Byzantine Empire Economic Growth: Did Past Climate Change Play a Role?

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Abstract
Different chronicles of the Byzantine Empire's history have noted various economic data gleaned from historical documents and accounts of the Empire's existence. I provide conjectures on approximate real GDP per capita for the Empire over its existence from AD 300 to 1453. I use these to investigate whether climate forcing variables are associated with real GDP per capita fluctuations. Some hypotheses on factors that would have affected Byzantine economic performance are tested using climate/environmental factors in time series regression. The results support and confirm some findings on how the Byzantine economy may have been affected by periods of regional climate change.

Keywords Byzantine Empire · Climate change · Real GDP per capita · Empire size · Antique ice age · Medieval climate anomaly · Little ice age

JEL N13 · N14 · Q54

Introduction

The field of cliometrics has developed over the last six decades to apply the statistical techniques of econometrics to the questions of and research on historical issues and sometimes on economic systems other than capitalism (Haupert & Diebolt, 2020). Two major studies have covered economic growth in England and later the UK from the 13th to the 19th centuries (Broadberry et al., 2015; Clark, 2009). This paper has found no cliometric studies of the Byzantine Empire's economic growth and development.

The Byzantine Empire was the eastern half of the Roman Empire, which survived the decline and fall of the western half in the fourth century. It was beset by many challenges, including conflicts with hostile and powerful neighboring nations and tribes (Treadgold, 1997, 2020); internal warring religious and aristocratic factions (Treadgold, 1997, 2020); recurring plagues (Treadgold, 1997; Stathakopoulos, 2004); frequent famines (Treadgold, 1997; Stathakopoulos, 2004). According to some historians and climatologists, periods of adverse climate change hindered the Empire, making it challenging to attain previous levels of political and economic power (Haldon et al., 2014).

The primary purpose of this paper is to see if any approximations of the climate factors while controlling for other factors correlate with estimated Byzantine actual output trends and agricultural productivity trends from the 4th to fifteenth centuries. The emphasis on developing the estimates is to construct approximate real Gross Domestic Product (GDP) trends and not to establish precise estimates for year-to-year output fluctuations.

In researching for this paper, no literature has been found that gives estimates of the Byzantine Empire's imperial revenues or economic output over an extended period. I attempt to fill this gap in the literature by using reliable data sources to construct different conjectures of trend real GDP per capita and agricultural productivity (wheat output rates) trends from AD 300 to 1453. Additionally, to

1 All data developed in and used by this paper can be furnished by the author upon request.
2 The empire ended in 1453 with the Ottoman Turks conquering Constantinople, yet the last good year of reliable estimates for imperial finances is for the year 1320 (Treadgold, 1997, 2020). Nonetheless, conjectures can be made for the last decades of the empire using writings of historical events and empire size in terms of population and geography.
see if climate changes during the Empire’s time could have impacted the Empire’s actual output, I used paleoclimatic climate estimates to predict both trends and weather-related catastrophes (floods, severe droughts, etc.). These results can support or diminish those papers that claim a connection between past climate changes and Byzantine economic fortunes. However, none of these uses estimates of long-term Byzantine real GDP per capita. The paper proceeds as follows: the following section outlines the methods used to develop the estimates and some analysis of the results; after that, the discussion and conclusion section includes the results and key findings; the last section outlines the limitations of the findings, provides some ideas on the implications of the conjectures, and gives suggestions for further research.

Methods

Estimating Real GDP per Capita

To estimate real GDP per capita, one must first estimate production per head. Output per capita can be derived using relevant data from Treadgold (1982, 1997, 2020), who gives estimates of Byzantine imperial budgets for different years from AD 300 to AD 1320, and Milanovic (2006) claims that any Byzantine budget is probably 5% to 8% of the amount of the Byzantine economy or gross output. This would not be unusual given that most scholars have written that tax revenues usually would be the equivalent of around no more than 5% of a medieval economy, and most of the tax burden fell on peasants and laborers (Brown, 2017; Lambert, 2020a, b). For the Byzantine Empire, it appears that most tax rates usually never exceeded and averaged 10% of land values, sales of goods, etc., and that if there were any surcharges, these usually never exceeded 20% for an overall average rate of 12% at the most (Treadgold, 1982, 1997, 2020; Harvey, 1989; Le Goff, 2012; Herrin, 2007).

According to Treadgold (1982), in the eighth and ninth centuries, only 5% to 10% of Byzantine state revenues came from commerce and activities outside of agriculture (p. 93), and land and hearth taxes made up the bulk of agricultural revenues at around 88% or so (pp. 52–58). Land taxes mostly came from agricultural lands, according to their fertility/productivity, which meant that government finances were heavily influenced by the economic condition and size (in total square kilometers) of the agricultural sector of the economy. Treadgold also noted that Byzantine tax collection efforts were most efficient and effective due to highly professional public administrators, although some tax evasion occurred.

Hendy (1985) wrote that 80% to 95% of all Byzantine revenues came from land and 5%-20% from trade (p. 157). Treadgold (1982, 2020) believed these estimates to be close to and consistent with those of other periods of the Empire and thought most economic expansion or contraction in the Empire depended upon demographic and territorial gains and losses through war (p. 94). Laiou (1977) and Laiou and Morrisson (2007) claimed that agriculture usually made up 67% to 75% of Byzantine economic activity.

Estimating inflation effects on output per capita needs to be considered to get an accurate idea of changes in actual output over time. Treadgold (1982) and Laiou and Morrisson (2007) note that around half of the Byzantine economy is not cash-based, and some payments, aside from land tax payments, to the government could be in-kind. Treadgold admits that this means his estimates of government revenues for different years only include cash payments to the government, which means his estimates may be underestimates. He also notes other writers (2020, pp. 258–259) have wide variations in their estimates of government revenues, but his research is the only one this paper found to give so many years of data over the empire’s life. Finally, it can be claimed that Treadgold’s estimates have been adjusted for inflation or debasement in Byzantine currency value over the centuries since he puts budget values in terms of the original nomismata/solidus of 1/72 of an ounce of gold issued during the late Roman Empire. Milanovic (2006) and Laiou (2002) note that from around the 500s to the 1300s average wages and prices did not change that much in Byzantium, although regional level exceptions existed during times of war, sieges, pandemics, and other crises. Finally, medieval church teachings also emphasized the concept of “just prices,” which, to some degree, might have kept inflation under control through price controls, as was done in the empire in different periods (Melitz, 1971; Blaug, 1991; Homer & Sylla, 2005).

