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Crop yield responses to temperature fluctuations in 19th century Finland: provincial variation in relation to climate and tree-rings

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Past agricultural responses to climate variability can helps us to better understand the current and future impacts of climate change on agricultural production. We studied rye (*Secale cereale*) and barley (*Hordeum vulgare*) yield responses to temperature fluctuations in Finland during the period 1861–1913. Our analyses demonstrate the high sensitivity of non-industrialised northern agriculture to temperature anomalies. We found evidence of a strong relationship between monthly and seasonal mean temperatures and crop yields. In particular, high spring temperatures were associated with higher yields. Additionally, we tested temperature-sensitive tree-ring series for their value in indicating previous agricultural outputs. The results imply that tree-ring proxies (in particular, maximum latewood density) can provide novel material for studies of historical periods and locations where instrumentally measured climate and harvest data are not available.

Introduction

Current and future impacts of climate change on crop production have gained increasing interest in recent decades (Porter *et al*. 2014). Studies of historical responses to climatic variability can provide important insight into the vulnerability of agricultural production to climate change and its temporal and spatial fluctuations (Pfister 2010). Past experiences help us to better understand the present, and to identify vulnerabilities in a long-term context. However, the vast majority of research on climate variability and crop production has focused on recent decades, and studies that have investigated periods prior to the 20th century frequently lack precision at temporal and/or spatial scales, partly due to poor availability of instrumental meteorological measurements. In this context, climate and crop data from 19th century Finland can

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contribute to the discussion on the impacts of climatic change on less industrialised agricultural margins (Parry 1975). In fact, 19th century Finland provides an interesting example of crop production responses to climate fluctuations, as the modernisation of agriculture had just begun (Myllyntaus 2009). Moreover, Finland is often referred to as the "most northerly agricultural country in the world" (*see* e.g., Mukula and Rantanen 1987, Mela 1996, Häkkilä 2002, Hollins *et al.* 2004), and climate variability is considered to have a special significance in marginal areas of crop cultivation (Parry 1975). Although nationwide quantitative statistics of provincial yield fluctuations are not available prior to 1861, fragmentary yield series from Finland can be found from the 16th century onwards (Tornberg 1989, Seppälä 2009), but the earliest continuous meteorological measurements extend only to 1829 (Tuomenvirta 2004). Nonetheless, a long-term perspective is required, to improve our understanding of socio-environmental responses to climate variability and to illustrate the full spectrum of potential agricultural responses to climate change. Therefore, for future investigations covering periods prior to the 19th century, the applicability of using tree-ring data as indirect evidence in harvest-climate analysis was tested. It is acknowledged that years of crop failure in Finland were usually also unfavourable for the annual growth of trees (Mikola 1950). To date, however, the relationship between historical crop yields and tree-ring growth has not received comprehensive investigation.

Finland's geographic position in the northern coastal zone of the Eurasian continent (60°–70°N, 20°–31°E), is the main factor influencing Finland's climate and creates conditions for rapid variations in weather. Temperature-related climate variables show a considerable zonal pattern, decreasing from the south and south-west towards the north and north-east. For example, the annual mean temperature decreases northwards by approximately 0.7–1.0 °C per degree latitude (Heikkilä and Seppä 2003). The south-to-north decrease in solar radiation values and the direction of dominant airflows explain the zonal pattern. The southern and western parts of the country are mostly influenced by the Atlantic air flow, which is associated with an unstable weather pattern and milder winters in Finland, whereas the eastern parts are influenced by the Eurasian high-pressure system, which is associated with more stable air, and high summer and low winter temperatures (Johannessen 1970, Heikkilä and Seppä 2003, Tikkanen 2006, Kersalo and Pirinen 2009). The North Atlantic Oscillation (NAO) is frequently used to characterise atmospheric fluctuations and explain variations in the weather in Finland (Helama & Holopainen 2012) and it has been proposed that even harvest fluctuations are directly affected by the NAO (Hurrell *et al.* 2003).

Climatic conditions have considerably affected agricultural practices and crop variations in Finland (Holopainen and Helama 2009). Climatic anomalies and weather extremes have caused crop failure and famine among agrarian Finnish society, and even minor disturbances might have damaged the harvest seriously (Jutikkala 2003a, 2003b, Myllyntaus 2009). However, crop failures and poor harvests very seldom occurred simultaneously all over the country (Melander and Melander 1924, Holopainen and Helama 2009) and instead, were usually local- or regional-scale phenomena, most likely due to the inter-regional climate variability that is characteristic for the Finnish climate (*see* e.g., Mukula and Rantanen 1987, Kersalo and Pirinen 2009, Venäläinen *et al.* 2009, Himanen *et al.* 2013). Regional characteristics of the crop-yield responses to climate variability and weather anomalies historically in Finland have not been comprehensively studied. In this study, we investigated the crop yield responses to temperature fluctuations in Finland during the period 1861–1913, with a special focus on short-term, year-to-year variations in climate and crop yield. The time-series of crop yields were correlated with monthly and seasonal temperature variables, to reveal the relationships between the intermonthly temperature changes and agricultural output. The analyses were carried out using provincial data of crop yields, to identify any differences in the crop-yield responses in different parts of the country. Similarly, the series of crop yields were compared to the time-series of temperature-sensitive tree-ring proxies in the region. We discuss the feasibility of these proxy records for exploring the relationships between climate variability and crop yields in the pre-instrumental temperature records.

Material and methods

Crop-yield data

Data from eight administrative provinces of the 19th century Finland (Uusimaa, Turku–Pori, Häme, Viipuri, Mikkeli, Kuopio, Vaasa and Oulu) were used to explore regionally expressed crop-yield responses to temperature fluctuations. The responses of the two most important bread crop species at the time, winter rye (*Secale cereale*) and barley (*Hordeum vulgare*), were investigated. The data for year-to-year crop-yield fluctuations were collected from historical statistical reports that are available from 1861 onwards (Statistical reports: Tilastollinen toimisto 1868–1904a: *Suomen virallinen tilasto* 2, *Katsaus Suomen taloudelliseen tilaan* 1–8, Tilastollinen toimisto 1878–1902b: *Suomenmaan tilastollinen vuosikirja* 1–23, Tilastokeskus 1903–1916: *Suomen tilastollinen vuosikirja* 1–13). The provincial data sets have some missing values (Table 1) and the values for the year 1876 are missing from all provinces. This is probably due to the new regulations concerning the compilation of statistics enacted in January 1877 (Tilastollinen toimisto 1884a). Here, we made use of relative crop figures; the amount of harvested grain in relation to that sown (i.e., the volume of harvested seed per volume of sown seed, which is a common yield unit to record harvests over historical periods in the Nordic countries). Using relative instead of absolute crop figures reduces the biases caused by variations in the intensity of planting and population size (Hayward *et al*. 2012). Furthermore, relative crop figures are not biased by increases in the area of cultivation, because during the studied period, new areas were constantly cleared for cultivation.

