Hum Ecol (2009) 37:213–225
DOI 10.1007/s10745-009-9225-6

Little Ice Age Farming in Finland: Preindustrial Agriculture on the Edge of the Grim Reaper's Scythe

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Published online: 11 March 2009

Abstract This study examines potential climatic influences on historical agrarian populations in Finland by means of historical weather diaries, rye phenology, and rye and barley grain-figure (ratio between sown and harvested grain) data from the sixteenth to the nineteenth centuries. Crops exhibited great temporal variation. During the poorest years, the amount of harvested grain was less than that sown whereas during the better years the sown grain was harvested more than tenfold. Depending on the locality, 37–84% of this variability could be explained by monthly variables of growing season temperature and precipitation over the latter half of the eighteenth century. Although the grain-figure data showed clear spatial synchrony, it was found that this synchrony was much weaker than that of temperature, precipitation or rye phenology. Consequently, individual crop failure years should not be extrapolated over widely extended areas from spatially restricted data. Further, it was found that the desertion of farms in the sixteenth and the seventeenth centuries occurred coterminously with long-term summer temperature cooling, indicating that the desertion may have resulted from climatic deterioration that significantly impeded agriculture as a means of subsistence.

Keywords Human ecology · Environmental history · Crop yield · Biometeorology · The Moran effect

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Introduction

Recent examples in the debate on the role of climate on human ecology and societal development include Abate (1994), Binford *et al.* (1997), Haberle and Chepstow (2000), deMenocal (2001), Hodell *et al.* (2001), Weiss and Bradley (2001) and Zhang *et al.* (2007). Preindustrial agrarian populations obtained their main subsistence from the utilizable output of cultivated plants, often different kinds of cereals. If the climate influenced such populations it was most likely through its impact on the production of these grains. In preindustrial agrarian Finland, crop yields were the principal source of carbohydrates. Rye was the principal grain species followed by barley. Cultivation of arable land was the most important method of grain production, followed by burn-beating (slash and burn). However, arable cultivation was limited by a number of factors: the wheel plough was unknown, there was a lack of fertilization due to an insufficient number of livestock in relation to field area, and there were drainage problems due to primitive ditching systems. Burn-beating was more important in the eastern part of the country than in the southwest (the study region), but the local impacts of famine were magnified through the country due to poor communication and transportation systems. Historical documents show a qualitative correspondence between years of crop failure and times of famine (Grotenfelt 1919; Melander and Melander 1928; Kovero 1944; Tornberg 1989, 1990). Thus, the examination of available data could document the varying potential for survival under the fluctuating northern climate.

Evaluating the exact role of climate on human ecology requires data on environmental fluctuations with high chronological precision. Finnish documents of historical crop yields, agrophenology and early meteorological observations provide an overlapping time-series of preindustrial crop yields and agricultural activities in the context of the high-latitude climate of northern Europe (Linkola 1924; Tornberg 1989; Holopainen 1999, 2004; Holopainen *et al.* 2006). In general, the phenological series are of great importance in assessing the past, present and future responses of vegetation to climate changes (Sparks and Carey 1995, Menzel *et al.* 2006) and, correspondingly, the agrophenological series reveal climatic influence on cultivated species and on agricultural strategies. Importantly, the early meteorological observations provide a quantified picture of the relationships between the agricultural output and climatic variation. Tree-ring records from Finland and wider areas provide information on long-term climate change in the context of warm-season climatic variability (Helama *et al.* 2005b; Briffa *et al.* 1998, 2003). Here we examine these data to throw more light on the resources and subsistence patterns of preindustrial agrarian populations in the context of environmental history, with special emphasis on paleoclimatic alterations over interannual to multicentury time scales. The study periods range from the mid fifteenth century until the early nineteenth century, the period that has been termed the Little Ice Age due to multicentury cooling over various areas of the Northern Hemisphere (Grove 1988, Bradley and Jones 1993, Matthews and Briffa 2005).

Materials and Methods

The general climatic and environmental features of the study region (Fig. 1), southwestern Finland (here, from 60°40′ N to 60°10′ N and from 23°45′ to 21°34′ E), can be briefly described as follows. Over recent decades, the length of the growing season, during which the temperature remains above +5°C, averages 170–180 days, while the effective temperature sum is around 1,300 degree-days. Annual precipitation is on average 600 mm and the length of the permanent snow cover season totals 120 days. The major type of arable land is clay, and in addition silt and very fine sand occur (Mukula and Rantanen 1987; Rantanen and Solantie 1987). In historical context, the study region belongs to the arable land district of western Finland (Soininen 1974).

The present study benefited greatly from the significant temporal and spatial (geographic) overlap of the historical datasets of agricultural performance in southwestern Finland. The data are fragmentary but cover parts of the sixteenth, seventeenth, eighteenth and nineteenth centuries comprising agricultural and climatological records as described below. These data were complemented by the continuous paleoclimatic record from tree-rings that covered the full period.

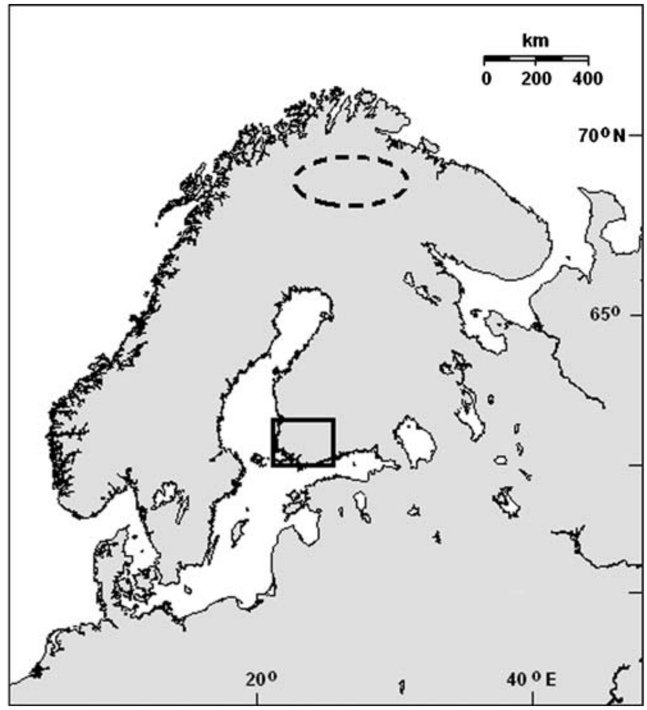

Fig. 1 Map of northern Europe showing the study area in southeastern Finland (*box*) and the approximate area of sampling sites of Finnish tree-rings (*oval*)

Grain-Figure Data

During historic times annual harvests were documented in Nordic countries as multiples of the seed used for sowing (i.e., yield per sowing). All the time-series of grain-figures on which this study is based originate from southwestern Finland. The sixteenth and seventeenth century grain-figure data come from the Crown estates, and these values are exact ratios between harvested and sown grain on each estate. The eighteenth and nineteenth century grain-figure data come from a number of different districts in southern Finland and these values are estimates by contemporary officials. Burnbeating was a minor practice in the region (Soininen 1974; Orrman 2003) and all the grain-figure data here refer, in all likelihood, to crops from arable farming. The data are now available in an accessible format due to an exhaustive preliminary analysis by Tornberg (1989), who examined the body of original historical documents and drew the curves for the grain-figures for visual comparison. The historical rye and barley grain-figure series were temporally divided into two distinct subsets, those originating from the early period (1549–1619) and the late period (1756–1800), which are based on data from four and eight localities (Table 1), respectively. In Finland, winter rye has traditionally been the most important bread grain (Mukula and Rantanen 1989a), whereas only spring barley survives under the northern climate (Mukula and Rantanen 1989d).

