



Simulating agricultural fragility in past societies: climate change, wheat, and grapes in ancient Rome

E. W. Marthe Deij¹ · Kyle Harper^{2,4} · Ep Heuvelink³ · Kirsten M. de Beurs¹

Received: 11 April 2025 / Accepted: 23 April 2026 / Published online: 29 April 2026
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Abstract

Food production is a primary process through which climate change affects human societies, yet the response of agricultural systems to past climate variability and change is poorly understood, largely because detailed data on yields is lacking before the 20th century. To address this gap, we used crop simulation models adapted for relatively simple, low-yield farming to simulate wheat (*Triticum aestivum*, *Triticum durum*) and grape (*Vitis vinifera* ‘Syrah’) yields under realistic environmental conditions for Italy during Roman times. To capture regional variability, simulations were conducted for one grape-growing and five wheat-growing locations. We used existing paleoclimate proxy records to test the potential sensitivity of agriculture to variations in temperature and precipitation across the Roman Climate Optimum (RCO) (ca. 200 BCE–100 CE) and Late Antique Little Ice age (LALIA) (ca. 530–680 CE). Our simulations indicate that yields for both wheat and grapes declined substantially under the colder conditions associated with the Late Antique Little Ice Age compared with the Roman Climate Optimum. Grapes appear notably sensitive to temperature variation from year to year, while wheat responds most directly to changes in water availability. Because both climatic inputs and crop parameters are reconstructed from proxy and historical data, the precise magnitude of simulated yields depends on modeling assumptions. However, the consistent pattern of substantially declining productivity under sustained cooling is robust across locations and sensitivity tests. Our analysis highlights both the uncertainties and the explanatory potential of model-based reconstructions for understanding the impacts of climate change on ancient agricultural systems.

Keywords Crop growth models · Roman Italy · Roman climate optimum · Late antique little ice age · Historical climate · Historical agriculture

1 Introduction

Natural climate change throughout the Holocene offers an opportunity to examine how human societies responded to environmental stress. Agriculture is a primary medium through which the climate system affects human well-being, particularly in pre-industrial

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societies, where agriculture was the dominant economic sector. Prior to the last two centuries, which saw the advent of mechanized traction, synthetic fertilizer, and the globalization of high-yield strains, productivity was much lower. Growing seasons tended to be longer, and the harvest index, the ratio of edible (seed) to inedible (stalk) was lower in ancient grain crops (Frankin et al. 2021). Agricultural systems were vulnerable to environmental perturbation, and societies responded with a number of strategies such as diversification and storage. Despite recent interest in the question of how premodern societies responded to climate variability and change, progress has been impeded due to the lack of detailed regional and national-level data on harvest yields prior to the twentieth century. The literature on the resilience and fragility of past societies has often proceeded without detailed analysis of how sensitive agricultural systems were to climate stress (Erdkamp 2021).

The role of climate variability and change in ancient Roman times is an important test case that has received ample attention. Although its exact chronology, nature, and magnitude have been debated, the Roman Climate Optimum (here, ca. 200 BCE to 150 CE) was a recognized phase of Holocene climate history characterized by warm, stable, and possibly humid conditions in the Mediterranean region (Bini et al. 2020; Büntgen et al. 2011; Joerin et al. 2006; McCormick et al. 2012). However, starting in the second half of the second century, greater instability is evident in a range of proxies (Harper 2019; Steinhilber et al. 2009). In the sixth century CE, volcanic eruptions triggered significant cooling and instability during what has been proposed as the Late Antique Little Ice Age (LALIA) (Büntgen et al. 2011; Peregrine 2020). The LALIA was marked by lower temperatures, while the hydro-climate varied significantly throughout this time frame (Büntgen et al. 2011).

We note that the term “Roman Climate Optimum” remains debated in both historical and paleoclimatic scholarship. While some studies suggest a relatively warm and wet period in Italy coinciding with early Roman expansion (Paparella et al. 2025), others emphasize substantial regional variability and question the notion of a unitary climatic phase with clear historical consequences (Bernard et al. 2023; Büntgen et al. 2020). The timing, duration, and societal impacts of this period are therefore not firmly established, and the concept oversimplifies complex human–environment interactions. We use the term here as a general descriptor familiar to readers, while acknowledging its limitations and the ongoing scholarly discussion surrounding its definition and significance. Indeed, simulating agricultural yields offers one way to clarify the possible impact of climate changes that manifest through continuous variations of multiple interacting parameters.

The social effects of these changes have been widely debated (Büntgen et al. 2011; Peregrine 2020). It is acknowledged that the impact of climate stress was mediated through the agricultural system, yet the response of Roman agricultural yields to specific climate conditions is poorly understood. One oft-cited claim is that higher average temperatures allowed wheat cultivation at higher altitudes (Lo Cascio and Malanima 2005). Others have begun to apply simulation approaches. For instance, Dermody et al. (Dermody et al. 2014) simulated cereal yields under changing climate conditions around 200 C.E., particularly as affected by water availability and virtual water trade by using a cost-distance analysis. Our approach directly simulates crop yields based on daily weather data, employing a novel method introduced in this study to reconstruct historical weather patterns and assess agricultural productivity. Bernigaud et al. (Bernigaud et al. 2021) modeled wine production in pre-Roman and early Roman Gaul, finding that successful vineyards may have expanded as far as northern Gaul during the RCO. Bernigaud et al. (Bernigaud et al. 2024) likewise

