the fraction of disturbed samples as a function mean decadal replication, (C) chronology of the total mean amount of growth attributable to disturbance releases, and (D) mean size of growth release over time considering only those series which contain disturbance releases at a particular time (results in (B), (C), and (D) are displayed only for periods when mean replication is > 20 for both subregional chronologies). Figure provided in colour online.



periods with replication ≥ 10 series) against a composite MXD chronology utilising data from 12 Highland sites (Fig. 1 and Table 1) extending over the period 1713–2009.

The MXD composite chronology was developed by fitting negatively sloping linear functions to the MXD series with the application of SF detrending. Detrended indices were calculated as residuals of the measured series and the fitted curves. To produce the MXD chronology, the biweight mean of the series indices was calculated, and chronology variance was stabilised using a 51 year window to account for changing sample replication and mean interseries correlation (RBAR) over time.

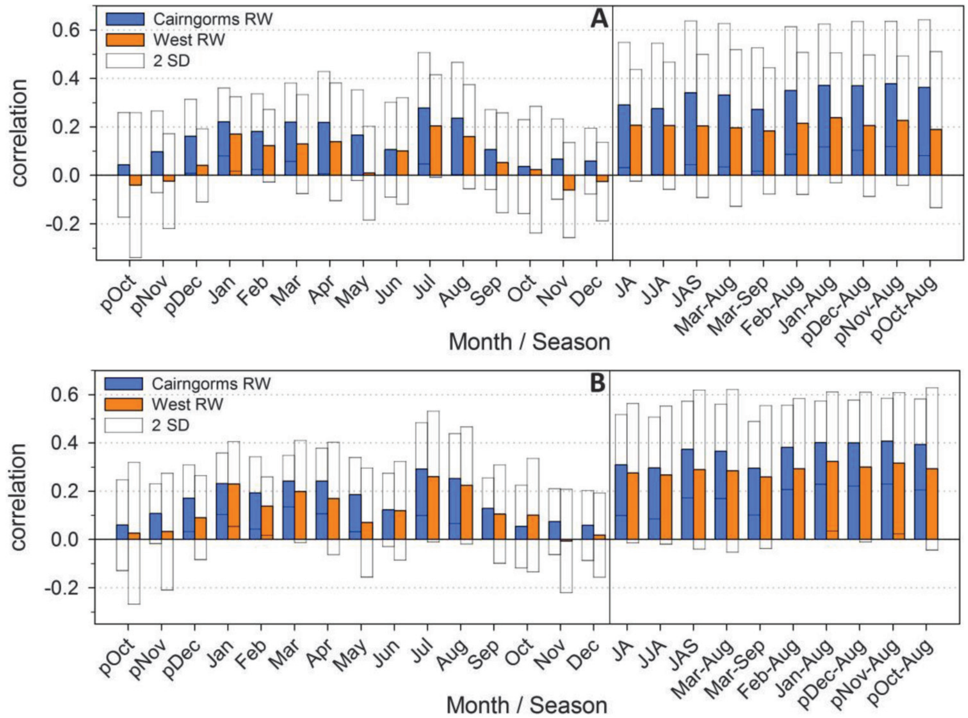
3. Results

3.1. Subregional disturbance timeline

The incidence of identified disturbances in the Highlands is summarised in Fig. 3 for each decade (for individual site chronology disturbance assessments, see Supplementary material[1]).

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2015-0366.

Fig. 4. Correlation response functions for Cairngorms and West vs. extended monthly surface temperatures (ESMT) temperature using (A) preCID and (B) postCID ring width (RW) chronologies with negative exponential or linear detrending. Note that the 2 standard deviation (SD) range is based on correlations of all individual site chronologies in each subregion with instrumental temperatures. Figure provided in colour online.



These results represent the subregional scale history of years in which the initiation of disturbance related growth releases was detected. Even though sample replication in the West Highlands remains lower than that of the Cairngorms during most periods, the absolute number of identified events is greater in the former, particularly during the early 18th to mid-19th centuries.

By adjusting for changes in replication, a clearer comparison of disturbance frequency can be determined (Fig. 3B). With the exception of the mid-17th century, the proportion of disturbance events remains consistently higher in the West until ~1860. Thereafter, the proportion of disturbance events decreases to a lower level and remains similar for both subregions. A significant correlation (r = 0.36, p = 0.022) between the Cairngorms and West disturbance frequency histograms in Fig. 3B was observed for the 1600–1999 period. This relationship was found to be stronger when only the periods 1700–1999 (r = 0.67; p < 0.001) and 1800–1999 (r = 0.73; p < 0.001) were considered. Using first-differenced data, the respective correlations for the three periods were as follows: r = 0.58, p < 0.001; r = 0.58, p = 0.001; r = 0.56, p = 0.011.