Meteorological time series

Monthly mean temperature measurements from Helsinki, Turku, Kuopio, Kajaani, Oulu and Tornedalen (Sweden) meteorological stations were selected to represent the regional temperature fluctuations in Finland (Finnish Meteorological Institute, Klingbjer and Moberg 2003, Tuomenvirta 2004). Measurements from the year 1861 onwards were available from all stations, excluding Turku, where the data were available from 1873. In addition, the Kuopio and Kajaani data sets included some missing years (Table 1). All of the data sets were corrected for inhomogeneities (Klingbjer and Moberg 2003, Tuomenvirta 2004). However, as historical meteorological data are available only with monthly precision, we investigated the crop data in relation to monthly and seasonal mean temperatures. The monthly mean temperature series from the six weather stations were averaged into three regional series: southern Finland (Helsinki and Turku stations, S-FIN T), eastern Finland (Kuopio and Kajaani, E-FIN T) and northern Finland (Oulu and Tornedalen, N-FIN T). In addition, countrywide monthly mean series were averaged from all of the six stations (FIN T).

The NAO is one of the most important atmospheric patterns that affects European weather (Hurrell *et al*. 2003). The NAO index is defined as the standardised difference in the sea-level pressure (SLP) between the Azores high and the Iceland low. The NAO index corresponds to the strengths of the westerlies over Europe especially during winter and can be either negative or positive. If the SLP over the Azores is

Table 1. Annual availability of historical crop-figure and monthly temperature series. For locations, *see* Fig. 1.

Crop figures	
1: Uusimaa	1861 –1875, 1877–1913
2: Turku–Pori	1871–1875, 1878–1913
3: Häme	1861–1875, 1877–1913
4: Viipuri	1866–1875, 1877–1913
5: Mikkeli	1866–1870, 1877–1913
6: Kuopio	1861–1875, 1877–1913
7: Vaasa	1861–1875, 1877–1913
8: Oulu	1866–1875, 1877–1913
Temperature measurements	
A: Helsinki*	1861–1913
B: Turku	1873–1913
C: Kuopio	1861–1874,1 876–1877, 1884–1913
D: Kajaani	1861–1872, 1887–1913
E: Oulu	1861–1913
F: Tornio	1861–1913

* Kaisaniemi.

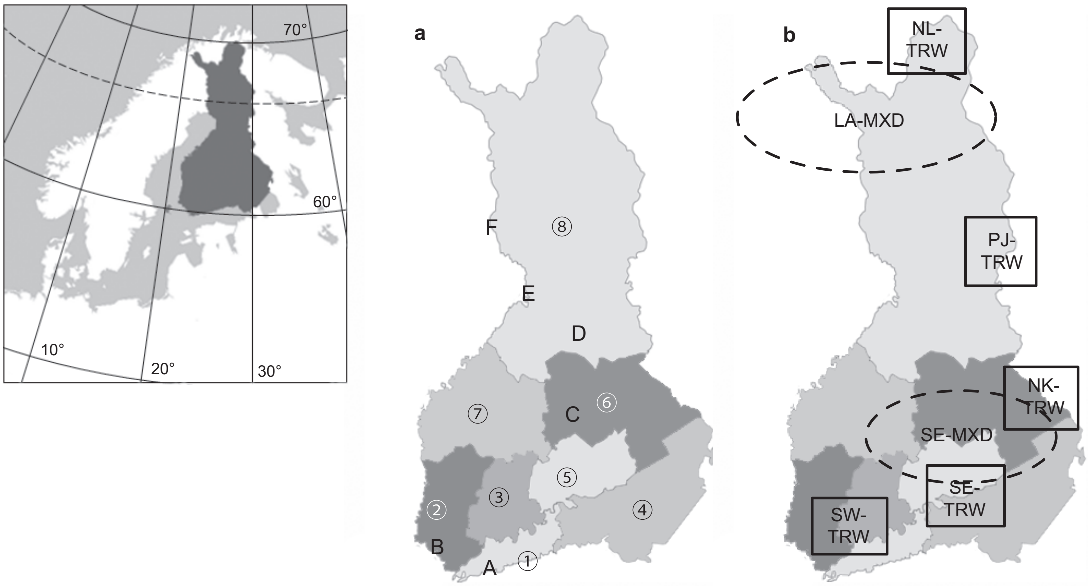

Fig. 1. Nineteenth century Finland. (**a**) Weather stations (A: Helsinki [Kaisaniemi], B: Turku, C: Kuopio, D: Kajaani, E: Oulu, F: Tornedalen), and historical provinces of 19th century Finland: (1) Uusimaa, (2) Turku–Pori, (3) Häme, (4) Viipuri, (5) Mikkeli, (6) Kuopio, (7) Vaasa, (8) Oulu. (**b**) Map of approximate sampling sites of the tree-ring series: ovals indicated maximum latewood density series from Lapland (LA-MXD) and southeastern Finland (SE-MXD), and squares indicated tree-ring width series from northern Lapland (NL-TRW), Pääjärvi (PJ-TRW), North-Karelia (NK-TRW) south-east Finland (SE-TRW), south-west Finland (SW-TRW).

above normal and the SLP over Iceland is below normal, the NAO is positive and the westerlies are distinctive. This pattern usually brings above-normal temperatures and precipitation to northern Europe and below-normal temperatures and precipitation to southern Europe. A negative NAO shows an opposite pattern on the SLP and also opposite anomalies of temperature and precipitation in Europe (Luterbacher *et al*. 1999, Hurrell *et al*. 2001, Saue and Kadaja 2009). For the NAO indices, we used a reconstruction with a monthly resolution (for the period 1659–1995) by Luterbacher *et al*. (2002), which is based on high-resolution documentary evidence and instrumental data from western Eurasia. The instrumental data included mostly monthly station pressure, temperature and precipitation time series (Luterbacher *et al*. 1999) and the documentary data consisted of estimates of snow and ice features, cloud cover, biological and phenological observations (Luterbacher *et al*. 2002). The NAO was calculated by subtracting 5° × 5° longitude–latitude gridded-point SLP data over Iceland and instrumental data from Reykjavik, from gridded SLP data over the Azores and instrumental data from Ponta Delgada (Luterbacher *et al*. 2001). The NAO index data set is available from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/historical/north_atlantic/nao_mon.txt.