Table 1 Statistical characterization of rye and barley grain-figure data in different localities over the early (1549–1619) and late (1769–1800) periods of available data was calculated by the mean, standard deviation (SD) and the mean correlativity of the series to all other series (*r*)

Grain	Locality	First year	Last Year	Mean	SD	Max	Min	r
Rye	Ruissalo	1549	1608	7.4	2.0	11.0	1.8	0.488
Rye	Iso-Heikkilä	1549	1608	4.2	1.5	7.5	1.3	<u>0.569</u>
Rye	Näse	1557	1619	4.0	1.8	8.6	1.3	0.348
Rye	Vähä-Heikkilä	1557	1608	3.4	1.5	7.7	1.1	0.465
Rye	*Grand mean*			4.8				
Barley	Ruissalo	1558	1608	5.7	1.9	10.3	2.5	0.489
Barley	Iso-Heikkilä	1549	1608	4.8	2.2	10	1.1	<u>0.539</u>
Barley	Näse	1558	1619	3.6	1.5	7.2	1.0	0.521
Barley	Vähä-Heikkilä	1557	1608	3.8	1.9	9.2	0.7	0.529
Barley	*Grand mean*			4.5				
Rye	Korppoo	1769	1797	5.6	1.5	9.0	1.5	0.603
Rye	Nauvo	1769	1797	6.1	1.5	8.0	1.5	0.72
Rye	Rymättylä	1769	1797	5.5	1.4	8.0	1.5	<u>0.788</u>
Rye	Meri-Masku	1769	1797	5.4	1.5	8.0	1.5	0.774
Rye	Lemu	1769	1797	5.0	1.4	8.0	1.5	0.736
Rye	Mynämäki	1769	1797	4.9	1.5	7.0	1.0	0.529
Rye	Lohjalainen	1756	1780	8.7	2.4	13.5	4.0	0.557
Rye	Korppoolainen	1781	1800	7.6	2.6	10.5	0.5	0.582
Rye	*Grand mean*			6.1				
Barley	Korppoo	1769	1797	4.9	1.3	7.0	2.0	0.68
Barley	Nauvo	1769	1797	5.1	1.0	7.0	3.0	0.723
Barley	Rymättylä	1769	1797	4.7	1.3	7.0	2.0	<u>0.812</u>
Barley	Meri-Masku	1769	1797	4.7	1.4	7.0	2.0	0.778
Barley	Lemu	1769	1797	4.8	1.3	7.0	2.0	0.768
Barley	Mynämäki	1769	1797	4.8	1.2	7.0	2.0	0.703
Barley	*Grand mean*			4.8				

Highest correlations amongst the groups are underlined. Series are plotted in Fig. 2

Phenological Observations

Additional agricultural data used in this study are comprised of rye phenology (coming into ear, flowering and harvesting). The initial data show the annual variation in days of the onset of the three phenomena. The data originate from the records compiled into one dataset by Linkola (1924) and further reanalyzed by Holopainen *et al.* (2006), who also entered the Julian onset dates of the phenomena into a digital database system. In all, the data consisted of 836 observations of rye phenology in 39 independent sites around southwestern Finland (i.e., the study region and areas immediately adjacent). Here we adopted the data covering the period 1750–1807 that overlapped both the grain-figure and the early meteorological data. The information from fragmentary, partly overlapping records was combined into a continuous time-series of phenological indices. In so doing, all site- and phenomenon-specific series were normalized to present an average of zero and standard deviation of one. The mean phenomenon-specific series were then averaged as arithmetic means for annually resolved time-series representing the variability in the particular phenomenon. Consequently, each phenomenon-specific mean series was based on spatially normalized site-specific index series. By inverting the series, positive correlations occurred between warm temperatures and high phenological indices, analogous to the positive influence of warm temperatures on plant development (Holopainen *et al.* 2006).

Early Meteorological Data

The town of Turku (60°27′ N; 22°16′ E) was the largest population center of the study region and several types of meteorological observations were made there by skilled contemporaries from the 1730s to the 1820s. Calculation and homogenization (adjustment for time of observation) of daily temperature data for the period 1748–1800 from Turku were presented and discussed in detail by Holopainen (1999). The complete climatological records from Turku for the period 1730–1827 were also described by Holopainen (2004), along with the presentation and discussion of monthly temperature data from 1748–1823 and monthly precipitation data from the period 1749–1800. The variables used here were the monthly mean temperatures and monthly precipitation totals of the growing season (April through September).

Paleotemperature Reconstructions from Tree-Rings

In order to create a reliable long-term climatic context, the evidence of historical agricultural activity was compared to previously determined temperature reconstructions that spanned the study period in its entirety. These reconstructions were based on temperature-sensitive tree-rings that originated from northern Finland (Helama *et al.* 2005b) (Fig. 1) and the Northern Hemisphere (Briffa *et al.* 1998, 2003). The former record was considered to be particularly accurate for mid-summer temperatures (Helama *et al.* 2004, 2005a) and especially reliable with regard to their low-frequency variations (i.e., variability in past temperatures at timescales of decades and centuries) (Helama *et al.* 2005b). The hemispheric tree-ring dataset was previously shown to be sensitive to abrupt cooling from volcanic forcing (Briffa *et al.* 1998) and to indicate the past temperatures of the April through September season (Briffa *et al.* 2003). The reconstruction of Briffa *et al.* (2003, Fig. 5) represented the large-scale climate signal from the hemispheric (north of 20 °N) tree-ring density database and can be expected to depict climate variability over short (interannual) and long (multicentury) timescales (Briffa *et al.* 2003). We note that the preobservational climate variations in the study region have occasionally been estimated using the ice-core based paleotemperature estimates from Greenland (e.g., Jutikkala 2003a). The ice-core evidence was not employed here since the large-scale atmospheric dynamics over the intervening areas (i.e., North Atlantic Oscillation [Hurrell *et al.* 2001]), are likely to obscure any correlativity between the air temperature fluctuations of Greenland and Finland (Tuomenvirta *et al.* 2000; Karimova *et al.* 2007).

Results

Comparisons were made over the early (1549–1619) and late (1769–1800) periods of available grain-figure data. Over the early period the locality-mean grain-figures varied between 3.4 and 7.4 for rye and between 3.6 and 5.7 for barley (Table 1). These early values were on the same order as the grain-figure values from the late period in which the locality-mean grain-figures varied between 4.9 and 8.7 for rye and between 4.7 and 5.1 for barley. Moreover, investigation of the extreme values revealed the great amplitude of interannual variations in the crop yield. During the poorest years, the amount of harvested grain was less than that sown whereas in the better years the sown grain was harvested more than tenfold (Table 1).

The grain-figure series from different localities correlated well over both subperiods having multisite data (Table 1), implying a common (external) force on the observed variability. Importantly, the correlativity between the grain-figure data from different localities enabled the construction of averaged grain-figure time-series. That is, the series with highest correlation with all other series was selected as a base series and the other series were rescaled over the common period to the mean and standard deviation of that series (Table 1). For the early period, the base series for both rye and barley were from Iso-Heikkilä and for the late period the base series for both grain types came from Rymättylä (Table 1). Comparison between the mean series revealed that the rye and barley grain-figure series correlated positively and significantly over the early period ($r_{1549–1619}$=0.459) but that their correlation approached zero over the late period ($r_{1769–1797}$=−0.003). Moreover, during the late period having phenological data of rye available, we found positive and significant correlations between the rye phenology and grain-figure (Table 2; Fig. 2).

In spatial investigation, both rye and barley grain-figures showed a markedly negative trend in correlation with increasing distance between the localities (Fig. 3). Compared to the rye phenology, which also exhibited a negative trend as a function of distance (Fig. 3), the trend of grain-figures was notably steeper.

Last, the variability and intercorrelativity of the agrological time-series were viewed in the biometeorological context. Monthly variables of growing season climate explained 37% to 84% of the observed variability in the grain-figures (Table 3). It was found that while the variability in the rye grain-figure was predominantly controlled by thermal climate, the barley grain-figure data showed a more pronounced dependence on precipitation variability. More precisely, rye grain-figure variability was better explained by the temperature than by precipitation variables in seven out of eight localities. In the case of barley, the grain-figure variability in all six localities was better explained by precipitation rather than by temperature variables.