Replication-adjusted chronologies of the mean size of disturbance-related growth releases provide an indication of the mean amount of additional increment growth attributable to disturbance releases (Fig. 3C). The results provide further indication that, overall, sites in the West Highlands experienced relatively more disturbance-related growth release, particularly throughout the 19th century. A further notable difference is the presence of higher magnitude, shorter-term growth release pulses in the West, which do not occur to the same extent or degree in the Cairngorms network. Comparing the mean size of growth releases in the West and Cairngorms demonstrates that the magnitude of the growth release remains similar for both subregions with the exception of the mid-18th and the 19th century when the mean size of released growth is greater in the West (Fig. 3D).

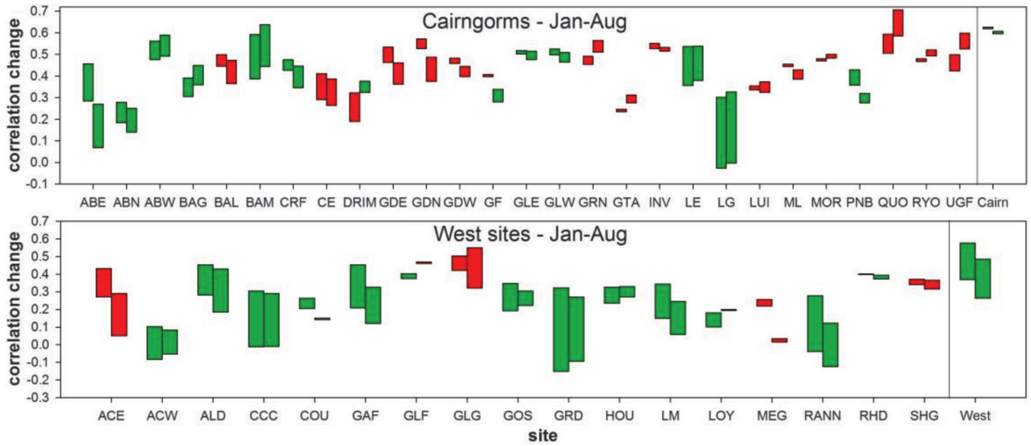
3.2. Pre- and post-CID comparison with instrumental, VS-Lite, and MXD data

The seasonal response of the Cairngorms and West RW chronologies to temperature (based on mean results of individual site chronologies in each subregion) is primarily weighted to the July to August summer season, although a broader winter–summer seasonal response from January or December of the previous year until August is also seen (Fig. 4). The preCID response of the western composite is considerably weaker than that of the Cairngorms. However, although the response of chronologies from both subregions improves after CID correction, the degree of post-CID improvement is much greater for the West.

The general postCID improvement in the correlations between chronologies and gridded instrumental temperature data are illustrated in Fig. 5. In general, greatest improvement is observed with the West chronologies, whereas there is little overall change in the pre- and post-CID Cairngorms chronologies, although the extent of the changes varies from site to site. Although correlations for some sites are lower after CID correction, these poorer results are mostly slight in nature and generally involve sites that already display reasonably high preCID correlations. Despite minor differences, primarily in the absolute magnitude of the relationship, the correlation changes between simulated VS-Lite chronologies and real pre- and post-CID site chronologies (also presented in Fig. 5) overall agree with and support (in their sign and magnitude) the correlation changes identified with the instrumental temperature data.

Subregional chronologies of the Cairngorms and West Highland sites (Fig. 6A) highlight differences in trends during several periods. Persistent departures between the two chronologies lasting more than a decade occur in the early 18th century, mid to late 19th century, and after ~1970. Correlations with the ESMT January–August mean temperature over the 1866–2009 period indicate that, overall, the West Highland chronology expresses a weaker climate signal (r = 0.37) than the Cairngorms chronology (r = 0.62).

Fig. 5. Change in correlation between the pre- and post-CID versions of individual site chronologies with January–August mean seasonal temperature (left bars, using the 1886–2009 period) and with simulated VS-Lite chronologies (right bars, using the 1901–2009 period). Size of bars indicates magnitude of post-CID correlation increase or decrease with instrumental or VS-Lite data in relation to preCID versions. Rightmost results represent mean overall change for each subregion. Note that chronologies BAG, BAM, CE, GDE, GDW, GLE, GLW, LUI, ML, and PNB end in 2008, HOU and LOYNE end in 2007, and GF ends in 2006. Figure provided in colour online.



Periods when differences occur between the regional chronologies coincide with patterns of disturbance release in Fig. 3C and, particularly, events in the mid-19th century.