Tree-ring data

Previous analyses produced Scots pine (*Pinus sylvestris*) tree-ring width (Helama *et al*. 2005, 2014a, Holopainen *et al*. 2006) and density chronologies (Helama *et al*. 2008, 2012, 2014b, Esper *et al*. 2012, Melvin *et al*. 2013) for different parts of the study region and adjacent areas (Fig. 1). These proxies were adopted here as records of past growth and climate variability and provide several benefits. Firstly, each of the chronologies contains tens to hundreds of individual tree-ring series. Tree-ring analysis of these series enables chronology construction where conspicuously narrow and wide rings of several series are synchronised through cross-dating (Fritts 1976, Holmes 1983). Subsequently, the growth anomalies can be dated to exact calendar years, facilitating comparisons with documentary data (Holopainen 2006). Secondly, the cross-dated series are averaged into a mean chronology for a robust estimation of year-to-year growth variations (Fritts 1976, Cook *et al.* 1990b). Thirdly, the multiple tree-ring parameters provide estimates of past climate and environmental variations of different types. By far the highest dendroclimatic correlations in the study region are typically derived from latewood maximum densities (MXD) (Briffa *et al.* 1988, 1992, Helama *et al.* 2012, 2013).

The first set of tree-ring data originated from MXD proxies of Lapland (Matskovsky and Helama 2014) and southeastern Finland (Helama *et al.* 2014b), produced previously as reconstructions of past temperature variability. Before computation of these reconstructions, the biological long-term trends that were not related to climatic variations were removed from individual MXD series, using the dendrochronlogical routine of regional curve standardisation (Briffa *et al.* 1992). The MXD chronologies were subsequently calculated, the variance of the mean chronologies were stabilised (Osborn *et al.* 1997), and the reconstructions were derived using the transfer functions describing the statistical climate-proxy relationships as modelled over the period of instrumental temperature observations in each region. In northern Finland (Lapland), the summer (June–August) temperature reconstruction explained more than 60% of the observed temperature variance (Matskovsky and Helama 2014), whereas in southeastern Finland, the growing season (May–September) temperature reconstruction explained up to 60% of the observed variance (Helama *et al.* 2014b). The reconstructions were further verified using statistical tests for the reduction of error (RE, Fritts 1976) and the coefficient of efficiency (CE, Briffa *et al.* 1988). The RE and CE tests indicated reasonable skill in the temperature reconstructions both for the northern and southeastern Finland. The MXD-based time-series of Lapland (Matskovsky and Helama 2014) and southeastern Finland (Helama *et al.* 2014b) were obtained here as provided in their original publications.

The second set of tree-ring proxy data originated from tree-ring width (TRW) proxies from five separate localities in Finland (Fig. 1) (Helama *et al.* 2005, 2014a). Similar methods of dendrochronological standardisation were applied to these five sets of data, to produce consistently comparable TRW chronologies for each locality. During this process, the long-term trends of non-climatic origin were removed from the individual series using an approach of double-detrending (Cook *et al.* 1990a). Compared with MXD data, TRW proxies commonly display considerably higher serial correlation (i.e., autocorrelation) and, consequently, the detrended TRW series were further pre-whitened using autoregressive-moving average modelling (Box and Jenkins 1970, Cook *et al.* 1990a), before averaging the series into the mean chronology, as detailed in the original publications (Helama *et al.* 2005, 2014a). Furthermore, the variance of the mean chronologies was stabilised (Osborn *et al.* 1997). An expressed population signal (EPS) was used as an indication of chronology reliability and an EPS > 0.85 was considered an acceptable level of chronology confidence (Wigley *et al.* 1984). All the chronologies exhibited an EPS above this pre-determined level throughout the study period. In comparison with MXD proxies, the dendroclimatic correlations of TRW proxies were lower. Typically, the TRW proxies also correlated significantly with multiple climate variables. In this context, the three northernmost TRW proxies exhibited statistically significant correlations with mid-summer (July) temperature variability (Helama *et al.* 2005). In addition, the TRW proxy of southeastern Finland showed a relatively strong and positive correlation with spring and early-summer (May–June) precipitations (Helama *et al.* 2009). However, the three northernmost TRW proxies exhibited a statistically significant, albeit weaker, linkage to May precipitation (Helama *et al.* 2005), whereas the TRW proxy of southwestern Finland correlated with June precipitation (Helama *et al.* 2014a). Moreover, the TRW proxies of northern Lapland and southwestern Finland indicated that pine growth in these regions was positively affected by winter/spring temperatures (Helama *et al.* 2005, 2014a, Holopainen *et al.* 2006) and late-autumn/winter precipitation in southwestern Finland (Helama *et al.* 2014a, Holopainen *et al.* 2006).

Statistical analyses

Prior to making any climatic assessment, all of the series were linearly detrended to avoid spurious correlation coefficients that could arise purely because of this long-term development of harvests. The initial value of the crop figure (F) was obtained as a residual from the estimate of the linear model ($\hat{F}$) as follows:

$$F' = F - \hat{F} - \bar{F} \quad (1)$$

where F' is the value of the detrended crop-figure scaled to maintain its original long-term (1861–1913) mean ($\bar{F}$) (*see* e.g., Monserud 1986). After detrending, no indications of strong autocorrelations were found in the transformed series. However, most of the transformed crop-yield time-series were strongly skewed (Table 2). The transformed series were tested for normality using the Shapiro-Wilk test. The results of the normality test and the skewness and kurtosis statistics implied that most of the crop-yield series were non-normally distributed. This is hardly surprising considering the length of the time-series and the frequency of crop failures (i.e., extremely low values in the data sets) in 19th century Finland. Therefore, the analyses were carried out with non-parametric tests.

Correlations between the measured temperature, the NAO index, the TRW and the MXD and the detrended crop-figure series were investigated using Spearman's rank-order correlation (Spearman's rho, ρ). All correlations were calculated for the period of 1861–1913. Firstly, the crop-figure series were correlated with the mean regional (S-FIN T, E-FIN T and N-FIN T) and with the countrywide (FIN T) monthly mean temperature series starting 14 months prior to the harvest (from the previous year's August to the harvest year's September). As rye in Finland was sown in autumn, the crop was exposed to weather throughout the autumn and winter prior to the harvest year (Holopainen *et al*. 2012). Secondly, if the correlations between monthly temperature and the crop-figure series indicated some seasonal trends, the seasonal means were correlated with the crop-figure series. Thirdly, the crop-figure series were correlated with monthly and seasonal NAO indices. Lastly, the MXD and the TRW series were correlated with the crop-figure series on annual precision over the period of 1861–1913.