Discussion

Spatiotemporal Agricultural Context

In a global perspective, Finland is situated in the agricultural periphery of northern Europe. This phytogeographical position entails agricultural hardships due to climate (Parry 1975; Parry and Carter 1985), which, even during the industrialization of the late twentieth century, have markedly influenced farming practices and crop variations

Table 2 Pearson correlations between the three phenological series of rye (Holopainen *et al.* 2006) and the averaged rye grain-figure series (Table 1) over the common period 1756–1800

	Rye coming into ear	Rye flowering	Rye harvesting	Rye grain-figure
Rye, coming into ear	1.000			
Rye, flowering	0.764**	1.000		
Rye, harvesting	0.857**	0.616**	1.000	
Rye, grain-figure	0.567**	0.464*	0.462**	1.000

Positive correlations between the phenological and grain-figure series indicated that earlier onset of the three phenomena predicted higher crop yield in the region. Barley grain-figure series did not correlate significantly with any of the rye series over this period. Series are plotted in Fig. 2

**p*=0.05; ***p*=0.01 (all correlations were significant)

(Mukula and Rantanen 1987, 1989a, b, c, d, e; Rantanen 1987; Rantanen and Solantie 1987). Due to several technical and methodological developments as well as changes in the genetic plant material (i.e., introduction of improved rye and barley varieties), specifically over the post-WW II period (Mukula and Rantanen 1987, 1989a, d), knowledge about the modern relationships between climate variability and crop yields cannot be straightforwardly interpreted in the context of past agrarian environments and historic human populations. In the northern context, it would however seem justifiable to expect to find climatic imprints in the records of past agricultural production in the region, as proposed by Solantie (1997). Here we studied historic grain-figure, phenological and meteorological data from southwestern Finland to examine the interactions between environmental fluctuations and the population of the time. The vigorous grain-figure variability over the study periods (Table 1; Fig. 2) already indicates that the agrarian populations did live in an environment of great temporal variability of subsistence resources. In the context of modern Finnish agriculture, the interannual variability in rye and barley crop yields is among the lowest in the study region compared to other areas (Mukula and Rantanen 1989a, d). This would suggest that the other parts of the country may have experienced even larger year-to-year variations in the past as well. In addition, the past fluctuations between the individual years appeared larger than the grain-figure differences between the localities (Table 1), indicating greater variability over temporal rather than spatial scales. Since, ecologically, the climate can in general be described as the generator of temporal variability and upholder of spatial synchrony (Fritts 1963, 1976; Post and Forchhammer 2002; Post 2003; Menzel *et al.* 2006), this would imply the dominance of climatic anomalies in producing the observed crop variations.

Interannual Variability over the Early Period

Over the early study period, there existed no meteorological records for direct comparison with the grain-figure data. Interannual variability in the crop yield could however be compared with the known years of hemispheric and subhemispheric summer cooling due to large volcanic eruptions (Briffa *et al.* 1998, Gervais and MacDonald 2001, Helama *et al.* 2005a). Within this early period, 1601 is known as probably the severest volcanic signature year as an abrupt cooling (an anomaly of −0.8°C from long-term mean temperatures) spread over the Northern Hemisphere, possibly due to the eruption of Huaynaputina (Peru) in 1600 (Briffa *et al.* 1998; de Silva and Zielinski 1998). This year was previously noted as an extremely weakly grown tree-ring in the dendrochronologies of northern Fennoscandia and northwest Russia (Lindholm and Eronen 2000; Gervais and MacDonald 2001; Helama *et al.* 2005a) and it could be assumed that at least the summer of that year was cool in the study region as well. The year 1601 was in fact one of the poorest in terms of both barley and rye grain-figures, and was followed by several poor crop years (Fig. 2), indicating that the harshness of the climate probably continued and that agriculture had not yet recovered (Jutikkala 1958). In this context, 1601 seemed to be followed by several years of cooling, as evidenced by tree-rings in Finland (Lindholm and Eronen 2000) and in general in the Northern Hemisphere (Briffa *et al.* 1999, 2003), thus suggesting concomitant agricultural hardships and temperature control over the grain-figures for that period. According to Atwell (2001), 1601 and the following years were also associated with agricultural difficulties and harvest failures similar to the study region in geographically distant areas of Russia, Egypt and Japan.

Regarding other years of extremely poor crop yield over the early period (see Fig. 2), only 1587, which was poor especially for barley, was found to correlate temporally with any of the known sixteenth century volcanic years of large-scale cooling (Briffa *et al.* 1998).

Interannual Variability over the Late Period

Examination of the late study period benefited from contemporaneous phenological and meteorological obser-

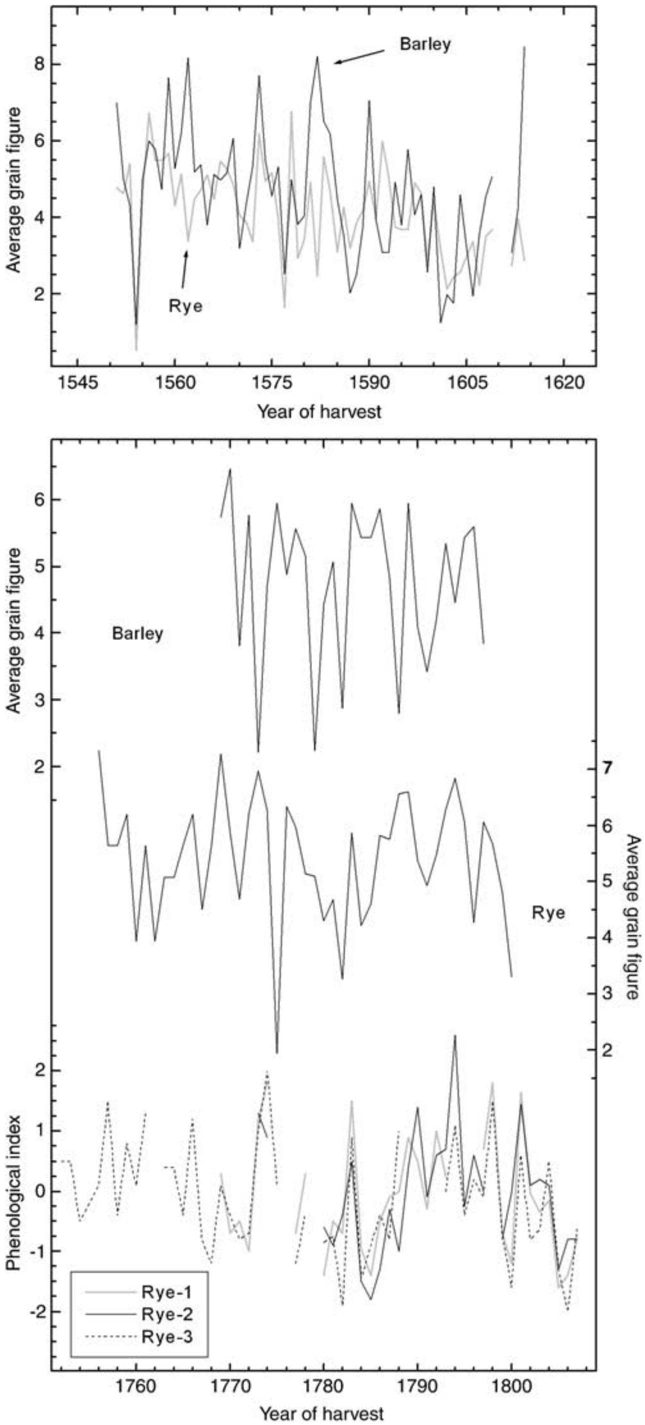

Fig. 2 Temporal variability in rye and barley grain-figures over the early and late periods along with the three phenological series of rye: coming into ear (Rye-1), flowering (Rye-2) and harvesting (Rye-3). Statistical correlations are presented in Table 2

vations (Holopainen 1999, 2004; Holopainen *et al.* 2006). Positive correlations were obtained between rye phenology (coming into ear, flowering and harvesting) and grain-figure data (Table 2), indicating that earlier rye development could in general be associated with higher crop yield. Early ripening could actually be a clear benefit due to the brevity of high latitude summers since later harvesting comes with an increasing risk of frost damage as the air temperatures in general cool towards the end of the growing season (Rantanen 1987). In this respect, it is known that delayed harvesting also decreases the quality of rye grain (Mukula and Rantanen 1989a). In addition, it was found that while the rye grain-figure variability was better explained by temperature variables, precipitation variables better explained barley grain-figure variability (Table 3). This result is consistent with the climatic influence on rye and barley crop yields over recent years (Mukula and Rantanen 1989a, d) in that barley is known to suffer particularly from both dryness and excessive soil moisture to a greater extent than rye (Mukula and Rantanen 1989d). Observations over recent years show that rye and barley are quite similar in their requirements for ripening in terms of a degree-day basis (Lallukka *et al.* 1978; Mukula and Rantanen 1989a); rye is somewhat earlier than later barley varieties. However, due to lack of detailed grain type information, further speculation has been avoided here.