The comparison of pre- and post-CID chronologies (Figs. 6B–6D) demonstrates that differences in the Cairngorms chronology before and after correction are minimal. However, a more extensive transformation is observed with the West chronology. Among the most apparent postCID differences in the West chronology are the lower mid-19th century indices and also higher index values in the late 20th century. Increases in index values additionally occur in the early 18th century and around 1800. These changes also translate to a considerable improvement in the correlation with instrumental temperature data between 1866 and 2009 (r_{preCID} = 0.37; r_{postCID} = 0.58). Greater similarity between the Cairngorms and West chronologies after CID correction over the 1650–2010 period is also observed (r_{preCID} = 0.64; r_{postCID} = 0.72).

Comparison of real Cairngorms and West subregional chronologies against chronologies simulated by VS-Lite (Fig. 7) reinforce the findings of the chronology assessments performed using instrumental temperature data (Fig. 6). The Cairngorms chronologies before and after CID correction are nearly identical with no statistically significant change in agreement against the "best" VS-Lite model (r = 0.60 and r = 0.62 against model output, respectively). More extensive changes to the trend of the postCID West chronology (specifically the lower postCID values around 1940 and a more positive trend from ~1970 onwards) result in considerably better agreement with the VS-Lite model simulation (r = 0.48) compared with the preCID results (r = 0.26).

In addition to including correlation changes with instrumental temperatures (also presented graphically in Fig. 5), changes in the correlation between individual-site RW chronologies and the Scotland MXD composite chronology are presented for the Cairngorms in Table 3 and for the West in Table 4. Correlation changes of RW chronologies evaluated with the VS-Lite simulations were not included in this assessment because overall results were similar to the instrumental temperature assessment, as was already noted in relation to Fig. 5. Regardless of the actual direction of the change, when comparing the RW chronology correlations with ESMT temperature and with the MXD chronology, there is general agreement in the direction of change (either correlation increase or decrease) in 21 out of 27 of the Cairngorms chronologies (Table 3). When considering correlation change results of the West chronologies (Table 4), there is agreement in 15 out of 17 chronologies, which is proportionally more than for the Cairngorms.

4. Discussion

4.1. Disturbance patterns

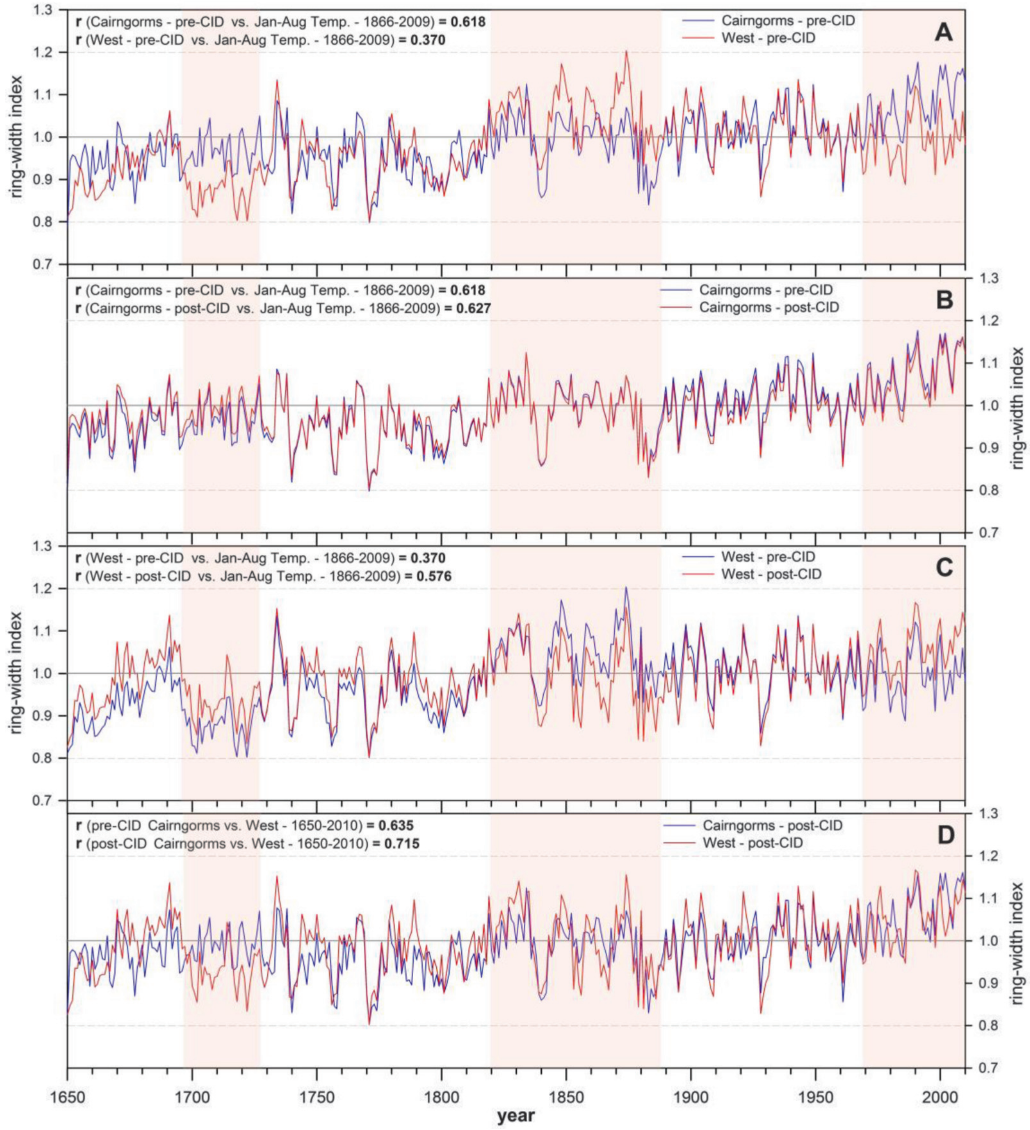
Although disturbance events were detected in the Cairngorms chronologies, the number of identified interventions are far fewer, less clustered, and temporally more evenly spread out than in the West. Although a few individual sites such as Loch Gamnha (LG in Fig. 5) showed considerable postCID improvement, minor changes to the overall Cairngorms chronology after CID correction (Fig. 6A) suggests limited influence of disturbance on the climate signal in this subregion, which is also supported by comparison with the VS-Lite simulations (Fig. 7A). Conversely, our results indicate a substantial degree of disturbance at sites in the west of the Highlands, which partially obscures the climate signal and, specifically, the longer term trends (Fig. 2).