Treadgold (1997) shows changes in pay for soldiers and sailors, and these go up and down over the centuries, although allotted rations for the soldiers and sailors do not change in value. Morrison and Cheynet (2002) display wheat prices for different parts of the Empire over the centuries and across regions. Although wheat is a food staple, it is hard to use these data to pinpoint an overall average Empire-wide price of all goods over time. Pamuk (2007) claims that wages and prices went up dramatically in the Byzantine Empire after the Black Death and cites Morrison and Cheynet (2002) for evidence. However, the price and wage

3 The data is in the table displayed in the appendix of this paper.

4 On page 57 Treadgold writes that the Byzantine treasury lost substantial land tax revenues due to farmlands ravaged by war. These lands usually were exempted from taxes for 30 years after an attack or siege.
increases appear to be mostly confined to some regions versus others. For wheat (see Table 5 in Morrisson and Cheynet (2002)), prices went down in some regions after the Black Death than up. Wine prices and wages for domestic servants show gains (servant pay went from 10 to 14hyperpyra after the plague started). However, prices for horses remain stable before and after the pandemic. In Table 14 of their book (Mossisson & Cheynet, 2002), the prices of slaves increased from AD1300 to AD1350, which supports Pamuk’s claim that these prices rose during and after the Black Death period. However, slave purchases would have primarily been made by the Byzantine upper classes, which made up a tiny segment of the population. Morrisson and Cheynet (2002) write:

“When one takes the devaluation of the hyperpyron into account, slave prices are seen to have remained remarkably stable from the Justinianic period until the beginning of the fourteenth century. This stability was all the more remarkable in that these prices were the outcome of a real market, partly international in nature. Prices subsequently rose, particularly after 1350, perhaps due to the effect of the plague on the population, despite the pirate warfare in which Turks and Latins were actively engaged.” (pg. 850)

To come up with an accurate price or inflation index would be complicated because the Byzantine Empire was often subjected to price controls imposed by the government following the concept of “just prices.” Additionally, most markets in Byzantium and medieval societies were localized so that food shortages and famines could exist in only parts of the Empire. Although periods of inflation could be followed by deflation during bountiful harvests or the issuance of new coinage, currency was often debased to help the government pay its bills. In order to help with wheat and grain shortages, emperors would release surpluses to be used by the public. Finally, many medieval transactions were non-monetized, and goods were often not sold on markets but bartered instead or used as payment in kind for debts, tax payments, or rental payments on theme lands (Treadgold, 1997, 2020; Laiou & Morrisson, 2007). These facts make estimating inflation difficult. Nonetheless, given the claim by some scholars that there were few overall price changes during most of the history of the Empire, and given Treadgold’s use of the value of the nomismata (N) from around AD 300 as a base currency, the real GDP per capita trend estimates developed for this paper should be rough but somewhat legitimate conjectures.

Dividing the budget totals in nomisma (the main Byzantine currency throughout most of the history of the Empire) given by Treadgold by 6.5% (the average of 5% and 8%), and then dividing these numbers by his population estimates for the corresponding budget years (2020), the results in Table 1 are determined for GDP per capita for various years

| Year | Real GDP per Capita in Nomismata |
|------|---------------------------------|
| 300  | 6.89                            |
| 457  | 7.50                            |
| 518  | 6.71                            |
| 540  | 6.69                            |
| 565  | 6.71                            |
| 641  | 5.42                            |
| 668  | 3.08                            |
| 775  | 4.18                            |
| 842  | 5.96                            |
| 959  | 6.67                            |
| 1025 | 7.56                            |
| 1143 | 7.54                            |
| 1320 | 3.85                            |
| 1453 | 1.38                            |

Table 1: Estimated Real GDP per Capita using Treadgold data (1997, 2020)

5 Table 5 (pages 826 and 827) shows that in 1343 the price of a modius thalassius in Constantinople was greater than 1/4 hyperpyron, and it ranged from 1/5 to 3/8 hyperpyron in 1366 after the Black Death had started.

6 The hyperpyron was a currency that replaced the nomismata in the latter centuries of the empire, and on average it was the equivalent of 0.5 Nomismata (N).

7 Milanovic (2006) calculates that during the 11th Century subsistence levels were no less than real 3.5 to 3.7 N with an average minimum expenditure of around 6.3 N per year. He calculates real average income levels of 6 N per person per year. Treadgold (1982, page 3) cites Ostrogorski (1969) and Jenkings (1967) estimating subsistence for a Byzantine family from the early to middle years of the empire at around 17 N per year. If wages and prices did not change on average during the history of the empire, then an approximate trend average of 6 N per year per person is plausible throughout the history of the empire. The data analysis for this paper supports this, and this is mentioned later in the paper.

8 For the last two years the Byzantine currency of the hyperpyron was converted to nomismata by Treadgold.

9 The use of 6.5% is only used for simplification purposes. However, if one divides the estimated government revenues by a randomly generated number between 5 and 8%, the overall trend pattern shown in Figs. 1 and 2 do not change that much. The author can provide these results upon request.
in the Empire. Using these values and developing a regression model, one can estimate GDP per capita trend values for the Empire from AD 300 to AD 1453. Figure 1 plots the data given by Treadgold, and Fig. 2 shows the trend pattern developed from the scatterplot in Fig. 1. When the equation yielded from the scatter plot in Fig. 1 is used to create the estimated real GDP per capita trend for each year from AD 300 to 1453, a diagram in Fig. 2 is yielded. The polynomial in Figs. 1 and 2 is the one that best fits the plot/pattern with an r-square of around 89% and an equation of:

\[
\text{Predicted Real GDP} = -0.000000000000315x^5 - 0.00000000142x^4 + 0.0000024x^3 - 0.00187x^2 + 0.665x - 78.187
\]

(1)

When plotting a linear function across Fig. 2, the resulting line is almost flat but slopes downward, reflective of a long-term Malthusian zero growth economy with short-run fluctuations that are considered typical of many medieval economies by many economic historians (see Clark, 2007).