From Interspecific Synchrony to Lack of Synchrony

As quantified statistically in the results section, the interannual variability in the grain-figures of rye and barley correlated positively over the early study period whereas they did not show any temporal correlativity during the later period (for visual comparison, see Fig. 2). The difference could be potentially associated with factors connected to temporal or spatial change. Temporally, the change in correlation could occur due to changes in climate that influence the growth of rye and barley differently (Mukula and Rantanen 1989a, d), varying cultivation customs, or quality or variety of grains (Wilmi 2003). Spatially, the difference could be due to soil or field types since the localities were different for the early and the late periods.

What we do know is that the dissimilarity in the rye and barley crop yields over the late period can be clearly associated with the differing climate correlations over the late period as the rye was more clearly affected by temperatures whereas the barley was more sensitive to precipitation (Table 3). Likewise, the similarity in crop yields over the early period could thus be due to a more uniform climate response. In fact, as discussed below, in the early period rye and barley exhibited a more or less identical response, especially to the climatic cooling phase that started in the 1570s. For example, since barley is known to be more sensitive to atmospheric dryness and excessive soil moisture (Mukula and Rantanen 1989d), it could be that the moisture conditions of the climate of the early period were more suitable to barley and that therefore,

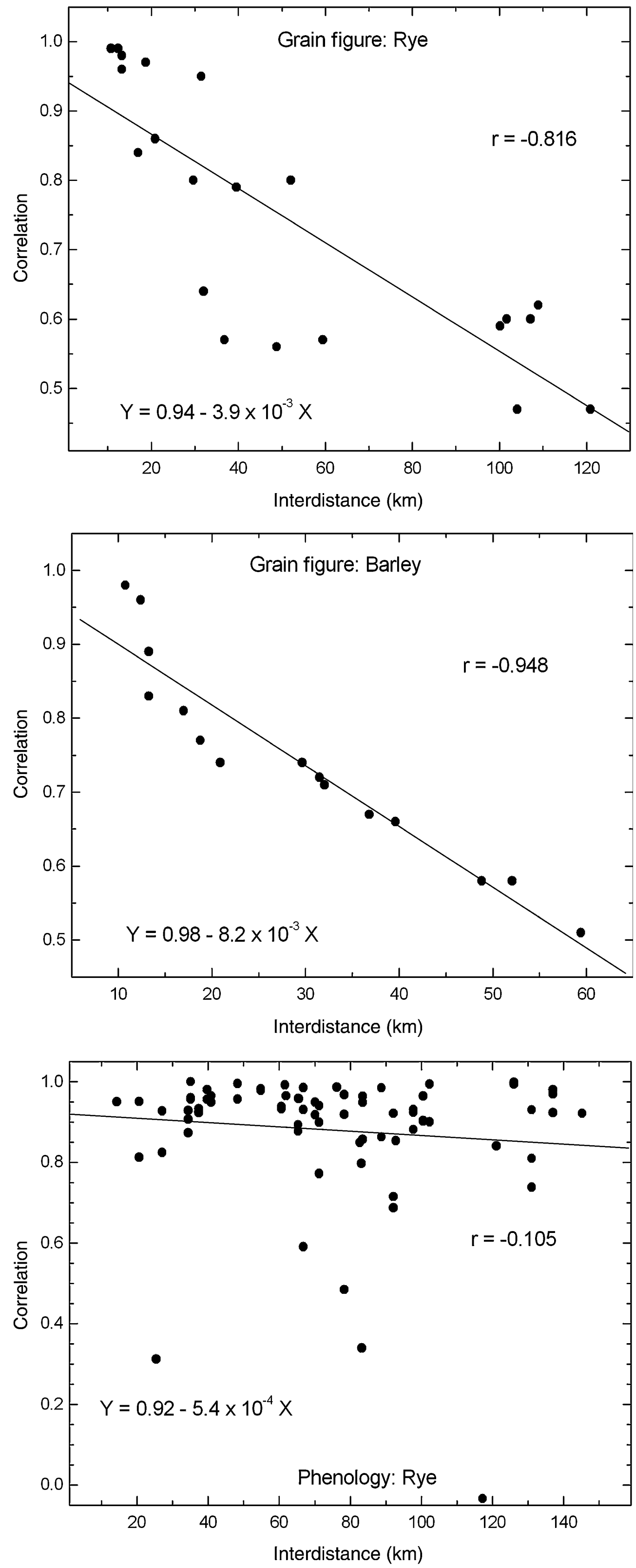

Fig. 3 Spatial synchrony of grain-figure data of rye and barley. Correlations between the localities were highest for nearby localities. This is indicated by the negative slope of the trend line and quantified further by Pearson correlation (*r*). Rye phenology (composite data of the three phenomena) also showed a negative trend as a function of distance. Equations quantify the linear dependence between the correlativity (*Y*) and distance (*X*)

its crop fluctuations responded more directly to temperature variations in the same way as rye. Alternatively, it could be that the temperature variations of the early period were so large (especially towards the end of the sixteenth century) that their influence overwhelmed the moisture signal in barley crops, which then perhaps responded more like rye crops. Apart from climatic factors, it is also known that there were changes in cereal varieties over the studied period but the exact nature of these changes and the potentially differing climatic response of different historical varieties are not known (Soininen 1974). Unfortunately, apart from the proposed hypothetical explanations, we are thus far unable to provide precise reasons for the change between the sixteenth and eighteenth centuries.

It is, however, noteworthy that the lack of rye–barley synchrony over the eighteenth century may actually indicate improved security in food availability. During the early period, when the crop yields of rye and barley varied more or less in concert, there was an increased danger of simultaneous crop failure in both grains, whereas over the late period, a crop failure of rye was not necessarily accompanied by a barley crop failure, and vice versa (Solantie 1997). Given that the described change was locality independent (see above), this provides a mechanism to explain how agrarian subsistence could have become more secure from the sixteenth century to the eighteenth century.

Paleoclimatology and Farm Desertion

The early and late periods both fall within the time frame of the climatic period often termed the Little Ice Age (Grove 1988; Bradley and Jones 1993; Broecker 2000; Matthews and Briffa 2005). This is the climatic phase from the thirteenth or fourteenth century until the mid nineteenth century during which long-term temperatures over large areas of the Northern Hemisphere exhibited pervasive cooling. Briffa *et al.* (1999) reviewed a body of tree-ring and non-dendroclimatic evidence and noted that a large region in mid- and northern Europe north of the Alps experienced cooling around the1570s. Clearly, such cooling could have reduced crop yields, especially in northern areas that are marginal in terms of agriculture (Parry 1975), and thus particularly in the study region, which is located on the very northern fringe of European agriculture. The grain-figure data from the sixteenth to eighteenth centuries

Table 3 Biometeorological relationships between the grain-figures of rye and barley, phenology of rye (Holopainen *et al.* 2006) and the growing-season climate