Differences between the West and Cairngorms disturbance records can be interpreted to reflect the disparity of woodland exploitation. This suggests a greater scale and extent of exploitation in the West from the beginning of the 18th century until the mid-19th century, which is also apparent in the RW chronology. The timing of disturbance events occurs systematically in the West Highlands around the mid-19th century. The presence of inflated RW indices in the West chronology (Fig. 6B) around 1850 affects the empirical statistical fit of the detrending curve, biasing the calculation of indices towards the end of the time series (Melvin and Briffa 2008). This results in an underestimation of indices in the latter part of the West chronology, which is most apparent in the recent ~40 year period.

After CID correction, lower mid-19th century indices in the West chronology translate into higher index values in the late 20th century, resulting in considerable chronology and climate signal improvement (Fig. 6C). The evaluation of West and Cairngorms chronologies before and after CID correction against VS-Lite model simulations supports the instrumental correlation results by validating the general improvement of the climate signal in the postCID chronologies.

Using two approaches to assess corrected and uncorrected chronologies (Tables 3 and 4), some additional insight can be gained about whether the full length of a postCID chronology displays improvement or whether any apparent improvement is restricted to the recent period. Based on this information, a more informed

Fig. 6. PreCID chronologies for (A) the Cairngorms and the West subregions, pre- and post-CID chronologies for (B) the Cairngorms and (C) the West, and (D) postCID chronologies for both subregions using signal free (SF) detrending (notable periods of preCID disagreement are highlighted).



decision can be made regarding the suitability of pre- or post-CID chronologies for climate reconstruction. In the majority of cases, both assessment methods favour the same chronology version. However, in the few instances where there is disagreement, the magnitude of the correlation change of each assessment approach was considered when deciding which version of the chronology should be used for reconstruction development (Rydval 2015).

4.2. Disturbance synchronicity

The synchronicity of detected disturbance events in the Cairngorms and West chronologies (particularly after ~1700 and even more so after ~1800) may be the result of three possible scenarios: (*i*) the record of inferred disturbance is exogenous (i.e., $\delta D2_t$ in eq. 1) and, specifically, the result of the similar pattern and timing of woodland exploitation that occurred throughout most of the Scottish Highlands as a whole over time; (*ii*) at least some of the disturbance events are related to exogenous causes other than timber clearance, which simultaneously affect larger areas or the entire region (for example, this may include damage to forests as a result of wind and storms); (*iii*) some of the trends that are being removed are in fact related to climatic variability, and their identification and removal from site chronologies throughout the network is reflected in spatially synchronous patterns misinterpreted as disturbance.