Table 2. Descriptive statistics and the results of the normality test (Shapiro-Wilk's test) for the detrended provincial rye and barley crop-figure (c.f.).

c.f. series	*n*	Min.	Max.	Mean	SD	Skewness	Kurtosis	Shapiro-Wilk's statistic	*p*
Rye									
1: Uusimaa	52	4.49	9.41	7.07	0.98	–0.50	0.56	0.963	0.104
2: Turku–Pori	41	4.38	8.65	6.74	0.78	–0.77	1.60	0.936	0.024
3: Häme	52	4.18	7.98	6.67	0.81	–0.80	0.69	0.957	0.059
4: Viipuri	47	3.81	7.45	6.32	0.73	–1.16	2.08	0.929	0.007
5: Mikkeli	42	4.48	7.29	6.25	0.71	–0.45	–0.41	0.958	0.127
6: Kuopio	52	2.81	9.98	6.92	1.45	–0.91	0.86	0.919	0.002
7: Vaasa	52	3.10	9.20	6.16	1.29	–0.51	0.60	0.957	0.060
8: Oulu	47	2.36	8.36	6.23	1.42	–1.08	0.99	0.911	0.002
Barley									
1: Uusimaa	52	3.20	7.45	5.19	0.70	0.03	2.28	0.951	0.031
2: Turku–Pori	41	3.63	6.00	5.01	0.51	–0.23	0.27	0.981	0.696
3: Häme	52	2.88	6.24	5.36	0.66	–1.06	2.35	0.920	0.002
4: Viipuri	47	3.75	6.28	5.27	0.59	–0.44	–0.06	0.975	0.400
5: Mikkeli	42	2.83	5.83	4.93	0.61	–1.27	2.46	0.919	0.006
6: Kuopio	52	1.39	6.15	4.82	0.96	–1.35	2.35	0.899	< 0.001
7: Vaasa	52	2.76	6.84	5.59	0.97	–0.98	0.91	0.925	0.003
8: Oulu	47	2.12	5.54	4.48	0.87	–1.33	1.12	0.852	< 0.001

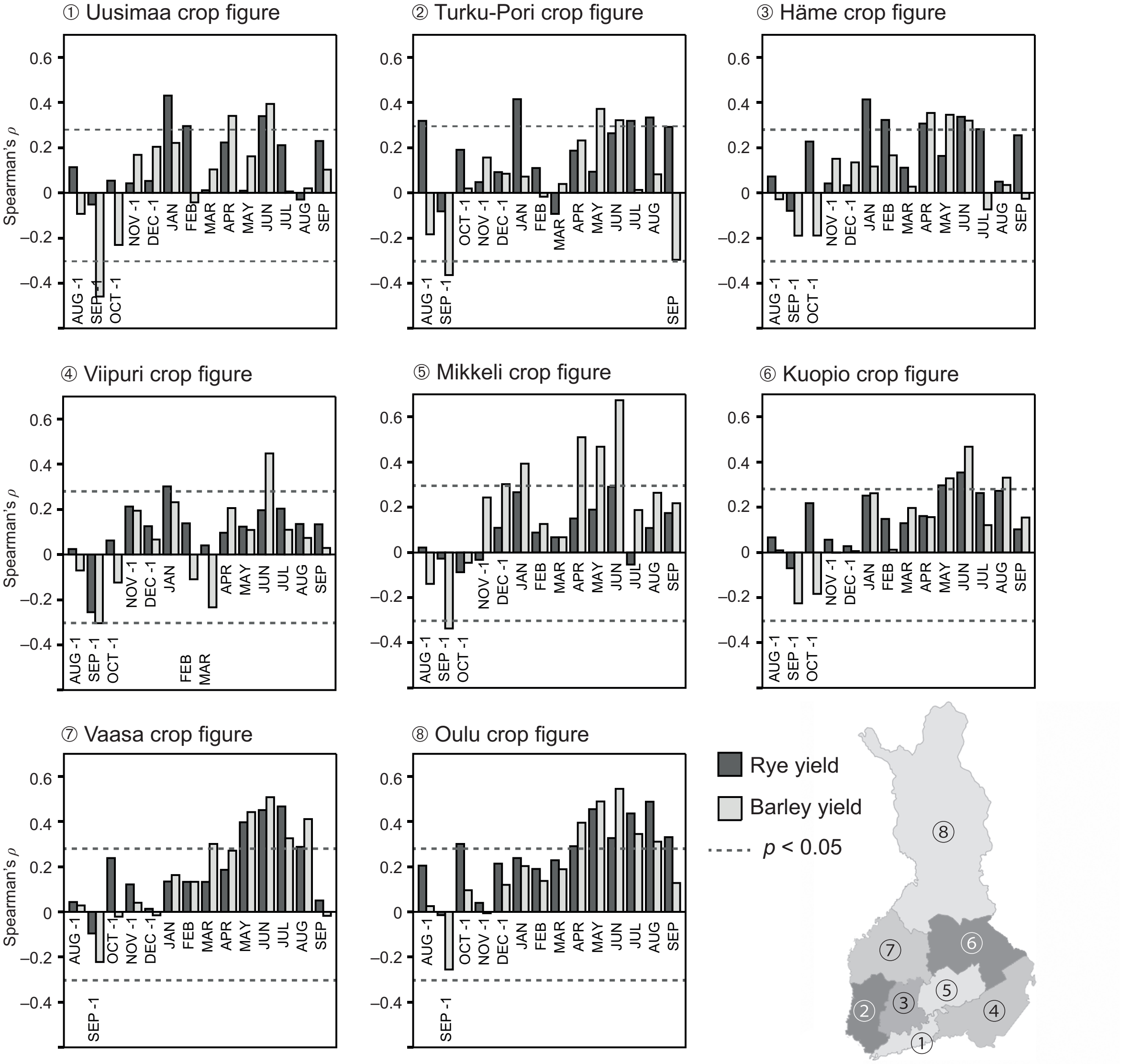

Fig. 2. Spearman's rank correlation coefficients (Spearman's ρ) between detrended provincial rye and barley crop-figure series and averaged monthly mean temperature for all six stations (Helsinki [Kaisaniemi], Turku, Kuopio, Kajaani, Oulu and Tornedalen, denoted FIN *T* in the text) and for series of the previous and concurrent year to the harvest.