Surprisingly, suppose economic fortunes are linked to territorial size, as Treadgold believes. Harvey (1989) claims that the Byzantine economy experienced an expansion from around AD 900 to AD 1200 because records indicate greater urbanization and population density. In contrast, Laiou and Morrisson (2007) write that it was from AD 800 to AD 1200. These notions are illustrated in and supported by Fig. 2, and the accounts of this period provisionally boost the possible validity of the estimates given in Fig. 2. The decline in actual output in Fig. 2 shown during the seventh century could reflect dramatic losses by the Empire in the territory and critical ports located in agriculturally productive land, such as the Levant and Egypt, due to the rise of Islam and the subsequent Arab conquest. In that case, there were declines in real GDP during the sixth century when Byzantium took territories previously part of the Western Roman Empire. At the same time, however, there are claims that a Late Antique Ice Age (AIA) existed during the 6th and part of the seventh centuries in Europe due to volcanic eruptions, less sunlight, and cooler temperatures. This could have hindered agricultural production, resulting in lower actual output during these times despite gains made from conquest (Buntgen et al., 2016). Finally, in the sixth century, the Plague of Justinian killed at least 30% of the Empire’s population (Laiou & Morrisson, 2007, p. 38).

The adverse "exogenous shocks" of war, bad climate, and pandemics in some regions could be offset by continued or even increased production in other regions when adjusted for population. If "poorer" regions are lost in war while the Empire retains its more productive ones and thereby possibly raises real GDP per capita, these shocks usually can have negative ripple effects across a medieval economy just as those in modern times. The Black Plague of the fourteenth century in Europe and the Covid-19 pandemic of the twenty-first century have been noted as having dramatic economic effects. Therefore, even though farming production in Anatolia and Greece would not have been directly affected by setbacks or crises elsewhere in the Empire during the seventh century, economic downturns can occur due to changing expectations about the future, if farmers and others become more pessimistic about imperial prospects and stability, which
in turn could lower actual output per worker and capita. Such expectations could have been the case as the Empire suffered significant military defeats and territorial losses, pandemics, or bad climate, even if these are contained in some regions and not present in others. Not only could overall output rise and fall according to shifting imperial boundaries but so could output per capita and standards of living.

**Estimating Land Agricultural Productivity using Wheat Production**

In medieval times, the bulk of land for any nation or state was mainly used for agricultural purposes. Since agriculture is the dominant industry of most, if not all, ancient and medieval economies, I attempt to generate estimates of Byzantine agricultural productivity by using the wheat prices (according to a modios thalassios (around 17 L)) for different Byzantine regions listed by Morrison and Cheynet (2002), from AD 361 to AD 1444. They list around 110 observations for prices. One can divide these prices by the estimates of a square kilometer of farmland values over the centuries to develop a simple agricultural productivity index similar to those done by Broadberry et al. (2015) and Clark (2009) for Britain.\(^{12}\) Unfortunately, not enough data exists to assess farm wages for peasant labor or farm income to assess agricultural labor productivity. Therefore, only capital or land productivity can be assessed. Generally, following the Broadberry et al. and Clark methods and using the equation \(PQ = wL + rK\), or nominal output (price*quantity) = wages * labor input + rate of return/rent * capital input, and holding labor inputs constant and rearranging to get \(r/p = Q/K\), where \(Q/K\) is the average productivity of capital, which can also be used to measure the average productivity of land, one can arrive at some estimate of Byzantine farm-land agricultural productivity.\(^{13}\)

The estimates of Byzantine Empire size and government revenues (Treadgold, 1997, 2020) during its history are used to approximate agricultural land space and value. Estimates of the Empire’s size are drawn from Treadgold’s data for his estimates of the Empire’s budgets and presented in his 1997 (a figure on p. 8) and 2020 (Table 8.1 on p. 258) books. Using Treadgold’s table (2020), Fig. 3 illustrates the changes in the Empire’s size over time, and, in trying to replicate his figure, the figure is similar to the one he presents in his 1997 book.\(^{14}\) The Empire gained some territory in the sixth century but lost vast land in the seventh and eighth centuries due to Arab military victories and conquests. Under the leaders Nicephorus II Phocas and Basil II, the Empire regained some lost territories and gained some new ones in the 10th and early eleventh centuries but then lost these and more land in subsequent centuries until its fall in 1453. Following the discussion above and adjusting the percentages to get

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\(^{12}\) If one year had multiple estimates from different regions, an average was taken of the values.

\(^{13}\) Morrison and Cheynet (2002) write that peasant labor is probably more important than land productivity when it comes to output. They also give prices for wine during the time of the empire going back to the 4th Century, but there are not nearly as many observations given for these prices as for wheat. The values that they list for land only go back to the 10th Century, yet for the values they give from AD 942 and on, these are correlated with the estimates for this paper at \(r=0.36\) which is statistically significant at alpha = 0.05 (n = 35 dates).

\(^{14}\) Unfortunately, the data upon which the figure is based no longer exists. They appear to be Treadgold’s estimates. The only actual numbers found are the 13 years of area estimates from his 2020 book. The author has received an email note from Dr. Treadgold that explains that he no longer has the notes or data upon which the figure is based. In the note he states that his estimates are based upon maps showing the size of the empire at different points in time, his knowledge of Byzantine historical events, and a useful atlas. The use of Geographic Information Systems (GIS) software to generate data is limited by the fact that there are large gaps in time periods between the dates for different maps. Therefore, Treadgold’s estimates may be the best available ones to use for continuous data. Dr. Treadgold’s note can be found in the appendix of this paper.
cautious/conservative estimates, and using 85% of Treadgold’s estimates for government revenues to approximate tax revenues from land and hearths, and then multiplying that amount by 50% for land tax revenues, and then dividing that by 15% (a high nominal tax rate), one can get an estimate of the value of farmland in the Empire. Land values imply capitalized rent payments over some time and thus serve as a proxy for a land factor payment such as rental payments. Taking these results and dividing them by Treadgold’s estimates of empire size in square kilometers for different years (see the Appendix for replication of Treadgold’s data from his books), one can try to roughly approximate the value of a square kilometer of land in the Empire. Next, using estimates of wheat prices based on Morrison and Cheynet (2002) data as the numerator of a productivity index with land prices as the denominator (similar to the Broadberry et al. and Clark methods), some type of approximate agricultural productivity index can be constructed based upon wheat. Figure 4 shows the general trend of conjectures for agricultural land productivity of Byzantine land from the 4th to the fifteenth centuries, and the trend follows this polynomial equation:

\[
y - \hat{y} = -0.000000000000000092x^6 + 0.0000000000005x^5
- 0.0000000011x^4 + 0.0000012x^3
- 0.00071x^2 + 0.21x - 23.39
\]

which has an adjusted r-square of 0.90.