The observed synchronous relationship is likely the result of some combination of all three factors. It is not generally possible to definitively attribute a given disturbance event to a specific causal factor, with the exception of instances that can be corroborated by documentary evidence. Detailed records do not exist for many locations; however, an overview of available historical information clearly identifies forest clearance as the dominant acting force shaping the landscape of the Scottish Highlands over many centuries (e.g., Lindsay 1974; Smout 2003; Smout et al. 2005). Although an assessment of the site-specific disturbance histories recorded in historical documentation is unfeasible as part of the analysis presented here, the overall documented patterns of woodland exploitation do offer some general insights.

4.2.1. *Historical context*

The history of woodland exploitation in Scotland is complex, and a detailed analysis of the disturbance history is beyond the scope of this study. However, it is important to explore the

Fig. 7. Pre- and post-CID chronologies with signal free (SF) detrending for (A) the Cairngorms and (B) the West compared with VS-Lite models derived using regional grid climate data for the 1901–2009 period (best model based on highest correlation with RW chronology; confidence limits based on minimum and maximum ranges from 2500 Monte Carlo simulations).

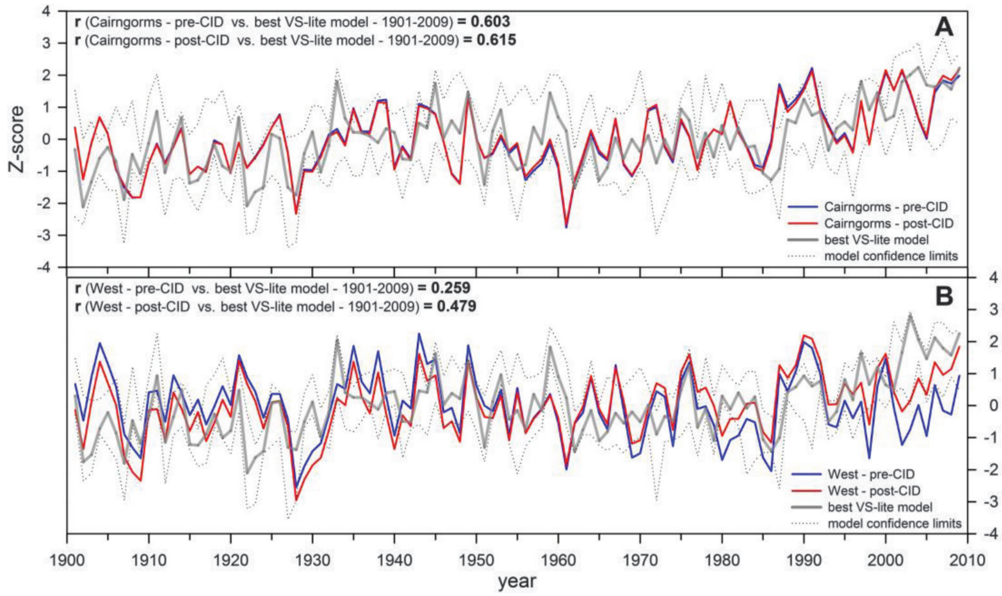


Table 3. Correlation results of individual Cairngorms site pre- and post-CID (signal free (SF)) chronologies with instrumental temperature and the Scotland maximum latewood density (MXD) chronology (SF detrending).