Results

Overall, the provincial series of crop yields correlated positively with the regional warm season (April–August) monthly-mean temperature series (Fig. 2). A similar high sensitivity to mean temperatures between April and August were found in neighbouring Estonia and Norway with 19th century data on rye and barley harvest dates (Tarand and Kuiv 1994, Nordli 2001). In southern and eastern Finland, the yields were the most sensitive to spring/early summer (April–June) temperature variability, whereas in northern Finland, the yields were temperature-sensitive throughout the entire warm season (April–August). The positive correlation peak in June in the northern provinces can be explained by the day-length maximum of this month (Solantie 2008). In addition, the crop yields of rye in southern Finland correlated positively with January mean temperatures (Fig. 2). Barley yield was more temperature-sensitive than that of rye yield throughout the country, especially in the eastern provinces. Surprisingly, although rye was sown in the previous autumn, hardly any significant correlations were found between the crop yields of this grain and the monthly mean temperatures from August to December of the previous year. Contrary, the crop yields of spring-sown barley in the southern provinces correlated negatively with mean temperatures of the previous September. The negative correlation between September temperatures and the following barley yield will be discussed below.

Notably, provincial series of crop yields did not indicate spatial trends in the context of the sub-regional temperature correlations (Table 3). For example, crop yields from southern Finland (provinces of Uusimaa, Turku–Pori and Häme) did not correlate particularly with their respective southern temperature series (S-FIN *T*). This might be explained by the biased and limited geographical availability of the early temperature measurements (Tuomenvirta 2004), resulting in averaged series that did not accurately represent regional temperature fluctuations. Moreover, the administrative provinces analysed in this study do not follow the agro-climatic zones of Finland (*see* Rantanen and Solantie 1987). When investigating regional and countrywide mean temperature series between April and August in relation to provincial series of crop yields, no clear spatial differences in correlations were found.

For both studied crop grains, rye and barley, the northern and eastern provinces (Oulu, Kuopio and Mikkeli) produced lower mean crop-figures than the southern provinces (Table 2), which can be partly explained by the differences in the length of the growing season there. The crop yields in the provinces of Kuopio, Vaasa and Oulu showed the greatest year-to-year variability. Furthermore, the crop yields of both grains responded strongly to temperature fluctuations in northern regions (Vaasa and Oulu; Fig. 2). The

Table 3. Spearman's rank correlation coefficients (Spearman's rho) between the provincial crop-figure (c.f.) series and regional April–August mean temperature series from southern Finland (S-FIN *T*), eastern Finland (E-FIN *T*), northern Finland (N-FIN *T*), countrywide averaged April–August mean temperature series (FIN *T*), maximum latewood density series from southeastern Finland (SE-MXD) and Lapland (LA-MXD) and tree-ring width series from northern Lapland (NL-TRW), Pääjärvi (PJ-TRW), North-Karelia (NK-TRW) South-East Finland (SE-TRW) and South-West Finland (SW-TRW). For locations, *see* Fig. 1. All correlations are significant at the 0.05 level (two-tailed), dash indicates no statistically significant correlation.

c.f. series	April–August mean temperature				MXD		TRW				
	S-FIN *T*	E-FIN *T*	N-FIN *T*	FIN *T*	SE-MXD	LA-MXD	NL-TRW	PJ-TRW	NK-TRW	SE-TRW	SW-TRW
Rye											
1: Uusimaa	–	–	–	–	–	–	0.337	–	–	–	–
2: Turku–Pori	0.316	–	0.364	0.363	0.364	0.436	–	–	–	–	–
3: Häme	–	0.321	0.308	0.330	–	0.287	0.371	–	–	–	–
4: Viipuri	–	–	–	–	–	–	0.446	–	0.346	–	–
5: Mikkeli	–	–	–	–	–	–	–	–	–	–	–
6: Kuopio	0.402	0.310	0.423	0.422	0.409	0.282	0.402	0.364	0.372	–	–
7: Vaasa	0.458	0.489	0.511	0.546	0.515	0.476	0.495	0.422	0.319	–	–
8: Oulu	0.541	0.516	0.554	0.617	0.527	0.601	0.453	0.391	0.345	–	–
Barley											
1: Uusimaa	0.338	0.334	0.321	–	–	–	–	–	–	–	–
2: Turku–Pori	0.361	–	0.375	0.328	0.513	–	0.313	–	–	–	–
3: Häme	0.279	–	0.328	0.339	–	–	–	–	–	–	–
4: Viipuri	0.293	0.322	0.327	–	–	–	–	–	–	–	–
5: Mikkeli	0.564	0.589	0.649	0.610	0.536	0.488	0.488	–	–	–	0.318
6: Kuopio	0.451	0.401	0.474	0.439	0.421	0.317	0.386	–	–	–	–
7: Vaasa	0.583	0.564	0.593	0.622	0.546	0.475	0.379	–	–	–	–
8: Oulu	0.597	0.582	0.608	0.620	0.600	0.472	0.627	–	–	–	–

variability in the series and the low mean crop-figures indicates that crop cultivation was more unstable and less productive in northern and easternmost Finland in comparison with that in southern Finland. However, these provinces produced a substantial harvest when temperature anomalies did not restrict crop growth, due to high-yielding slash-and-burn agriculture in the eastern, and high soil fertility in the northern, parts of the country (Tilastollinen toimisto 1875a).

The results imply that crop cultivation was the most temperature-sensitive north of 62°N, whereas the temperature linkage was rather weak in southeastern Finland. The temperature linkage with the crop yield of rye disappears almost entirely in the provinces of Uusimaa, Viipuri and Mikkeli (Fig. 2). A low-temperature link might indicate that the main limiting factor for crop yields in this region was not the warm-season temperature. For southeastern Finland, Himanen *et al*. (2013) found that the modern rye crop yield is negatively affected by increased precipitation. To further elucidate the potential role of precipitation on historical crop yields, we correlated (Spearman's rho, ρ) the only available instrumental precipitation series from the study region, consisting of monthly series of precipitation sums from the Helsinki-Kaisaniemi (1861–1913; Fig. 1, Province of Uusimaa) and Vyborg (1870–1913; 60°43´N, 28°46´E, Province of Viipuri) stations, with the crop-yield series of the corresponding provinces (Finnish Meteorological Institute, Tuomenvirta 2004), but hardly any relationships were found. For rye, precipitation in the previous November (Helsinki-Kaisaniemi station) correlated negatively with crop yield in the Province of Uusimaa ($\rho = -0.386$, $p = 0.005$, $n = 52$), i.e., high precipitation during that month coincided with a low crop yield of rye in the preceding year. In the Province of Viipuri, precipitation in February (Vyborg station) correlated negatively with the crop yield of rye ($\rho = -0.413$, $p = 0.008$, $n = 40$). No other statistically significant correlations with precipitation were found for rye, and no significant correlations were found for barley. Hence, the results suggest that precipitation did not play a primary role in controlling the crop yields of the studied grain.