Results

Did Climate Factors Affect Byzantium Real GDP and Agricultural Land Productivity?

1. Real GDP per Capita

In addition to estimating Byzantine real GDP per capita, it would be interesting and valuable to know what external or exogenous factors influenced the Byzantine economy and its output. Finding evidence of such effects could also help to establish validity for the real GDP per capita trend conjectures developed in this paper. Some scholars, such as Haldon et al. (2014), have given evidence that the Empire suffered from climatological problems which caused issues in agricultural production and famines in parts of the Empire or throughout the Empire in different epochs. Others (Bertrand et al., 2002; Jones & Mann, 2004) have created historical climate databases that go back to antiquity and that demonstrate the potential existence of a "Medieval Climate Anomaly" (MCA, and sometimes referred to as the "Medieval Warm Period") of the 10th to thirteenth centuries, and a "Little Ice Age" (LIA) of the 14th to
nineteenth centuries. Historical climate databases are published on the website of the US National Centers for Environmental Information of the National Oceanic and Atmospheric Administration (NOAA) and contain: estimates of greenhouse gas (GHG) forcing in watt per square meter (based on Crowley, 2000); solar irradiance (sun energy) in watt per square meter (based on Crowley, 2000); regional volcanic ash estimates based on work by Ammann and Naveau (2010) for the Mediterranean and Europe according to longitude and latitude; estimated above or below normal/trend temperatures of degrees Celsius from AD 1 to 2001 (Luterbacher et al., 2016); and tree ring data from Europe for over the last 2500 years which can serve as a proxy measurement for rainfall amounts (Buntgen et al., 2011).

During ancient and medieval times, potent greenhouse gas (GHG) could dampen crop production if they resulted from forest fires, forest clearings through burning trees, or activities that can hinder or reduce carbon absorption and cause warmer than average growing seasons (Sapart et al., 2012). Volcanic ash circulating globally or regionally can block the sunlight necessary for agricultural production. Too little or too much energy or irradiance emitted by the sun or too little or too much rainfall can reduce agricultural output or cause crop failures. Emissions of volcanic ash and temperatures too far above or below average can also harm farming efforts if they help to cause drought or excessive heat. For example, Stathakopoulos (2004) writes about the "Dust- Veil" event of AD 536–537, which darkened the skies of the Empire from AD 536 to 537. He notes that some believe that this occurrence originated from volcanic activity.

The trends for these variables over several centuries for Europe and the Mediterranean are shown in Figs. 5, 6, 7, 8 and 9. Each factor appears to increase except for the volcanic ash measure during the MCA in Europe from around AD 950 to AD 1250 (Jones & Mann, 2004; Goose et al., 2006; Mann et al., 2009). At the same time, there are slight to moderate absolute decreases in these, except for ash measurement, during the AIA (AD 536 to 660) and the LIA (AD 1300 to 1453).

These climate variables are used as independent variables to predict imperial real GDP per capita trend estimates from AD 300 to AD 1453 and then to see if climate may have correlated with Byzantium agricultural activity. Additionally, dummy variables for each period—Antique Ice Age (AIA), Medieval Climate Anomaly (MCA), and Little Ice Age (LIA)—are used. If a year is in one of the periods, the variable is coded "1"; otherwise, it is coded as "0". The AIA is estimated to have existed from around AD 536 to 660 (Buntgen et al., 2016); the MCA is estimated to have been from AD 950 to 1250 (Diaz & Hughes, 1994; Lamb, 1965); and, the LIA is supposed to have been from AD1303 to
1860 (Fagan, 2001; Lamb, 1995, among others). These variables are used to see if different climate epochs influenced the Empire’s economy. If the Byzantine economy is considered primarily agricultural, abnormal climate factors would matter more to it than in a modern economy with a greater mix of industries with less vulnerability to weather extremes. Laiou (1977) and Laiou and Morrison (2007) claim that most of the Empire’s output was agricultural, and around half of this output was not sold on markets. However, it was for personal, familial, or community consumption.

Next, the approximate size of the Byzantine Empire in millions of square kilometers from 300 to 1453 is used to predict real GDP per capita (Treadgold, 1997, 2020). This variable approximates territorial gains and losses over time due to war victories and losses or through treaties with rival nations. This variable is exogenous and endogenous to actual output due to imperial conquests or losses helping GDP growth. The hypothesis is that this variable should matter to real GDP per capita in that if the Empire loses important lands that have key ports or fertile and productive agricultural lands, then overall GDP per capita would be expected to suffer. Usually more fertile arable lands and waterways are preferred to less fertile and navigable areas, especially in medieval times, and such lands are often targets of conquest. However, at the same time, a healthier economy could help to make military provisions and conquest easier than what would otherwise be the case.

The cataclysmic events include famine, plagues, and sieges of different cities that happened in large areas of the Empire (e.g., Egypt or Mesopotamia) or throughout the Empire, as mentioned in Treadgold (1997, 2020); Stathakopoulos (2004); and Haldon et al. (2014). A siege of several cities is seen as a cataclysmic event rather than an outcome of the war — civilian and worker lives are lost in addition to military ones, and the former losses may be more relevant to estimating GDP per capita. Cataclysmic events that happened in just one city are ignored, and for some years, more than one type of event occurred. However, since it is difficult to assess the impacts of each type of disaster event, only a value of 1 is used to indicate that at least one type of adverse event occurred. Finally, a dummy variable that indicates the years in which a cataclysm occurred (1 = yes, 0 = no) is used as a predictor variable of real GDP per capita to see if external "shocks" to the economic system have any substantive effects. This variable, similar to territory size, can be both an endogenous and exogenous factor to the Empire’s economy in that these cataclysms can be
internal and external – famines caused by crop failures, plagues exacerbated by poor health policies, and sieges caused by poor defense planning and population losses from both internal and external events, which in turn lower subsequent economic output.