Grain	Quantity	Locality	$R^2(T+P)$	$R^2(T)$	$R^2(P)$
Rye	Grain-figure	Korppoo	0.40	0.27	0.11
Rye	Grain-figure	Nauvo	0.54	0.40	0.11
Rye	Grain-figure	Rymättylä	0.71	0.46	0.19
Rye	Grain-figure	Meri-Masku	0.67	0.41	0.21
Rye	Grain-figure	Lemu	0.62	0.32	0.18
Rye	Grain-figure	Mynämäki	0.58	0.34	0.11
Rye	Grain-figure	Lohjalainen	0.37	0.22	0.30
Rye	Grain-figure	Korppoolainen	0.84	0.55	0.61
Rye	Grain-figure	Locality-mean	0.43	0.25	0.24
Barley	Grain-figure	Korppoo	0.62	0.26	0.51
Barley	Grain-figure	Nauvo	0.62	0.18	0.40
Barley	Grain-figure	Rymättylä	0.53	0.14	0.39
Barley	Grain-figure	Meri-Masku	0.45	0.13	0.35
Barley	Grain-figure	Lemu	0.52	0.15	0.28
Barley	Grain-figure	Mynämäki	0.49	0.17	0.24
Barley	Grain-figure	Locality-mean	0.57	0.16	0.40
Rye	Coming into ear	SW Finland (mean)	0.79	0.74	0.29
Rye	Flowering	SW Finland (mean)	0.82	0.74	0.42
Rye	Harvesting	SW Finland (mean)	0.77	0.70	0.36

Results from multiple linear regression are shown as variance explained by monthly mean temperatures and monthly precipitation sums, R^2 $(T+P)$, variance explained solely by temperature variables, R^2 (T), and variance explained by precipitation variables, R^2 (P). Comparison was performed with the early meteorological data over the period AD 1750–1800.

examined here stand as a body of evidence about the contemporary populations' efforts to earn their bread, literally, during these times of climatic stress.

Post-medieval farm desertion in the study region and wider adjacent areas in and around southwestern Finland, starting during the 1580s and lasting approximately 150 years also potentially serves as evidence for the instability of agriculture and the inability to provide subsistence (Jutikkala 1958; Mäkelä 1979; Orrman 1986; Harju 1995). According to Atwell (2001), the period between the mid 1580s and 1610 was clearly a time of climatic upset on a global scale, with widespread poor harvests in numerous regions. Jutikkala (1958) was also of the opinion that the crop failure of the year 1601 influenced the desertion of farms in Finland. On the other hand, farm desertion has been explained in the context of inability to pay taxes, as noted on contemporary documents, possibly as a result of heightened taxation due particularly to the war between Sweden–Finland and Russia 1570–1595 (Mäkelä 1979; Orrman 1986). Heino (1995) and Harju (1995) have provided a geological and paleogeographical explanation for farm desertion, speculating that the postglacial land uplift, which is currently responsible for an approximately 3–5 mm annual rise in the study region (Ekman 1996), could have played a role. Kivistö (2002) postulated that land uplift during the sixteenth century may actually have contributed an additional factor to increased taxation because of the documented uplift-incurred costs of repair and rebuilding of several important stone constructions and castles in the region. Sundquist (1931) suggested that at the end of the 1610s, approximately 13% of the farms in Finland were deserted.

Our examination of the series of continuous tree-ring-based temperature records of regional (Helama *et al.* 2005b) and hemispheric (Briffa *et al.* 2003) spatial coverage revealed that the seventeenth century, which was the central period of farm desertion, was a markedly cool interval compared to the preceding and the following centuries (Fig. 4). The grain-figures of rye and barley both already showed potential temperature-dependent decline at the end of the sixteenth century and the beginning of the seventeenth century. It could thus be theorized that the lowered summer temperatures from the 1570s until the beginning of the eighteenth century probably had a significant and negative influence on agricultural success in the region over the period that strikingly overlapped the desertion of farms. Importantly, an expected consequence of such a persistent cooling would be an increased crop failure frequency (Parry and Carter 1985). Using historical records Tornberg (1992) estimated that the frequency of poor crop years or total failures was much higher in the study region during the seventeenth century compared to the eighteenth century.

Interestingly, Parry (1975) found a desertion of farms in high-lying areas of southeastern Scotland between the 1300s and the 1600s and linked the farmstead abandonment to coeval climatic cooling. Our interpretation also follows the general picture given by Appleby (1980), suggesting that the period from the sixteenth to the seventeenth century was characterized by great survival instability in Western Europe with periods of both low and high human mortality. Although

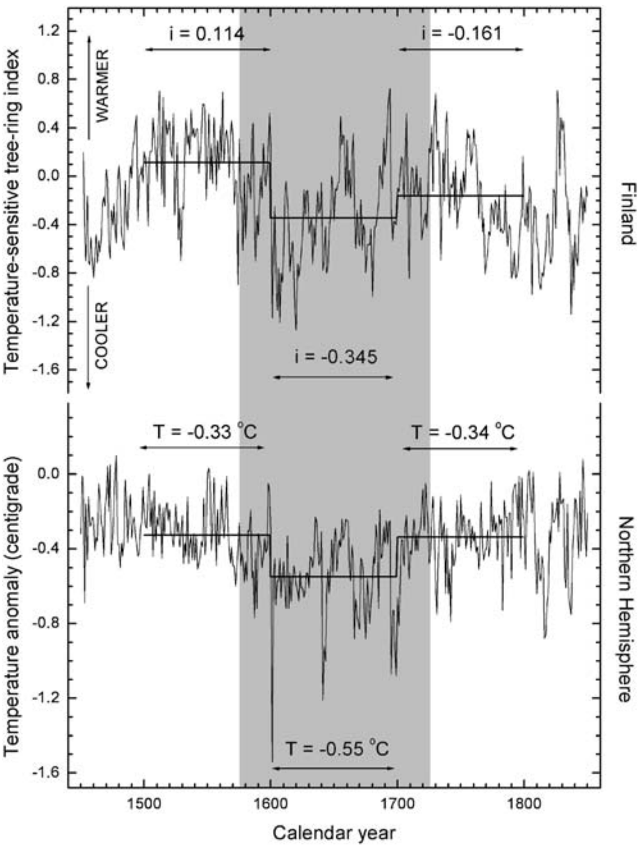

Fig. 4 Alternations of paleotemperatures (*black line*) over the study period as demonstrated by temperature-sensitive tree-ring index (*i*) from Finland (Helama *et al.* 2005b) and the Northern Hemisphere (Briffa *et al.* 2003) with the numerically given century-wise mean temperatures of the 1500s, 1600s and 1700s. The grey area approximates the phase of farm desertion. Hemispheric temperatures (*T*) are given in anomalies with respect to the 1961–1990 mean

it would be unwise to ignore the influence of the societal issues (i.e., the Sweden–Finland–Russia war and more stringent taxation) on farm desertion in the study region and adjacent areas, we would like to emphasize that climatic cooling would provide an additional perspective of environmental history to this phase that has long been studied without such a context in Finland. Previous studies have demonstrated the importance of soil management for arable production to buffer the cereal yield during times of climatic hardship and cooling (Simpson *et al.* 2002; Adderley and Simpson 2005). The general weak point of arable cultivation in pre-nineteenth century Finland was tillage (Soininen 1974). Evidently, the primitiveness of the cultivation methods amplified the climatic influences during these years.

Spatial Synchrony, the Moran Effect and Historical Agriculture

Spatial synchrony refers to spatial autocorrelation of variation through time. Since spatial synchrony is a ubiquitous feature of many natural phenomena (Ranta *et al.* 1995; Koenig 1999; Liebhold *et al.* 2004), it may not be surprising that the grain-figure data were also found to be spatially synchronized (Fig. 3). Since the rye and barley were, however, cultivated by historic humans and their crop yields provided the lifeline for the cultivators themselves, the spatial autocorrelation of the grain-figures may serve as unique guidelines for us to better understand past agrarian environments and the effects of their subsistence variability on historic human populations.

Spatial synchrony may be caused by three primary mechanisms: dispersal among populations, congruent dependence of population dynamics on a synchronous exogenous random factor such as climate, a phenomenon known as the Moran effect, and trophic interactions with populations of other species that are themselves spatially synchronous or mobile (Liebhold *et al.* 2004). In principle, the grain-figure data consist of ratios between the output at the end of the growing period and the input at the start of the period and cannot, as such, be influenced by dispersal. The Moran effect predicts that similarity (e.g., correlativity) of ecological time-series over long distances is driven by climate. Moran's (1953) original study was based on observations of the Canadian lynx. Subsequently, Fritts (1963) showed that a dataset of 21 tree-ring chronologies from Mexico to Canada exhibited a statistically significant correlativity with distances up to 1,000 km, while the dendrochronological correlativity was found to decline as a function of increasing distance with a rate similar to the corresponding decline in winter precipitation in the same region. More recently, climate has been shown to explain synchronized dynamics of different species of plants and animals over considerable distances (Ranta *et al.* 1995; Post and Forchhammer 2002; Post 2003; Liebhold *et al.* 2004).