The relationships between crop yield and monthly and seasonal NAO indices were not as strong as with temperature. Nonetheless, the crop yield of rye correlated positively with the January NAO index values in the provinces of Uusimaa ($\rho = 0.421$, $p = 0.002$, $n = 52$) and Häme ($\rho = 0.323$, $p = 0.019$, $n = 52$) and with the August NAO index in the province of Turku–Pori ($\rho = 0.314$, $p = 0.046$, $n = 41$). In Viipuri, the rye crop-figure series correlated negatively with the May NAO index values ($\rho = -0.370$, $p = 0.010$, $n = 47$). The crop yield of barley correlated negatively with the previous year's September NAO index in the provinces of Uusimaa ($\rho = -0.428$, $p = 0.002$, $n = 52$) and Kuopio ($\rho = -0.292$, $p = 0.036$, $n = 52$) and with the same year's September NAO index in the province of Turku ($\rho = -0.316$, $p = 0.044$, $n = 41$). In Kuopio, the barley crop yield correlated positively with January and August NAO indices ($\rho = -0.341$, $p = 0.013$, $n = 52$ and $\rho = -0.299$, $p = 0.032$, $n = 52$, respectively). Overall, the correlations between the crop-figure series and the NAO indices were in the same direction as those between the crop-figure series and temperature. In addition, the years of countrywide poor harvest and crop failures, i.e., years 1862, 1867, 1881, 1892, 1899 and 1902, coincided with the negative phases of the winter NAO.

As the MXD proxies captured the effect of warm-season temperatures (Helama *et al*. 2014b), correlations between the series of crop yields and the MXD records were analysed in relation to instrumentally measured mean temperature series for April to August. Notably, most of the provincial series of crop yields showed correlations with the MXD series that were almost as high as those with the instrumentally measured regional temperature series (Table 3). In comparison to the MXD proxies, the TRW series correlated overall more weakly with the series of crop yields. Only the TRW series from northern timberline correlated significantly with most of the provincial crop yield series.

Discussion

Seasonal and monthly variations

This study found evidence of strong relationships between monthly and seasonal mean temperatures and the quantity of crop yields in Finland over the period 1861–1913. Mean temperatures between May and August correlated positively with rye crop yields in northern Finland, and mean temperatures between April and June with crop yields of barley throughout the country (Fig. 2). Previously, similar correlations were found between the mean temperature between May and September and the quality of crop yields in early 19th-century Finland (Solantie 2012). Positive correlations were also found for rye phenology (coming into ear, flowering and harvesting) and crop yields in 18th- and 19th-century Finland, indicating that earlier rye development resulted in a higher crop yield (Holopainen and Helama 2009). Moreover, Holopainen *et al.* (2012) suggested that the relationship between temperature and crop yield variability in 19th-century Sweden was meditated by early ripening. Early ripening reduced the risk of crop failure caused by early autumn (August and early September) night-frost, which was a considerable threat to Finnish crop cultivation (Myllyntaus 2009). The found connection between the April temperature and barley yield (Fig. 2) is interesting, because barley was sown in mid-May (Rantanen 1987). In present-day Finland, earlier sowing can be largely explained by warmer springs (Kaukoranta and Hakala 2008). Thus, the correlation between April temperature and barley crop yield is probably connected to the ripening of the crop in relation to the optimal sowing date. As the fields needed to thaw completely and the soil surface to dry adequately before sowing (Kaukoranta and Hakala 2008), cool April temperatures would have prolonged the process of thawing and drying of the fields. Solantie (2012) suggested that spring temperatures in Finland are affected by the extent of Baltic Sea ice; low winter temperatures cause a thick and wide ice cover over the Baltic Sea, and a thicker and wider ice cover takes longer to melt, which results in a longer period of increased surface albedo.

In Finland, historical crop failures have been largely explained solely by the occurrence of early autumn night-frost (Jutikkala 2003a, 2003b, for exceptions, *see* Solantie 2012). Our results suggest that high April and May temperatures were probably essential for early rye and barley ripening in the 19th and early 20th century in Finland. Early ripening, in turn, reduced the crop damage from early autumn night-frosts. Therefore, it can be speculated that the consequences of early autumn night-frost on historical crop yields were partly dictated by preceding spring and winter temperatures.

Concerning spring and winter temperatures, NAO dictates the climate variability of the northern hemisphere, especially during the boreal winter over the Atlantic/European sector (Trigo *et al.* 2002, Hurrell *et al.* 2003), and a strong relationship exists in Finland between springtime NAO and temperature variability (Helama and Holopainen 2012). Years of negative NAO phases are associated with low winter temperatures and decreased winter and increased summer precipitation in Finland (Luoto and Helama 2010). Although the correlations between the crop-figure series and monthly and seasonal indices were relatively weak (*see* above), we found that the years of countrywide poor harvest and crop failures, i.e., 1862, 1867, 1881, 1892, 1899 and 1902, coincided with the negative phases of the winter NAO (December to March). The connection between the negative winter NAO phase and poor harvest was especially evident in the crop yields of rye in southern Finland, which probably relates to the overwintering of the autumn-sown grain. In addition, a negative NAO phase can delay the onset of the warm season, as the snow cover melts later and the spring temperatures are lowered by increased soil moisture (Ogi *et al.* 2003). According to Jaagus *et al.* (2003), this relationship is clearly observable in the study region where the start date of spring has a close negative correlation with NAO indices in January, February and March. The late onset of the warm season can also increase the risk of frost during spring/early summer (Kaukoranta and Hakala 2008). The historical connection between NAO and northern crop yields has received little attention. However, previous studies (*see* e.g., Kim and McCarl 2005, Saue and Kadaja 2009, Persson *et al.* 2012) and our tentative results, imply that further study might provide greater insight into the connection between large-scale atmospheric variability and regional crop-yield fluctuations.