Since Augmented Dickey-Fuller tests (Cheung & Lai, 1995) show nonstationarity in the dependent variable of real GDP per capita and the independent variables of the GHG Index (i.e., solar irradiance measure and Empire territorial size), the Johansen test for cointegration (1991) is used and indicates cointegration among the variables (see Table A1 in the Appendix). The Augmented Dickey-Fuller test result supports the rejection of the null hypothesis of nonstationarity. Table 2 shows the results of the multivariate linear regression analysis. The adjusted r-square of 0.84 indicates that the variables explain around 84% of the variance in real GDP per capita trends. Diagnostics of the regression output show no problems with multicollinearity (each independent variable has a variance inflation factor < 10.0, and the average VIF for all independent variables is 2.37 (Berenson et al., 2015, p. 608)). However, there are problems with serial correlation, so Newey-West standard errors are used to correct this. All variables are statistically significant at $\alpha = 0.05$.

The cataclysm variable shows that for each year, when at least one cataclysm is noted with a value of 1, the real GDP per capita trend goes down by 0.31 N on average. For the Empire territory size, a gain/decline of 1 million square kilometers in the Empire’s domain results in an increase/decrease in real GDP per capita of around 0.66 N. The temperature variable shows that a one unit above normal temperature score results in a 0.16 N decrease in real GDP per capita. The GHG variable shows that a one-unit increase in emissions yields a decrease in real per capita output of around 18 N. The volcanic ash measure coefficient suggests that a 1 unit change in this measurement is associated with a 0.04 N change in real GDP per head. Finally, a one-unit increase in the tree ring measure (a proxy for rainfall) indicates a 0.003 N increase in real output per head. Only the solar irradiance variable is not sta-

Table 2  Linear Regression Results

| Dependent Variable: Real GDP per Capita Trend | b (Newey-West SE) |
|----------------------------------------------|-------------------|
| Constant/Intercept                           | 3.97              |
| Cataclysm Dummy Variable                     | -0.31**           |
| (Yes = 1, No = 0)                            | (0.04)            |
| Size of Empire in Sq. Km. Millions           | 0.66**            |
| (Yes = 1, No = 0)                            | (0.09)            |
| Temperature Deviation, Celsius               | -0.16**           |
| (Yes = 1, No = 0)                            | (0.04)            |
| GHG Measure                                  | -18.15**          |
| (Yes = 1, No = 0)                            | (0.75)            |
| Solar Irradiance Measure                     | 0.02              |
| (Yes = 1, No = 0)                            | (0.04)            |
| Volcanic Ash Measure                         | 0.04**            |
| (Yes = 1, No = 0)                            | (0.02)            |
| Tree Ring Measure                            | 0.003**           |
| (Yes = 1, No = 0)                            | (0.0004)          |
| Antique Ice Age Dummy                        | -1.35**           |
| (Yes = 1, No = 0)                            | (0.074)           |
| Medieval Climate Anomaly Dummy               | 1.76**            |
| (Yes = 1, No = 0)                            | (0.04)            |
| Little Ice Age Dummy                         | -0.72**           |
| (Yes = 1, No = 0)                            | (0.1)             |

n = 1154 years
Adjusted r-square = 0.84

*p-value < 0.10
**p-value < 0.05
The average real GDP per capita over the centuries examined is around 6.30, so one-unit changes in the variables can have substantive impacts as a share of the predicted amounts. The finding of an average of 6.3 is similar to the average of 6 found by Milanovic (2006).

The dummy variables for each climate epoch show negative associations between the period of the AIA and real GDP per capita and the LIA and actual per head output. The AIA years decrease real output per head by 1.34 N on average, and the LIA period decreases real GDP per capita by 0.71 N on average. On the other hand, the MCA era is associated with an average boost of 1.76 N per year.

When the cataclysm variable is put on a one-year lagged basis and used with the other variables shown in Table 2 to predict real GDP per capita, the results do not change that much. These results are shown in Table A2 in the Appendix.

### Agricultural Land Productivity

Table 3 shows the results of time-series regression with Newey-West standard errors\(^\text{15}\) using the same independent variables from Table 2 to predict the Byzantine Empire’s estimated land agricultural/wheat productivity index. The Augmented Dickey-Fuller test shows the index to be stationary. A modest explanation of the variation in the index is found (around 42%) with all but the volcanic ash measurement statistically significant at the 5% or 10% alpha level. None of the independent variables has a VIF > 10, and the average VIF for all independent variables is 2.37. It appears that too cool of a temperature, too much sun or too little rain, and too high a level of GHG correlate with lower productivity levels. All three climate epochs have negative associations with the productivity index. That is, wheat production, on average, appears lower during these epochs. In most regions of the world, wheat typically grows best in well-drained, loamy soils and when temperatures, sunlight, and rainfall all stay within a specific range during its growing season (Global Precipitation Measurement Mission, n.d.).

The Empire was potentially able to show more agricultural resiliency than Table 3 implies, thanks to "adaptive change." On the other hand, while wheat was a crucial staple in the Byzantine Empire, among many other major crops grown by farmers, Haldon and Rosen (2018) have written that Byzantine agriculture probably adapted to climatic changes by emphasizing the cultivation of other crops. Xoplaki et al. (2018) believe that societal resilience plays a vital role in the Eastern Mediterranean during the MCA and LIA and, along with Haldon and Rosen (2018), believe that external forcings (solar, volcanic, etc.) cannot explain agricultural production variation. Instead, they attribute variations to internal climate dynamics.

When the cataclysm variable is put on a one-year lagged basis and used with the other variables shown in Table 3 to predict agricultural land productivity, the results do not change that much. These results are shown in Table A3 in the Appendix.

### Predicting Cataclysms

Table 4 displays the results of multivariate logistic regression in which the dependent variable of Weather Cataclysms (droughts, extreme temperatures, famines, floods, grain shortages, hailstorms, heavy snows, and severe winters for various parts of the Empire (see Appendix 1 of Haldon et al., 2014)) is predicted using the same independent variables as in the previous model except that of the general cataclysm variable used in

\(^{15}\) Used because the Breusch-Godfrey test of serial correlations shows serial correlation.
This model is developed because some scholars have written that climate change is a factor in influencing to one degree or another, Byzantine or British agriculture and life (Hirschfeld, 2004; Haldon et al., 2014; Xoplaki et al., 2016; Labuhn et al., 2016; Tello et al., 2017; Campbell, 2016; and Bar-Oz et al., 2019). When predicting Weather Cataclysms (1 = at least 1 type is present, 0 = none present), the volcanic ash and solar irradiance variables do not correlate well with the dummy variable, yet mean temperature deviations, GHG forcing, and the tree ring variables are associated with cataclysms. They are statistically significant at α = 0.05.