In ecological terms, climate variability could thus be described as a producer of temporal variability and a maintainer of spatial correlation and synchrony (see Fig. 3). Likewise, the temporal variability of the grain-figures was shown to be attributable to climate (Table 3). As a next step, the spatial correlativity of the agricultural data could be compared to the main components of the climate variability: temperature and precipitation. According to Heino (1994), temperature and time correlate over Finland with coefficients around 0.7 for distances up to 1,000 km, whereas precipitation clearly shows a lesser degree of spatial synchrony over long distances with coefficients of around 0.5 for distances up to 300–400 km. These values were parallel to Koenig's (2002), who examined global spatial synchrony in temperature and precipitation data in the context of the Moran effect and found a general decline in temperature correlations from 0.6 to 0.4 and in precipitation correlations from 0.7 to 0.2 as the distance increased from 100 to 1,000 km between European weather stations. In addition, data obtained from temperature-sensitive tree-rings studied in Finland, similar to the earlier examples of Fritts (1963) and Rolland (2002) with respect to their spatial synchrony, indicate correlation coefficients around 0.45 over distances up to 800 km (Helama *et al.* 2005a). Figure 5 shows the spatial correlativity of the grain-figure data as rather weak whereas the rye phenology shows a spatial trend similar to tree-rings. These results are consistent with the previously determined climatic relationships (Table 3), that is, the variability in rye phenology correlated highly with the temperature variations and the trend in phenological spatial synchrony is only moderately steeper than that of temperatures. The variability in the rye grain-figures is better explained by temperature than by precipitation variables whereas the barley grain-figure variability was better explained by the precipitation variables. Consistently, the rye grain-figures show spatial synchrony over longer distances than barley (Fig. 5). These results also follow the global view that shows precipitation synchrony falls off more rapidly with increasing distance than does temperature synchrony (Koenig 2002).

Although in spatial synchrony, the grain-figure data did show a spatial autocorrelation that declined with a slope steeper than could be expected by the corresponding spatial behaviour in temperature, precipitation, tree-rings or even agrophenology (Fig. 5). Importantly, the grain-figure is a measure of crop yield in relation to sown seeds and lacks information on grain size and grain quality that could, if included, compensate for the relatively low degree of spatial synchrony observed. Among other potential reasons are locality-dependent factors. For example, soil type affects the development of rye and barley differently during different seasons (Mukula and Rantanen 1989a, d) and we speculate that spatial synchrony could be weakened by differing soil types in different localities. In the case of overwintering rye, markedly different snow conditions, which could result, for example, from differential wind disposition, may also have created diverging habitats for parasitic fungi (Mukula and Rantanen 1989a) that in turn could cause grain damage of differing degrees in different localities. In addition, localities may have differential sensitivity to frost. We are also aware that differing farming practices may have caused deviating grain-figures among the farms. Interestingly, all these locality-dependent factors could in theory prevent large areas from being affected by simultaneous crop failures due to lowered spatial correlation and synchrony. As the lowered spatial autocorrelation of agricultural output is expected to result in spatially non-synchronized occurrence of crop failures, this would mean that the agrarian society would, on larger spatial scales, remain more insensitive to climatic perturbation.

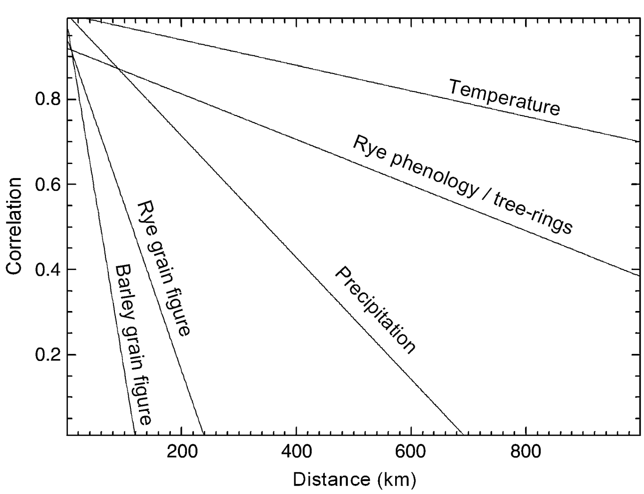

Fig. 5 Outline of spatial synchrony in grain-figure data (adapted from Fig. 2), agrophenology (adapted from Fig. 3), dendrochronology (Helama *et al.* 2005a) and temperature and precipitation climate (Heino 1994). While the rye phenology, similarly to tree-rings, correlates well over several hundreds of kilometers, the spatial synchrony of grain-figures is even weaker than that of precipitation

These findings may indeed bear implications for studies of human survival through years of limited food resources. Finnish agricultural science has a long tradition of documenting years with crop failures (Grotenfelt 1919; Melander and Melander 1928; Kovero 1944; Tornberg 1988, 1990). However, these studies have so far proceeded without grain-figure information (with the exception of Tornberg 1988, 1990). With regard to our late study period, Melander and Melander (1928) provided a list of years with crop failure and famine including 1749, 1751, 1752, 1754, 1755, 1757, 1762, 1763, 1766, 1769, 1770, 1771, 1772, 1774, 1776, 1783, 1784, 1785, 1790, 1791 and 1797. Likewise, according to Kovero (1944), 1755, 1784, 1787, 1788, 1791, 1797 and 1798 could be described as years with crop failure in Finland. Tornberg (1989) added the information that the crop failure of rye occurred in 1776 and 1783 whereas the barley crops failed in 1774, 1780, 1783 and 1789. Putting this together, the period 1749–1798 experienced a total of 26 years with crop failure and famine in Finland. It is noteworthy that all this information has been gathered from spatially more or less fragmentary data from Finnish historical documents. An important caveat in this respect is the spatial representativeness of the data regarding the crop yields, or at least grain-figures (Figs. 3 and 4). While we find no reason to question the reliability of the crop failure dates above, it should be emphasized that data on a crop failure in any one or several neighbouring localities would not necessarily give reliable information about crop figures in other localities at distances of roughly 200 km or more (Fig. 5). As a consequence, Finnish famine history may actually not be as dark as assumed based solely on the listed years. While we do not question the severity of the major historical famine years (Jutikkala 1955, 2003b; Neumannn and Lindgren 1979), the present results suggest that Finnish crop failures and famines were in general spatially more restricted than previously appreciated.

Conclusions

This study examined preindustrial agricultural data from southwestern Finland in the context of the northern environment and Little Ice Age climate variability. The great temporal variability of grain-figures provided singular evidence that preindustrial agrarian populations did live in an environment of severe variations and concomitantly insecure subsistence. Further, we found evidence that rye and barley grain-figures were markedly influenced by the large-scale temperature variations that occurred between the mid-sixteenth and early seventeenth century. Thereafter, the long-term summer temperature cooling due to the Little Ice Age may have contributed to farm desertion due to increased crop failure frequency. Over the later half of the eighteenth century, the variability in barley grain-figures was better explained by precipitation variables rather than by temperature whereas the rye grain-figures were better explained by temperature variables. This deviation in climatic relationships probably decreased the risk of coincident crop failure of both kinds of cereals and thus provided improved security of agricultural subsistence. The correlation between the rye phenology and rye grain-figures indicated, however, that frost damage was a constant threat and earliness in ripening a benefit. It was also found that the grain-figure data exhibited spatial synchrony (the Moran effect) that was, however, much weaker over long distances than could have been expected purely from the climate or by inspection of other natural time-series. This indicated that crop failures did not necessarily extend over large areas (albeit they evidently did in some years). Over large spatial scales, the poor spatial synchrony of grain-figures would provide an additional buffering mechanism against massive nutrition-mortality events.