	January–August temperature	MXD	Agreement?		January–August temperature	MXD	Agreement?
ABE-pre-CID	0.285	0.404		GLW-pre-CID	0.498	0.420	
ABE-post-CID	0.457	0.375	red	GLW-post-CID	0.526	0.371	red
ABN-pre-CID	0.183	0.301		GRN-pre-CID	0.492	0.454	
ABN-post-CID	0.279	0.370	green	GRN-post-CID	0.453	0.456	green
ABW-pre-CID	0.476	0.520		GTA-pre-CID	0.247	0.345	
ABW-post-CID	0.562	0.502	red	GTA-post-CID	0.235	0.324	green
BAG-pre-CID	0.304	0.335		INV-pre-CID	0.552	0.570	
BAG-post-CID	0.392	0.397	green	INV-post-CID	0.528	0.552	green
BAL-pre-CID	0.499	0.517		LE-pre-CID	0.356	0.368	
BAL-post-CID	0.445	0.405	green	LE-post-CID	0.537	0.486	green
BAM-pre-CID	0.387	0.372		LG-pre-CID	−0.027	0.195	
BAM-post-CID	0.592	0.540	green	LG-post-CID	0.302	0.272	green
CRF-pre-CID	0.426	0.416		LUI-pre-CID	0.355	0.351	
CRF-post-CID	0.475	0.396	red	LUI-post-CID	0.336	0.368	red
CRNE-pre-CID	0.412	0.333		ML-pre-CID	0.456	0.352	
CRNE-post-CID	0.291	0.264	green	ML-post-CID	0.444	0.353	green
DRIM-pre-CID	0.323	0.241		MOR-pre-CID	0.480	0.468	
DRIM-post-CID	0.190	0.009	green	MOR-post-CID	0.470	0.461	green
GDE-pre-CID	0.534	0.578		PNB-pre-CID	0.358	0.293	
GDE-post-CID	0.463	0.524	green	PNB-post-CID	0.429	0.344	green
GDN-pre-CID	0.572	0.586		QUO-pre-CID	0.594	0.485	
GDN-post-CID	0.527	0.483	green	QUO-post-CID	0.504	0.414	green
GDW-pre-CID	0.483	0.440		RYO-pre-CID	0.480	0.470	
GDW-post-CID	0.458	0.420	green	RYO-post-CID	0.467	0.447	green
GF-pre-CID	0.407	0.400		UGF-pre-CID	0.499	0.501	
GF-post-CID	0.397	0.405	green	UGF-post-CID	0.424	0.379	green
GLE-pre-CID	0.502	0.480					
GLE-post-CID	0.519	0.407	red				

Note: Numbers in green indicate postCID correlation increase, numbers in red indicate postCID correlation decrease, numbers in blue indicate minimal postCID correlation change (≤0.01). The last column summarises whether the direction of change (increase or decrease) in correlation with instrumental temperature is in agreement (green) or disagreement (red) with the change in correlation with the Scotland MXD chronology (note that for each site where there is no considerable correlation change (marked as blue) in at least one of the indicators, this is not considered to constitute disagreement regardless of the direction of change in the second indicator).

general historical context for the disturbance patterns identified at the subregional scale. The lower relative amount of disturbance detected after the mid-19th century coincides with a general decrease in the overall intensity of wood extraction in the late 19th and 20th century. Although some periods of felling also occurred in the 20th century, in particular during the first and Second World Wars, such activities were arguably perhaps more localised, less extensive, and of a lower magnitude when compared

Table 4. Correlation results of individual West site pre- and post-CID (signal free (SF)) chronologies with instrumental temperature and the Scotland maximum latewood density (MXD) chronology (SF detrending).

	January–August temperature	MXD	Agreement?		January–August temperature	MXD	Agreement?
ACE-pre-CID	0.431	0.456		GRD-pre-CID	−0.152	−0.035	
ACE-post-CID	0.271	0.338	green	GRD-post-CID	0.323	0.326	green
ACW-pre-CID	−0.084	0.062		HOU-pre-CID	0.234	0.225	
ACW-post-CID	0.103	0.224	green	HOU-post-CID	0.326	0.327	green
ALD-pre-CID	0.283	0.480		LM-pre-CID	0.149	0.223	
ALD-post-CID	0.453	0.472	green	LM-post-CID	0.344	0.440	green
CCC-pre-CID	−0.011	0.116		LOY-pre-CID	0.100	0.298	
CCC-post-CID	0.305	0.320	green	LOY-post-CID	0.182	0.384	green
COU-pre-CID	0.205	0.360		MEG-pre-CID	0.256	0.261	
COU-post-CID	0.265	0.313	red	MEG-post-CID	0.218	0.231	green
GAF-pre-CID	0.208	0.470		RANN-pre-CID	−0.038	0.127	
GAF-post-CID	0.453	0.564	green	RANN-post-CID	0.278	0.362	green
GLF-pre-CID	0.374	0.282		RHD-pre-CID	0.401	0.405	
GLF-post-CID	0.403	0.248	red	RHD-post-CID	0.398	0.387	green
GLG-pre-CID	0.503	0.498		SHG-pre-CID	0.371	0.338	
GLG-post-CID	0.422	0.441	green	SHG-post-CID	0.341	0.273	green
GOS-pre-CID	0.193	0.008					
GOS-post-CID	0.348	0.241	green				

Note: Numbers in green indicate postCID correlation increase, numbers in red indicate postCID correlation decrease, numbers in blue indicate no considerable postCID correlation change (≤0.01). The last column summarises whether the direction of change (increase or decrease) in correlation with instrumental temperature is in agreement (green) or disagreement (red) with the change in correlation with the Scotland MXD chronology (note that for each site where there is no considerable correlation change (marked as blue) in at least one of the indicators, this is not considered to constitute disagreement regardless of the direction of change in the second indicator).

with the scale, extent, and duration of exploitation in the 1800s and earlier centuries. Such activities possibly also focussed more on relatively recent plantations that were not sampled in this study. Furthermore, it is also possible that records of the 20th century events preserved in tree rings may be scarcer due to large-scale forest clearance where no seeding trees were left behind in some areas (Smout 1997). It has also been suggested that large surviving trees may become less sensitive to more recent disturbance events as they become the dominant canopy trees (Neil Pederson, personal communication, 2014).