Below-average temperatures are more likely to be associated with at least one event occurring. Greater GHG forcing (negative values) is more likely to be associated with such events, as do more significant amounts of rainfall. These results somewhat support the claims that the AIA and LIA possibly negatively affected the Byzantine economy. Finally, the larger the Empire is, the greater the probability of an event occurring. This variable is also statistically significant and makes sense because Haldon et al. (2014) use events from all parts of the Empire over time. As time went by, the Empire became smaller and smaller. As Table 4 indicates, around 63% of the dummy variable values are correctly predicted/classified. The results are the same when the independent variables are put on a one-year lagged basis to determine if there is a lagged effect between the climate variables and cataclysms.

### Discussion and Conclusion

The limits of this paper include the use of other conjectures to create further estimates. No conclusions can be made with certainty. There are also other variables, endogenous and exogenous, related to real GDP per capita that could have been used as predictors in a more developed model. To have actual numbers or estimates of the lives lost for various cataclysms, rather than a dummy variable, would have helped with the precision of the regression. Some of the data include gaps and are rough estimates, and some of the data for the MCA and LIA are documented by very few other databases. Therefore, the results displayed are only partial and general ones regarding Byzantine per head output. They are submitted as general trends of Byzantine economic activity and not exact year-by-year estimates.

The results of the linear regression analysis show a degree of statistically significant correlation between most of the climate forcing factors and actual per capita output estimates. This is not surprising given that Byzantine society’s primary industry is noted as agriculture. Too high temperatures and too high of GHG forcing result in a loss of output, probably because of so much heat for all agricultural output and not just wheat. However, the annual GDP per capita and Empire size estimates are reasonable as general trends based on the sources used and how they follow patterns exhibited in historical accounts. The positive sign for the volcanic ash measure concerning real GDP shows that higher scores or those closer to zero are associated with higher output, most of which would be agricultural. Little or no volcanic ash helps production, whereas its presence and magnitude can be detrimental.

The AIA and LIA variables have their expected signs for the three climate epoch dummy variables. According to different climatologists, colder weather is supposed to have lowered agricultural output in Europe and the Mediterranean during these periods. However, for the MCA period, the regression results show this variable has a positive sign, contrary to expectations given what has been written about a medieval warming era that could have impacted the region. However, this era is noted by historians as one of conquest and sound economic growth in the Empire due to increases in population, territory, and greater urbanization (Treadgold, 1997, 2020; Laiou & Morrisson, 2007). These factors may have offset bad
harvests or food production. Xoplaki et al. (2016, p. 248) conclude that despite bad climate conditions, Byzantium overcame the adverse conditions of the MCA. The results in Table 2 modestly support their conclusion. Of course, some of the reasons for conquest could have been to make up for poor agricultural output within the Empire's existing boundaries. At the same time, any adverse effects of crop failures or poor agricultural output by conquered opponents could have helped make them easy and weakened targets for conquest by the Byzantines during the MCA era. Finally, warmer weather could benefit some crops versus others, and Lüning et al. (2017) claim that the eastern Mediterranean region (the "Levant") of the Empire actually may not have had that warm of weather during the MCA period.

The fortunes of the Empire also seem to have rested on the territorial holdings it had. Historians have often noted that agricultural production could not keep up with population growth during Malthusian economic conditions, resulting in frequent periods of famine. Any adverse consequences of climate change could exacerbate problems of agricultural production. To make up for this, the conquest of foreign lands, which would provide more farmland, is an objective pursued by different kingdoms and nations. As society gained more land, its economic fortunes usually would rise. The same is probably true for Byzantium. However, as the Empire began to shrink, so did its income and wealth. Over time the Empire lost many of its significant assets, such as critical ports (e.g., Alexandria), trading routes and centers (e.g., Damascus), and best agricultural lands (e.g., Egypt, Anatolia, etc.). The estimates of real GDP trends used in this paper are drawn from government revenue estimates based on a tax system that primarily relied upon land tax receipts, making the link between empire size and economic performance unavoidable. As the size of the Empire shrank, so did government coffers, even when some tax rates could have been increased or other taxes could have been employed to make up for lost tax revenues.

Additionally, economic historians have noted economic problems in the empire and other medieval societies perhaps not related to climate change. Charanis (1953) along with Treadgold, Laiou, Alfani (2021), Brenner (1976), Milanovic (2010) and others note the growing inequality between rich and poor during late medieval times and toward the end of the empire’s time. The empire also loses control over its cities’ economy, the regulation of certain industries and sees foreign shipping fleets surpass its prominent merchant fleet (Charanis, 1953). These all occur as policies are started that favor the Byzantine upper class and large landholders and adverse policies toward shipbuilders (Treadgold, 2020). These, in turn, hurt the Empire’s economy and the government’s tax revenues. Of course, this period would have corresponded roughly to the beginning of the LIA period.

Regarding the measurement of agricultural productivity based on wheat production, some of the climate variables correlate well with the index, and all three climate epochs, territorial size, and the cataclysm variables also correlate with the index. The three periods of climate change weakened Byzantine agricultural output, which may have been offset by periods of conquest during the MCA.

Two of the climate forcing variables in the logistic regression model successfully predict weather cataclysms in a model that could have benefitted with more precision, yet is provided as a way to verify previous writings about the possible impacts of climate change on weather extremes in the Byzantine Empire. Cooler temperatures seem to be associated with more weather extremes such as flooding, famines, heavy snowfalls, and droughts. More significant GHG forcing has an association with these types of events. The more negative the GHG measurement, the more likely the weather cataclysm has a value of 1. Therefore, some support is given to the writings of others who have argued for linkages between climate change and weather hazards in the Empire.

The historians writing about the Byzantine Empire have focused on its progress and decline by mostly discussing the Empire’s gains and losses on the battlefield and the fights among internal factions, which often weakened the nation. It has only been recently that some scholars have started to examine the influence of climate change on the Empire. Which set of factors—climate versus political and military ones—is more important is a discussion beyond the scope of this paper. However, it can be speculated that bad climate conditions helped weaken Byzantium. It was more challenging to hold on to territories against foreign rivals, whether Arabs, Slavs, Western Europeans, or the Ottoman Turks.