Autumn and winter temperatures

Although rye was sown in the previous autumn, hardly any significant correlations were found between the crop yield of this grain and monthly mean temperatures from August to December of the previous year (Fig. 2). The mean August temperatures in Finland correlated positively with the provincial crop yields of rye in Turku–Pori, and the mean October temperature correlated positively with the provincial crop yields of rye in Oulu. Surprisingly, springn-sown barley yields correlated negatively with September mean temperatures of the previous year, especially in southern and southeastern provinces. Moreover, the September NAO indices from the previous year correlated negatively with the barley yield in the provinces of Uusimaa and Kuopio. The connection between autumn temperatures and the harvest success in the following year was perhaps indirect. Low September temperatures probably resulted in unfavourable conditions for rye germination and overwintering, and therefore, in the subsequent spring, increased the interest in barley cultivation by farmers. In 19th-century Finland, the amount of sown barley was closely related to the farmers' evaluation of how well rye had overwintered (Solantie 2012). Although the relative crop figures used here do not indicate the absolute increase in the barley yield, the relatively higher crop values might indicate an increased interest by farmers to obtain as high a yield as possible, e.g., at the expense of other agricultural tasks, or with taking care of proper fertilization.

In the southern provinces, the crop-yield series correlated positively with mean January temperatures. The mean temperature in January, which was the coldest month of the year, was critical for the onset of the growing season and thus, was also critical for the early ripening of both crops (*see* above). The highest correlation coefficients between January temperature and rye-figure series were found for the southern Finland provinces of Uusimaa, Turku–Pori and Häme (Fig. 2). In addition, our study identified a significant relationship between low rye crop figures and negative January NAO index values in southern Finland, where a negative NAO is associated with low winter temperatures, increased snow depth and thick ice cover (George *et al*. 2004, Koskinen 2005). Moreover, in southern Finland, low temperatures rather than increased winter precipitation, are associated with the amount of snow during the cold winter months (Heino 1994). Hollins *et al*. (2004) found that an increased accumulated snow depth in January and March had a negative effect on the quality of the modern rye yield in Finland, by extending the growing season and delaying harvest to a less-favourable time in late-August/early September. Thus, our results suggest that accumulated snow depth had a negative effect on the quantity of the rye yield in the 19th century, similar to its effect on the quality of the yield today; the delayed effect of cold and snow in January probably delayed the ripening of grains, which resulted in a poor harvest. Furthermore, it is known historically in Finland, that approximately 50%–60% of the interannual fluctuation in rye yield results from snow-mould fungi and other overwintering damage (Rantanen 1987, Solantie 2012). Snow mould is caused when permanent snow cover falls on unfrozen ground and the snow cover remains thick throughout the winter. Because cold winter temperatures in southern Finland are connected with increased snow depth and duration, a high January mean temperature might be associated with a reduced risk of snow-mould fungi, which reduces wintering damage and results in higher crop yields. Our results provide a different perspective on climate-yield connections to that previously suggested (Solantie 2012), by demonstrating the relationship between winter temperatures (and associated snow cover) and crop yields in southern Finland.

Extreme events and crop failures

In the study period, the lowest temperatures between April and August occurred in 1867 and 1902. In 1867, the mean Finland (FIN T) April–August temperature was 2.7 °C lower than the 1861–1913 mean and that in 1902, was 2.2 °C lower. In 1867, the weather extremes resulted in severe famine, but in 1902, the agricultural system was able to recover from this anomalous year. The famine years of 1867–1868 in Finland were Europe's last major peacetime subsistence crisis (Ó Gráda 2001). The harvest in 1866 was rather poor, and rainy sowing conditions in the autumn of 1866, poor overwintering conditions, and the extremely cold spring and summer of 1867, caused a countrywide crop failure (Tilastollinen toimisto 1875a, Jantunen and Ruosteenoja 2000, Koskinen 2005, Solantie 2012). Approximately every 12th Finn died from malnutrition and related diseases (Myllyntaus 2009). After the catastrophe of 1867–1868, agriculture in Finland slowly began to reorganise. Farmers no longer relied solely on the cultivation of bread grains, and gained more interest in animal husbandry. The cultivation of hay and fodder crops, such as oats (*Avena sativa*), increased notably. In addition, the scale of agricultural production increased and began slowly to be mechanised in the late 19th century (Myllyntaus 2009). Thus, when an extremely cold summer and severe crop failure struck the country again in 1902, Finland was able to avoid a widespread subsistence crisis.

Although our analysis identified no clear relationship between monthly precipitation and crop yield, this might not fully confirm that unusual rainfall anomalies had no effect on harvest success. Himanen *et al.* (2013) demonstrated that rye and barley yields in most parts of modern-day Finland were reduced by heavy rains during the growing season. Excessive early-season precipitation or drought has been shown to reduce modern barley yields (Hakala *et al.* 2012) and heavy early-autumn rains can ruin the harvesting and sowing of rye (Mukula and Rantanen 1989). In addition, barley yields were explained by precipitation variables when the 18th and 19th century yields were correlated with contemporary climatic records in southwestern Finland (Holopainen and Helama 2009), and Solantie (2012) suggested that a mortality peak in the Province of Uusimaa was triggered by drought-driven crop failures in the mid-1850s. Furthermore, contemporaries also described that extreme events, such as drought, hailstorms and floods, caused poor harvest and local crop failures (Tilastollinen toimisto 1894a, 1904a).

Tree-ring proxies as indicators of climatic signatures in crops

To evaluate the applicability of tree-ring records to understand better the climatic and environmental connections to historical agricultural output, the provincial series of crop yields were compared to tree-ring data. Notably, most of the crop yield series correlated in a similar way with the MXD proxy of southeastern Finland (Helama *et al.* 2014b) and with the instrumentally-measured regional temperature series (Table 3). The same main limiting factor, summer temperature, most likely explains the high correlation between the MXD proxy and the crop-yield series. The high correlation of the Oulu crop yield of rye and barley with this MXD proxy is probably due to the high sensitivity of northern Finland's crop production to temperature variability (Mukula and Rantanen 1987, Himanen *et al.* 2013). However, it cannot be ruled out that the strong correlation between the crop yields and the MXD proxy arises from their similar responses to light availability. It was recently shown that high-latitude tree rings not only show a strong relationship with summer temperature, but additionally reflect variation in the availability of light (Stine and Huybers 2014, *see* also Solantie 2005). Similarly, it could be hypothesised that the correspondence between the MXD and crop yields series might be interwoven by the synchrony of their light and temperature responses.