Large-scale timber extraction in the Highlands was dependent on a combination of factors, primarily determined by the profitability of such efforts and largely driven by demand for wood and the availability and price of foreign timber imports, with accessibility and ease of extraction also playing an important role. For these reasons, periods of more intensive, accelerated exploitation occurred during times of war or other instances of the limited availability and (or) higher cost of timber imports (Oosthoek 2013; Smout et al. 2005; Steven and Carlisle 1959). As a consequence of trade tariffs imposed in relation to the Napoleonic Wars, the beginning of the 19th century saw an increased demand for local Scots pine timber, which was generally of inferior quality to imported timber of predominantly Scandinavian and Baltic origin (Oosthoek 2013; Smout et al. 2005).

Though not explicitly acknowledged, there are indications that some western locations may have been more heavily exploited at certain times (Smout 1997; Smout et al. 2005). This is supported by suggestions that woodland exploitation in the West Highlands was also generally less well managed and controlled. Exploitation in general may have also been further exacerbated by land ownership changes after the Jacobite rebellion in 1745 (Callander 1986; Hobbs 2009). Among various ventures, including those of the York Building company, which operated in both the Cairngorms and West Highlands, Irish speculators were active in the West Highlands from the 1660s until the late 1730s (especially in the latter part of this period). Their activities included the purchase and indiscriminate exploitation of woodlands including pinewoods, which were purchased for timber to be marketed in Ireland where building timber was a scarce resource at the time (Smout et al. 2005). Unsurprisingly, this period of extensive felling coincides with early to mid-18th century disturbance pulses in the West Highland record (Fig. 3).

4.2.2. Wind disturbance and additional factors

Severe windstorms represent a plausible alternative source of some identified disturbance events. The importance of the limiting effects of wind on growth of Scots pine in the Scottish Highlands has previously been recognised (Moir 2008). There is certainly evidence for the occurrence of severe storms in the past and more recent decades (Dawson 2009), as well as for their damaging effects on stands in the Highlands (Steven and Carlisle 1959). A strong gradient in wind intensity between eastern and (north-)western Scotland (Quine and White 1993) would support the greater susceptibility of the West to windier conditions. This increases the possibility of more extensive and severe wind damage occurring at sites in the western and northwestern Highlands during severe storm events, which would also help to explain not only the greater disturbance in that subregion, but also some degree of synchronicity of detected disturbance events in the Highlands as a whole. It is quite possible that anthropogenic woodland exploitation may in fact promote windthrow by increasing wind exposure and weakening remaining stands by reducing the size and density of forest cover.

Locally, forest fires or insect outbreaks may also act as an additional source of disturbance (Steven and Carlisle 1959). Regarding the potential removal of common climatic information, individual site pre- and post-CID changes perhaps indicate some degree of overcorrection (type I errors) in those instances where chronologies display weaker agreement with instrumental and synthetic chronology data after CID correction. From a methodological perspective, CID is a relatively new approach for detecting disturbances. As such, the method is undergoing continued development and is evolving in its capability to detect and remove disturbance events. Nevertheless, the considerable improvement of chronologies from the west of Scotland, which are known to have experienced extensive episodes of disturbance, and also some Cairngorm sites is encouraging and indicates its ability to improve the climate reconstruction potential of RW chronologies affected by disturbance.

4.3. Mean disturbance releases

The mean size of additional growth due to disturbance in each of the subregions indicates that, in most time periods, the mean size of disturbance-related growth is the same or similar (apart from the 19th century period when more growth as a result of disturbance is observed in the West). One possible interpretation of this effect is that rather than experiencing a greater degree of disturbance, it is also possible that differential responses to disturbance exist at sites in the two subregions. In the periods in which additional growth from disturbances is greater in the West, trees in the western sites may be showing a greater response (or greater sensitivity) to disturbance events. This could arguably be related to a differential elevational response by less temperature-limited stands to decreased competition and the greater availability of light and nutrients as neighbouring trees are removed. Other factors could certainly also be involved, including differences due to genetic variation in Scots pine throughout Scotland (Forrest 1980), variations in soil type, or differences in water balance and soil moisture between the Cairngorms and parts of western Scotland with considerably wetter conditions in the west of the country (Met Office 2015; Oosthoek 2013).