Acknowledgements This analysis has benefited greatly from the previous studies of Kaarlo Linkola and Matleena Tornberg, whose publications and archives provided the phenological and agricultural data in an accessible format. Their work is highly appreciated. Part of the tree-ring material used (Briffa *et al.* 2003) was kindly provided to us by Keith R. Briffa and Thomas M. Melvin. Comments by Tapani Tuovinen, Kari Alifrosti and three anonymous reviewers on earlier versions of the manuscript improved the final presentation of the paper. We express our gratitude to Robert M. Whiting for his assistance in editing this manuscript. Figure 1 was aided by Online Map Creation. The distances between the sites were estimated using an online JavaScript by John A. Byers. The study was made possible by the Finnish Cultural Foundation-Satakunta Foundation (grant to JH) and the foundation of Koneen säätiö (grant to SH).

References

Abate, T. (1994). Climate and the Collapse of Civilization. BioScience 44: 516–519.

Adderley, W. P., and Simpson, I. A. (2005). Early-Norse Home-Field Productivity in the Faroe Islands. Human Ecology 33: 711–736.

Appleby, A. B. (1980). Epidemics and Famine in the Little Ice Age. Journal of Interdisciplinary History 10: 643–663.

Atwell, W. S. (2001). Volcanism and Short-Term Climatic Change in East Asian and World History. Journal of World History 12: 29–98.

Binford, M. W., Kolata, A. L., Brenner, M., Janusek, J. W., Seddon, M. T., Abbott, M., and Curtis, J. H. (1997). Climate Variation and the Rise and Fall of an Andean Civilization. Quaternary Research 47: 235–248.

Bradley, R. S., and Jones, P. D. (1993). 'Little Ice Age' Summer Temperature Variations: Their Nature and Relevance to Recent Global Warming Trends. The Holocene 3: 367–376.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., and Osborn, T. J. (1998). Influence of Volcanic Eruptions on Northern Hemisphere Summer Temperature over the Past 600 Years. Nature 393: 450–455.

Briffa, K. R., Jones, P. D., Vogel, R. B., Schweingruber, F. H., Baillie, M. G. L., Shiyatov, S. G., and Vaganov, E. A. (1999). European Tree Rings and Climate in the 16th Century. Climatic Change 43: 151–168.

Briffa, K. R., Osborn, T. J., and Schweingruber, F. H. (2003). Large-Scale Temperature Inferences from Tree Rings: A Review. Global and planetary change 40: 11–26.

Broecker, W. S. (2000). Was a Change in Thermohaline Circulation Responsible for the Little Ice Age. Proceedings of the National Academy of Sciences 97: 1339–1342.

deMenocal, P. B. (2001). Cultural Responses to Climate Change During the Late Holocene. Science 292: 667–673.

de Silva, S. L., and Zielinski, G. A. (1998). Global Influence of the AD 1600 Eruption of Huaynaputina, Peru. Nature 393: 455–458.

Ekman, M. (1996). A Consistent Map of the Postglacial Uplift of Fennoscandia. Terra Nova 8: 158–165.

Fritts, H. C. (1963). Computer Programs for Tree-Ring Research. Tree-Ring Bulletin 25: 3–42–7.

Fritts, H. C. (1976). Tree Rings and Climate. Academic, New York, 567 pp.

Gervais, B. R., and MacDonald, G. M. (2001). Tree-Ring and Summer-Temperature Response to Volcanic Aerosol Forcing at the Northern Tree-Line, Kola Peninsula, Russia. The Holocene 11: 499–505.

Grotenfelt, K. (1919). Aikaisemmista katovuosista Suomessa. Juhlajulkaisu E. G. Palménin 70-vuotispäiväksi. Werner Söderström Osakeyhtiö, Porvoo. pp. 65–74.

Grove, J. H. (1988). The Little Ice Age. Routledge, London.

Haberle, S. G., and Chepstow, A. (2000). Can Climate Influence Cultural Development? A View through Time. Environment and History 6: 349–369.

Harju, T. (1995). Ihmisen ja luonnon vuorovaikutus autioitumisen taustalla. In Nissinaho, A. (ed.), Ihmisen maisema. Kirjoituksia yhteisön ja ympäristön muutoksesta Lounais-Suomen rannikolla, Projekti Muuttuva Miljöö - muuttuva yhteisö. University of Turku, Åbo Akademi, Turku, pp. 65–75.

Heino, R. (1994). Climate in Finland During the Period of Meteorological Observations. Finnish Meteorological Institute Contributions 12: 1–209.

Heino, U. (1995). Ympäristöstäkö historiallisen kehityksen selittäjä. In Nissinaho, A. (ed.), Ihmisen maisema. Kirjoituksia yhteisön ja ympäristön muutoksesta Lounais-Suomen rannikolla, Projekti Muuttuva Miljöö - muuttuva yhteisö. University of Turku, Åbo Akademi, Turku, pp. 47–62.

Helama, S., Holopainen, J., Timonen, M., Ogurtsov, M. G., Lindholm, M., Meriläinen, J., and Eronen, M. (2004). Comparison of Living-Tree and Subfossil Ring-Widths with Summer Temperatures from 18th, 19th and 20th Centuries in Northern Finland. Dendrochronologia 21: 147–154.

Helama, S., Lindholm, M., Meriläinen, J., Timonen, M., and Eronen, M. (2005a). Multicentennial Ring-Width Chronologies of Scots Pine Along North–South Gradient Across Finland. Tree-Ring Research 61: 21–32.

Helama, S., Timonen, M., Lindholm, M., Meriläinen, J., and Eronen, M. (2005b). Extracting Long-Period Climate Fluctuations from Tree-Ring Chronologies over Timescales of Centuries to Millennia. International Journal of Climatology 25: 1767–1779.

Hodell, D. A., Brenner, M., Curtis, J. H., and Guilderson, T. (2001). Solar Forcing of Drought Frequency in the Maya Lowlands. Science 292: 1367–1370.

Holopainen, J. (1999). Turun vuosien 1748–1800 lämpötilamittaus-sarjan homogenisointi. Terra 111: 37–39.

Holopainen, J. (2004). Turun varhainen ilmastollinen havaintosarja. (English Abstract: The Early Climatological Records of Turku). Finnish Meteorological Institute Reports 8: 1–59.

Holopainen, J., Helama, S., and Timonen, M. (2006). Plant Phenological Data and Tree-Rings as Palaeoclimate Indicators Since AD 1750 in SW Finland. International Journal of Biometeorology 51: 61–72.

Hurrell, J. W., Kushnir, Y., and Visbeck, M. (2001). The North Atlantic Oscillation. Science 291: 603–604.

Jutikkala, E. (1955). The Great Finnish Famine in 1696–97. Scandinavian Economic History Review 3: 48–63.

Jutikkala, E. (1958). Suomen talonpojan historia. Suomalaisen Kirjallisuuden Seuran toimituksia 257: 1–480.

Jutikkala, E. (2003a). Halla aina uhkana. In Rasila, V., Jutikkala, E., and Mäkelä-Alitalo, A. (eds.), Suomen maatalouden historia. Osa1: Perinteisen maatalouden aika: esihistoriasta 1870–luvulle. *Suomalaisen Kirjallisuuden Seuran toimituksia* 914: 292–299.

Jutikkala, E. (2003b). Katovuodet. In Rasila, V., Jutikkala, E., and Mäkelä-Alitalo, A. (eds.), Suomen maatalouden historia. Osa1: Perinteisen maatalouden aika: esihistoriasta 1870-luvulle. *Suomalaisen Kirjallisuuden Seuran toimituksia* 914: 504–513.

Karimova, L., Kuandykov, Y., Makarenko, N., Novak, M. M., and Helama, S. (2007). Fractal and Topological Dynamics for the Analysis of Paleoclimatic Records. Physica A 373: 737–746.

Kivistö, T. (2002). Ympäristön vaikutus veronmaksuun keskiajan Varsinais-Suomessa. Turun yliopiston Historian laitoksen julkaisuja 62: 143–176.

Koenig, W. D. (1999). Spatial Autocorrelation of Ecological Phenomena. Trends in Ecology & Evolution 14: 22–26.