Having peace, a good climate, and avoiding famine and pestilence can be the keys to any nation’s political and economic survival. Losing too many battles and suffering from adverse climate conditions may have hastened the end of the Byzantine Empire after its expansion in the tenth and eleventh centuries. This paper supports climate factors as possible impacts on Byzantine economic viability. Most of all, if the climate change variables are plausible factors influencing the conjectures of the Byzantine economy, then perhaps some lessons can be drawn for the economic implications of modern-day climate change.

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Büntgen, U., Myglan, V., Ljungqvist, F., et al. (2002). Climate
Bar-Oz, G., Weissbrod, L., Erickson-Gini, T., Tepper, Y., Malkinson, D., Benzaquen, M., Langgut, D. O., Dunseth, Z. C., Butler, D. H., Shahack-Gross, R., Roskin, J., Fuks, D., Weiss, E., Marom, N., Kitalav, I., Blevis, R., Zohar, I., Farhi, Y., Filatova, A., Gorin-Rosen, Y., Yan, X., Boaretto, E. (2019). Ancient trash mounds unravel urban collapse a century before the end of Byzantine hegemony in the southern Levant. Proceedings of the National Academy of Sciences of the United States of America. 2019 Apr 23;116(17):8239–8248. https://doi.org/10.1073/pnas.1900233116. Epub 2019 Mar 25. PMID: 30910983; PMCID: PMC6486770.

Berenson, M. L., Levine, D. M., & Szabat, K. A. (2015). Basic Business Statistics: Concepts and Applications (Thirteenth). Pearson.

Bertrand, C., Loutre, M. F., Crucifix, M., & Berger, A. (2002). Climate of the last millennium: A sensitivity study. Tellus A: Dynamic Meteorology and Oceanograph, 54, 221–244. https://doi.org/10.1034/j.1600-0870.2002.00287.x

Blaug, M. (1991). Pioneers in Economics: St Thomas Aquinas (1225–1274). Aldershot, Hants GU11 3HR, England: Edward Elgar Publishing Limited.

Brenner, R. (1976). Agrarian Class Structure and Economic Development in pre-industrial Europe. Past & Present, 70(1), 30–75. https://doi.org/10.1093/past/70.1.30

Broadberry, S., Campbell, B., Klein, A., Overton, M., & Van Leeuwen, B. (2015). British Economic Growth, 1270–1870. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107070603 . Data set located at www.cambridge.org/gh/academic/subj ects/history/economic-history/british-economic-growth-12701870? format=PB . Accessed on June 18, 2020.

Brown, E. (2017). Taxes through the Ages. Knowable Magazine. https://knowablemagazine.org/article/society/2017/taxes-through-ages . Accessed on March 6, 2021.

Büntgen, U., Myglan, V., Ljungqvist, F., et al. (2016). Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. Nature Geoscience, 9, 231–236. https://doi.org/10.1038/ngeo2632

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trott, V., Kaplan, J. O., Herzeg, F., Heusser, K. U., Wanner, H., Luterbacher, J., & Esper, J. (2011). 2500 Years of European Climate and Environmental Variability and Human Susceptibility. Science, 331, 578–583. https://doi.org/10.1126/science.1197175

Campbell, B. (2016). The great transition: Climate, disease and society in the late-medieval world. Cambridge: Cambridge University Press. https://doi.org/10.1017/CO9781139031110

Charanis, P. (1953). Economic factors in the decline of the Byzantine Empire. The Journal of Economic History, 13(4), 412–424. http://www.jstor.org/stable/2114773

Cheung, Y.-W., & Lai, K. S. (1995). Lag order and critical values of the augmented Dickey-Fuller test. Journal of Business and Economic Statistics, 13(3), 277–280.

Clark, G. (2007). A farewell to alms: A brief economic history of the world. Princeton University Press.

Clark, G. (2009). The macroeconomic aggregates for England, 1209–2008. UC Davis, Economics WP 09–19. http://faculty.econ.ucdavis.edu/ faculty/gclark/data.html

Crowley, T. J. (2000). Causes of Climate Change Over the Past 1000 Years. Science, 289(5477), 270–277. https://doi.org/10.1126/scien ce.289.5477.270

Diaz, H. F.; Hughes, M. (1994). The Medieval warm period. Boston: Kluwer Academic Publishers. p. 134. ISBN 978–0–7923–2842–1

Fagan, B. M. (2001). The Little Ice Age: When Climate Made History, 1300–1850. Basic Books. ISBN 978–0–465–02272–4.

Global Precipitation Measurement Mission. (n.d.). Expert Group—Growing Wheat. GPM.NASA.gov/education. Accessed on September 21, 2021.

Goosse, H., Arzel, O., Luterbacher, J., Mann, M. E., Renssen, H., Riedwyl, N., Timmermann, A., Xoplaki, E., & Wanner, H. (2006). Climate of the past, (209–113), 2021. https://doi.org/10.5194/ cp-2-99-2006. Accessed on March 15

Haldon, J., Roberts, N., Izdebski, A., Fleitmann, D., McCormick, M., Cassis, M., Doonan, O., Eastwood, W., Elton, H., Ladstäter, S., Manning, S., Newhard, J., Nicoll, K., Telelis, I., Xoplaki, E. (2014). The Climate and Environment of Byzantine Anatolia: Integrating Science, History, and Archaeology. The Journal of Interdisciplinary History, 45(2), 113–161. https://doi.org/10.1162/JINH_a_00682

Haldon, J., & Rosen, A. (2018). Society and Environment in the East Mediterranean ca 300–1800 CE. Problems of Resilience, Adaptation and Transformation. Introductory Essay. Human Ecology, 46, 275–290. https://doi.org/10.1007/s10745-018-9972-3

Harvey, A. (1989). Economic Expansion in the Byzantine Empire, 900 to 1200. Cambridge University Press.

Hauwert, M., & Diebolt, C. (2020). Climometrics. In: Paul Atkinson, ed., SAGE Research Methods Foundations. London: SAGE Publications, Ltd. https://doi.org/10.4135/978152642103681880. Accessed 25 Feb 2021.

Hendy, M. F. (1985). Studies in the Byzantine Monetary Economy c.300–1450. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511896750

Herrn, J. (2007). Byzantium: The surprising life of a medieval empire. Princeton University Press.

Hirschfeld, Y. (2004). A Climatic Change in the Early Byzantine Period? Some Archaeological Evidence. Palestine Exploration Quarterly, 136(2), 133–149. https://doi.org/10.1179/003103204225014184

Homer, S., & Sylla, R. (2005). A History of Interest Rates (4th ed.). Wiley Finance.