Correlations between the MXD proxy of Lapland (Matskovsky and Helama 2014) and the series of crop yields were somewhat weaker than those with the MXD of southeastern Finland, and were similarly weaker than the correlations with the instrumentally-measured April–June mean temperature series. Firstly, the weaker correlation might originate from the geographical distance between the provenance of the MXD of northern Finland and the provinces where the crop yields were recorded. Simply, the MXD proxy of southeastern Finland is expected to represent the temperature variability in the southern and central parts of the country inherently better than the MXD proxy of Lapland. Secondly, the weaker correlations might result from the different seasonal sensitivity of the two MXD proxies. Our results indicate that the early summer temperatures were most critical for the early ripening of crops and hence, for high crop yields, whereas the MXD proxy of northern Finland mainly reconstructs fluctuations in June–August temperature variability (Matskovsky and Helama 2014). This result reinforces the impression that spring temperatures in particular might have a decisive effect on crop yields and that the tree-ring proxies that reconstruct summer and spring temperatures might explain the variability in the corresponding crop yields.

In comparison with the MXD series, the TRW series correlated considerably more weakly with the series of crop yields. This might be explained by TRW sensitivity to multiple climate variables. Even for summer temperatures, the TRW series typically only correlates with mid-summer temperatures i.e., with the mean July temperature (Helama *et al*. 2005, 2009). This type of correlation again means that the TRW series represents hardly any effect of spring temperature, the importance of which on crop yields is considered above. In addition to summer temperature, the TRW series can show a mixture of correlations with spring/summer precipitation and winter/spring temperatures (Helama *et al*. 2005, 2009, 2014a, Holopainen *et al*. 2006). As discussed earlier, the crop figures in this study hardly correlated with monthly precipitation totals, as far as precipitation data are available. Therefore, because the TRW series from southeastern and southwestern Finland correlated positively with early summer precipitation (May–June and June, respectively) (Helama *et al*. 2009, 2014a), no correlation between the southern TRW and crop yield series can be expected, due to their differing limiting factors.

Our results therefore, suggest that the MXD series might represent promising surrogate data for harvest–climate analysis, where reliable yield data are not available (Fig. 3). This is especially the case in boreal regions, where the crop yield and MXD proxy respond to the same limiting climatic factors. Preferably, the provenance of the MXD series should correspond to the studied area of crop production. Due to the strong correlation between the crop figures and the MXD series of southeastern Finland, we suggest that MXD evidence can be used for reconstructing crop-failure history in certain locations. According to our results, the MXD series of southeastern Finland provides strong evidence of barley crop failures, at least in the provinces of Mikkeli, Kuopio, Vaasa and Oulu. Although historians have considered that severe crop failures and subsistence crises occurred frequently across the country throughout history (Melander and Melander 1924, Jutikkala 2003a, Myllyntaus 2009), quantitative evidence for past crop failures in Finland, especially prior to the 17th century, is scant, and the existing information remains both temporally and spatially fragmented. The list of Finnish crop failures is spatially biased, and misleadingly also includes Russian and Swedish subsistence crises (Melander and Melander 1924). To date, it still remains unclear whether many of these events indeed extended to Finland. Therefore, additional sources of information to written records are urgently required and could possibly be recovered via proxy data.

Conclusions

We found evidence for strong relationships between monthly and seasonal mean temperatures and crop yield in historical Finland. High temperatures were consistently associated with higher crop yields, demonstrating the importance of temperature as a yield-limiting factor in Finnish agriculture. Years of countrywide crop failure coincided with years of low temperatures between January or April and August. The results imply that especially spring temperatures might have had a decisive impact on crop yields. As crop cultivation was the primary source of livelihood for most people living in late 19th- and early 20th-century Finland, it can be argued that climatic conditions not only limit crop production, but also human well-being in general. Weather extremes posed a serious risk to agricultural production. Moreover, our results suggest that harvest fluctuations were partly affected by winter NAO, especially in southern Finland. Although Finland as a whole is considered to be situated in the agricultural margin of the peripheral north, we found considerable inter-regional differences in the crop yield responses to temperature fluctuations within the country. Crop yields were substantially more sensitive to temperature fluctuations in the north than in southernmost Finland, where the temperature linkage nearly disappeared. This finding emphasises the importance of a spatially sensitive approach,

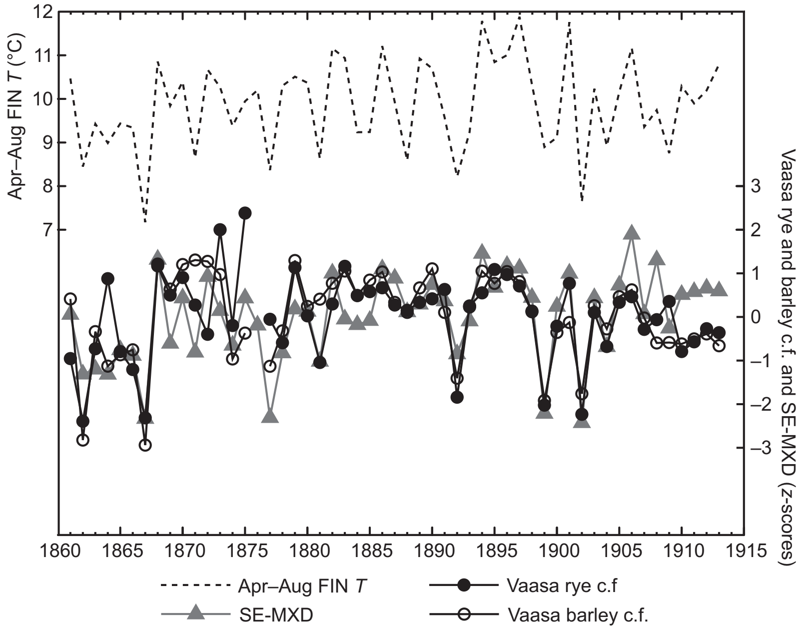

Fig. 3. Detrended rye and barley crop-figure (c.f.) series from the province of Vaasa, the southeastern Finland maximum latewood density (SE-MXD) series and the averaged mean temperature between April and August in Finland (Apr–Aug FIN *T*, all six stations) throughout the period 1861–1913. For locations, *see* Fig. 1.

which considers both data and analysis, in further studies on agricultural responses to climate variability.

In addition, a comparison between the correlations of crop yields with the MXD proxy and measured temperatures indicated that MXD evidence can be employed in harvest-climate analysis from the period prior to that of instrumental meteorological measurements. Furthermore, the findings imply that MXD proxies can offer a promising, new type of data for the reconstruction of crop failure history. Thus, MXD evidence might provide invaluable supplementary material for historical research into past agricultural outputs.

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