However, this interpretation is unlikely considering that the mean response to disturbance is similar in other periods. Replication does not appear to be a significant factor either, as a similar response in the West and Cairngorms chronologies can be observed during periods of high, intermediate, and low replication and also when total replication of one of the subregional chronologies is higher than for the other.

Alternatively, because the largest deviations between the two disturbance chronologies occur during or immediately after those decades when the difference in the relative number of disturbance events between the Cairngorms and the West is greatest, it could be the case that because a larger number of trees are experiencing disturbance-related growth releases at a similar time (i.e., in the early 18th century and to a greater extent around the beginning and middle of the 19th century), this simultaneous (multisite) cluster of detected disturbances and the subsequent growth release may be the cause of the larger size of expressed mean growth release in those periods. In other words, because the initial growth increase following a disturbance is relatively large, if these releases occur concurrently in many trees, then the mean size of the growth release around that particular time will appear greater than at other times. This would further indicate that the incidence of disturbance events is more synchronous at sites in the West than at sites in the Cairngorms.

5. Conclusion

5.1. General conclusions

The modern Scottish landscape reflects a long history of human modification of the environment. People have inhabited Scotland for at least 9000 years (Wickham-Jones and Woodman 1998) and have accelerated their influence on the landscape over recent millennia. During the last millennium, anthropogenic interactions with the landscape have had a particularly profound effect on the pine woodlands of Scotland, leading to potential biases affecting tree-ring series with nonclimatic disturbance trends.

This paper aimed to identify disturbance-related growth releases in RW data and minimise the influence of such trends on RW chronologies using the CID method in an attempt to improve the climate signal from those records. CID is a valuable new method for uncovering and reconstructing the ecological and environmental history of forested environments. As demonstrated in this study, using site chronologies from around the Scottish Highlands, it is possible to develop records of the spatial and temporal patterns of disturbance, with applications for the interpretation of woodland history.

In addition to identifying the presence of nonclimatic disturbance events in the RW record, the CID method is a useful approach for the identification and removal of disturbance influences to “improve” RW series for dendroclimatological purposes. Although the CID method should not be considered a panacea for identifying and correcting for disturbance events, it does provide the capability to enhance the climate signal in RW data from sites that have experienced these events in the past. The main conclusions from this study are as follows:

- The CID method enhances the climate signal in otherwise noisy RW chronologies affected by disturbance.
- Instrumental and VS-Lite model data could only be used to assess chronology performance from 1866 and 1901 onwards, respectively. Evaluation of the full length of individual pre- and post-CID site chronologies was performed by comparison to a Scotland-wide MXD composite chronology. The results of chronology comparisons with instrumental temperature data were in overall agreement with VS-Lite based assessments.
- Based on instrumental temperature data and VS-Lite model simulations, the Cairngorms were less systematically disturbed than the West, and therefore, only limited improvement was observed with the postCID chronologies. In contrast, the more disturbed West Highland sites showed considerable improvement after correction.
- Greater agreement between the two subregional chronologies was observed after CID correction. Identified disturbance patterns were primarily attributed to woodland harvesting and clearance.

5.2. Future research

Future research should focus on further development of the CID method such as the inclusion of alternative detrending curves, additional efficiency optimisation of the disturbance detection, and removal mechanisms, along with the addition of the detection of growth suppression events. Further development of this method will also explore potential advantages of utilising a multiplicative model of tree growth (Cecile et al. 2013). Application of CID to other types of disturbance events (e.g., pollution, insect or pathogen attacks, and storm and wind events) resulting in either prolonged release or suppression signatures should also be investigated, as well as its implementation using a variety of species in a range of environments. Determining whether disturbance events could also be detected in additional tree-ring parameters (such as MXD and stable isotopes) may also be beneficial. If detection in other parameters were possible, then the concurrence (or lack thereof) in these events between parameters could potentially yield additional useful information. Artificial or pseudo proxy time series could also be used to assess CID performance in more detail, including the likelihood of false detection or failure to detect actual disturbance events. Despite a general attempt to contextualise the identified history of stand disturbance and woodland exploitation within a historical context, this paper provides a new source of information about woodland disturbance in Scotland that could undoubtedly be exploited further. Future work should therefore focus on developing a more detailed examination and evaluation of the disturbance history together with an assessment of historical records for individual sites (where available) to assist with the interpretation of the findings of this study. Such an investigation could, for example, explore the links between societal and socioeconomic changes and woodland utilisation through time to develop a better understanding of past land use and management practices in Scotland. Assessing the role of additional natural factors such as soil moisture and wind on growth, particularly in western Scotland, may also prove useful.

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