Jenkins, R. J. H. (1967). Social life in the Byzantine Empire. In Hussey, J. M. (ed.), The Cambridge Medieval History: Volume IV, The Byzantine Empire: Part II Government, Church and Civilisation. Cambridge University Press, Cambridge, 79–104.

Johansen, S. (1991). Estimation and Hypothesis Testing of Cointegration Vectors in Gaussian Vector Autoregressive Models. Econometrica, 59(6), 1551–1580. https://doi.org/10.2307/2938278

Jones, P. D., & Mann, M. E. (2004). Climate over past millennia, Review Geophysics, 42, RG2002. https://doi.org/10.1029/2003RG000143. Accessed on March 6, 2021.

Labuhn, I., Finneé, M., Izdebski, A., Roberts, N., & Woodbridge, J. (2016). Climatic Changes and Their Impacts in the Mediterranean during the First Millennium AD. Late Antique Archaeology, 12(1), 65–88. https://doi.org/10.1163/22134522-12340067

Laiou, A. (2002). Writing the Economic History of Byzantium. In Laiou, A. (ed.) The Economic History of Byzantium: From the Seventh Through the Fifteenth Century, Washington, DC: Dumbarton Oaks.

Laiou, A., & Morrisson, C. (2007). The Byzantine Economy (Cambridge Medieval Textbooks). Cambridge University Press. https://doi.org/10.1017/CBO9780511816727

Laiou-Thomadakis, A. E. (1977). Peasant Society in the Late Byzantine Empire. Princeton University Press.
Lamb, H. H. (1965). The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology, 1*, 13–71. Bibcode:1965PPP..., 1--13L. https://doi.org/10.1016/0031-0182(65)90004-0. Accessed on March 24, 2021.

Lamb, H. H. (1995). *Climate, history and the modern world* (Second ed.). London: Routledge. ISBN 0-415-12735-1.

Lambert, T. E. (2020a). Paul Baran’s economic surplus concept, the Baran ratio, and the decline of feudalism. *Monthly Review*, 72(7). December 2020. https://monthlyreview.org/2020a/12/01/paul-barans-economic-surplus-concept-the-baran-ratio-and-the-decline-of-feudalism/

Lambert, T. E. (2020b). Investment, Deficits, and the Transition from Feudalism to Capitalism: An Exploratory Heterodox Analysis and Conjecture. Unpublished manuscript.

Le Goff, J. (2012). *Money and the Middle Ages: An Essay in Historical Anthropology*. Polity Press.

Linning, S., Galka, M., & Vahrenholt, F. (2017). Warming and cooling: The Medieval Climate Anomaly in Africa and Arabia. *Paleogeography, Palaeoclimatology, Palaeoecology, 32*, 1219–1235. https://doi.org/10.1016/2017PA003237

Lutérbacher, J., Werner, J. P., Smerdon, J. E., Fernandez-Donado, L., Gonzalez-Rouco, F. J., et al. (2016). European summer temperatures since Roman times. *Environmental Research Letters, 11*(2). IOP Publishing. https://doi.org/10.1088/1748-9326/11/2/024001

Mann, M., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M., Shindell, D., Ammann, C., Faluvegi, G., & Ni, F. (2009). Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. *Science, 326*, 1256–1260.

Melitz, J. (1971). Some Further Reassessment of the Scholastic Doctrine of Usury. *Kyklos, 24*, 473–492.

Milanovic, B. (2006). An Estimate of Average Income and Inequality in Byzantium around Year 1000. *Review of Income and Wealth, 52*(3), 449–470.

Milanovic, B. (2010). Income level and income inequality in the Euro-Mediterranean region: from the Principate to the Islamic conquest. *MPRA Paper No. 46660, posted 2 May 2013. https://mpra.ub.uni-muenchen.de/46640/^

Morrison, C., & Cheynet, J. (2002). Prices and Wages in the Byzantine World. In Laiou, A. E. (ed.), *The Economic History of Byzantium: From the Seventh through the Fifteenth Century*. Washington, DC: Dumbarton Oaks Research Library and Collection.

Ostrogorski, G. (1969). *History of the Byzantine state*. Rutgers University Press.

Pamuk, Ş. (2007). The Black Death and the origins of the “Great Divergence” across Europe, 1300–1600. *European Review of Economic History, 11*(3), 289–317. http://www.jstor.org/stable/41378468

Sapart, C., Monteil, G., Prokopiu, M., et al. (2012). Natural and anthropogenic variations in methane sources during the past two millennia. *Nature, 490*, 85–88. https://doi.org/10.1038/nature11461

Stathakopoulos, D. C. (2004). Famine and Pestilence in the Late Roman and Early Byzantine Empire: A Systematic Survey of Subsistence Crises and Epidemics. Ashgate Publishing Company.

Tello, E., Martínez, J. L., Jover-Avellà, G., Olarieta, J. R., García-Ruiz, R., González de Molina, M., Badia-Miró, M., Winiwarter, V., Koepeke, N. (2017). The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients. *The Journal of Interdisciplinary History, 47*(4), 445–474. https://doi.org/10.1162/JINH_a_01050

Treadgold, W. (1982). *The Byzantine State Finances in the Eighth and Ninth Centuries* (New York: East European Monographs, 1982).

Treadgold, W. (1997). *A History of the Byzantine State and Society* (Stanford: Stanford University Press, 1997).

Treadgold, W. (2020). *A Concise History of Byzantium* (2nd ed.). Red Globe Press.

Xoplaki, E., Fleitmann, D., Luterbacher, J., Wagner, S., Haldon, J. F., Zorita, E., Telelis, I., Toreti, A., Izdebski, A. (2016). The Medieval Climate Anomaly and Byzantium: A review of the evidence on climatic fluctuations, economic performance and societal change. *Quaternary Science Reviews, 136*, 229–252. ISSN 0277–3791. https://doi.org/10.1016/j.quascirev.2015.10.004. Accessed on March 24, 2021.

Xoplaki, E., Luterbacher, J., Wagner, S., et al. (2018). Modelling Climate and Societal Resilience in the Eastern Mediterranean in the Last Millennium. *Human Ecology, 46*, 363–379 (2018). https://doi.org/10.1007/s10745-018-9995-9. Accessed on April 17, 2022.

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