Koenig, W. D. (2002). Global Patterns of Environmental Synchrony and the Moran Effect. Ecography 25: 283–288.

Kovero, M. (1944). Katovuosista Suomessa Ruotsin vallan aikana isonvihan jälkeen. Kansantaloudellinen Aikakauskirja 40: 405–447.

Lallukka, U., Rantanen, O., and Mukula, J. (1978). The Temperature Sum Requirement of Barley Varieties in Finland. Annales Agriculturae Fenniae 17: 185–191.

Liebhold, A., Koenig, W. D., and Bjørnstad, O. N. (2004). Spatial Synchrony in Population Dynamics. Annual Review of Ecology, Evolution and Systematics 35: 467–490.

Lindholm, M., and Eronen, M. (2000). A Reconstruction of Mid-summer Temperatures from Ring-Widths of Scots Pine Since AD 50 in Northern Fennoscandia. Geografiska Annaler 82A: 527–535.

Linkola, K. (1924). Kesien aikaisuudesta Lounais-Suomessa vuosina 1750–1923. Talonpoika, Osa 1, Lounais-Suomi. Turku, Lounais-Suomen Maataloustuottajain Piiriliitto, pp 41–74.

Mäkelä, A. (1979). Hattulan kihlakunnan ja Porvoon läänin autioituminen myöhäiskeskiajalla ja uuden ajan alussa. Historiallisia tutkimuksia 109: 1–276.

Matthews, J. A., and Briffa, K. R. (2005). The 'Little Ice Age': Re-evaluation of an Evolving Concept. Geografiska Annaler 87A: 17–36.

Melander, K. R., and Melander, G. (1928). Katovuosista Suomessa. Oma Maa V. Werner Söderström Osakeyhtiö, Porvoo, pp. 350–359.

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F. M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczal, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., van Vliet, A. J. H., Wielgolaski, F. -E., Zach, S., and Zust, A. (2006). European Phenological Response to Climate Change Matches the Warming Pattern. Global Change Biology 12: 1969–1976.

Moran, P. A. P. (1953). The Statistical Analysis of the Canadian Lynx Cycle. II. Synchronization and Meteorology. Australian Journal of Zoology 1: 291–298.

Mukula, J., and Rantanen, O. (1987). Climatic Risks to the Yield and Quality of Field Crops in Finland: I. Basic Facts About Finnish Field Crops Production. Annales Agriculturae Fenniae 26: 1–18.

Mukula, J., and Rantanen, O. (1989a). Climatic Risks to the Yield and Quality of Field Crops in Finland: III. Winter Rye 1969–1986. Annales Agriculturae Fenniae 28: 3–11.

Mukula, J., and Rantanen, O. (1989b). Climatic Risks to the Yield and Quality of Field Crops in Finland: IV. Winter Wheat 1969–1986. Annales Agriculturae Fenniae 28: 13–19.

Mukula, J., and Rantanen, O. (1989c). Climatic Risks to the Yield and Quality of Field Crops in Finland: V. Spring Wheat 1969–1986. Annales Agriculturae Fenniae 28: 21–28.

Mukula, J., and Rantanen, O. (1989d). Climatic Risks to the Yield and Quality of Field Crops in Finland: VI. Barley 1969–1986. Annales Agriculturae Fenniae 28: 29–36.

Mukula, J., and Rantanen, O. (1989e). Climatic risks to the yield and quality of field crops in Finland: VII. Oats 1969–1986. Annales Agriculturae Fenniae 28: 37–43.

Neumannn, J., and Lindgren, S. (1979). Great Historical Events That Were Significantly Affected by the Weather: 4, the Great Famines in Finland and Estonia. Bulletin of the American Meteorological Society 60: 775–787.

Orrman, E. (1986). Bebyggelsen i Pargas, S:t Mårtens och Vemo socknar i Egentliga Finland under senmedeltiden och på 1500-talet. Historiallisia tutkimuksia 131: 1–293.

Orrman, E. (2003). Keskiajan maatalous. In Rasila, V., Jutikkala, E., and Mäkelä-Alitalo, A. (eds.), Suomen maatalouden historia. Osa1: Perinteisen maatalouden aika: esihistoriasta 1870-luvulle. Suomalaisen Kirjallisuuden Seuran toimituksia 914: 87–114.

Parry, M. L. (1975). Secular Climatic Change and Marginal Agriculture. Transactions of the Institute of British Geographers 64: 1–13.

Parry, M. L., and Carter, T. R. (1985). The Effect of Climatic Variations on Agricultural Risk. Climatic Change 7: 95–110.

Post, E. (2003). Large-Scale Climate Synchronizes the Timing of Flowering by Multiple Species. Ecology 84: 277–281.

Post, E., and Forchhammer, M. C. (2002). Synchronization of Animal Population Dynamics by Large-Scale Climate. Nature 420: 168–171.

Ranta, E., Kaitala, V., Lindström, J., and Lindén, H. (1995). Synchrony in Population Dynamics. Proceedings of the Royal Society of London. Biological Sciences 262: 113–18.

Rantanen, O. (1987). Lämpö- ja sadeolojen merkitys viljanviljelyssä. Kylvösiemen 26(3):6–8.

Rantanen, O., and Solantie, R. (1987). Climatic Risks to the Yield and Quality of Field Crops in Finland: II. Cultivation Zones and Sub-divisions. Annales Agriculturae Fenniae 26: 19–37.

Rolland, C. (2002). Decreasing Teleconnections with Inter-site Distance in Monthly Climatic Data and Tree-Ring Width Networks in a Mountainous Alpine Area. Theoretical and Applied Climatology 71: 63–75.

Simpson, I. A., Adderley, W. P., Guðmundsson, G., Hallsdóttir, M., Sigurgeirsson, M. Á., and Snæsdottir, M. (2002). Soil Limitations to Agrarian Land Production in Premodern Iceland. Human Ecology 30: 423–443.

Soininen, A. M. (1974). Vanha maataloutemme. Summary in English: Old Traditional Agriculture in Finland in the 18th and 19th Centuries. Historiallisia tutkimuksia 96: 1–459.

Solantie, R. (1997). Ilmaston, maankäytön ja väestön kolmiyhteys Suomessa vanhan maatalouden aikana. Abstract in English: The Tripartite Interdependence of Climate, Land Use and Population in Finland During the Old Agricultural Era. Finnish Meteorological Institute. Meteorological Publications 35: 1–73.

Sparks, T. H., and Carey, P. D. (1995). The Responses of Species to Climate over Two Centuries: An Analysis of the Marsham Phenological Record, 1736–1947. The Journal of Ecology 83: 321–329.

Sundquist, S. (1931). Finlands folkmängd och bebyggelse i början av 1600-talet. Meddelanden från Generalstabens krigshistoriska avdelning 2: 1–82.

Tornberg, M. (1989). Ilmaston- ja sadonvaihtelut Lounais-Suomessa 1550-luvulta 1860-luvulle. Turun Historiallinen Arkisto 44: 58–87.

Tornberg, M. (1990). Lisiä kansainväliseen pikku jääkausi-keskusteluun. Turun Historiallinen Arkisto 45: 55–76.

Tornberg, M. (1992). Ilmastohistoria - nyt. Turun yliopiston Historian laitoksen julkaisuja 24: 47–82.

Tuomenvirta, H., Alexandersson, H., Drebs, A., Frich, P., and Nordli, P. O. (2000). Trends in Nordic and Arctic Temperature Extremes and Ranges. Journal of Climate 13: 977–990.

Weiss, H., and Bradley, R. S. (2001). What Drives Societal Collapse. Science 291: 609–610.

Wilmi, J. (2003). Tuotantotekniikka ja ravinnonsaanti. In Rasila, V., Jutikkala, E., and Mäkelä-Alitalo, A. (eds.), Suomen maatalouden historia. Osa1: Perinteisen maatalouden aika: esihistoriasta 1870-luvulle. Suomalaisen Kirjallisuuden Seuran toimituksia 914: 159–182.

Zhang, D. D., Zhang, J., Lee, H. F., and He, Y. (2007). Climate Change and War Frequency in Eastern China over the Last Millennium. Human Ecology 35: 403–414.