combine paleoclimate reconstructions with crop modeling, embedding them in an agent-based framework (ROMCLIM) to evaluate how climate fluctuations influenced the profitability of vineyards, olive groves, and grain farms in Southern Gaul. Their model integrates potential yields with costs, prices, and transport to estimate farm profits across centuries, highlighting the impact of the Roman Climate Optimum and the Late Antique Little Ice Age on agricultural economies. Goodchild (Goodchild 2013) applied a multi-criteria evaluation methodology to investigate the yield of wheat, olives, and grapes in the Tiber valley, considering factors such as soil quality, vegetation patterns, and socio-economic variables. Agricultural yields in Roman Italy varied according to both natural geography (soil, altitude, latitude) and human choices (diversification, manuring, fallowing, timing of the agricultural cycle, etc.) (Erdkamp 2019). Contreras et al. (Contreras et al. 2018) take a related approach by combining paleoclimate reconstructions with process-based agroecosystem modeling to estimate potential agricultural productivity in Holocene Provence, linking these outputs to diachronic settlement patterns. Their focus lies on the spatial dynamics of resilience and vulnerability, examining how communities located themselves with respect to productive land over millennia. Our study shares the mechanistic modeling of crop yields under reconstructed climates but differs in scope and resolution: whereas Contreras et al. work at annual time steps for prehistoric Provence, we simulate daily weather inputs for Roman Italy, covering the Roman Climate Optimum through the Late Antique Little Ice Age.

To compare yields across various climatic periods, we applied crop models tailored to ancient wheat and grape cultivation under simulated Roman weather conditions. This approach requires the adaptation of growth parameters for wheat and grapes to align with realistic conditions of ancient farming. Yield calculations for winter wheat (*Triticum aestivum*), durum (*Triticum durum*), and wine grapes (*Vitis vinifera* ‘Syrah’) were conducted using the LINTUL-2 (Leffelaar 2011) and STICS (Brisson et al. 2003) crop growth models, respectively. These models provide insights into how agricultural yield was affected by climate change during the height of the Roman Empire and subsequent periods of climate instability. LINTUL-2 is a crop growth model designed for simulating crop development under potential and water-limited conditions (Leffelaar 2011). Local wheat landraces have been grown for thousands of years in a Mediterranean climate (Frankin et al. 2021), and LINTUL-2’s simplicity makes it valuable for these crops. Likewise, refining the STICS model with data on ancient grape varieties is crucial, as few other models effectively simulate grapevine systems (Valdes-Gomez et al. 2009). Crop models like LINTUL-2 and STICS capture the sensitivity of plant biology to climate conditions, but they have not been leveraged to understand agricultural yields in past times.

The immediate challenge is that crop models require daily historical weather data, which is lacking even in the highest resolution climate proxies for the pre-instrumental period. Paleoclimatic proxies such as tree-ring and marine-core records offer data at annual to decadal resolution. In order to use these inputs in simulations requiring daily resolution, we analyzed paleoclimatic temperature and precipitation reconstructions. Tree-ring data for Central Europe from Büntgen et al. (Büntgen et al. 2011) and marine-core data for the gulf of Taranto from Zonneveld et al. (Zonneveld et al. 2024) were analyzed; the latter is currently the highest resolution reconstruction for Italy, which also agrees generally well with contemporary tree-ring based reconstructions from the Alps. We selected these datasets because they provide regionally specific signals, capturing local variations in temperature and precipitation that would be smoothed out in large-scale hemispheric multiproxy recon-

structions. A more detailed discussion of their limitations, as well as their spatial and temporal resolution, is provided in the Methods section. Importantly, our method is not tied to these particular proxies and could be applied to any suitable paleoclimatic reconstruction.

We identified modern years with average weather patterns similar to those found in paleoclimatic records for our study areas. For our modern data, we used daily temperature, precipitation, and wind speed for the years 1850 to 2014 for six locations in Italy, sourced from the CMIP6 CMCC-CM2–HR4 model (Scoccimarro et al. 2017). This approach enabled us to convert yearly paleoclimatic proxies into plausible daily weather data, preserving local weather patterns and providing a realistic representation of paleoclimatic conditions. By comparing recent daily weather data to ancient years with similar temperature and precipitation patterns, we identified modern years that could serve as proxies for specific ancient periods. Using these modern years with daily values, we were able to run crop models for six locations in Italy (see Fig. 1).

2 Materials and methods

2.1 Study area

We selected six 5 km × 5 km study areas in Italy: five for wheat and one for wine grapes (Fig. 1). These areas were chosen based on modern maps of wheat and wine production (Amato 2007; Marletto 2009), with the expectation that current cultivation regions resemble historical Roman sites (Kaplan et al. 2009). We used a Digital Elevation Model (DEM) to ensure a range of elevations and geographical features. The criteria for selecting study areas included variations in geographical features such as north-south orientation, coastal-inland location, valley-upland positioning, and a comparison between Sicily and the mainland. Each location was cross-referenced with maps of ancient Roman settlements (Ahlfeldt 2020) to verify historical agricultural activity. Additionally, we confirmed that there were nearby settlements in the form of larger agricultural estates known as ‘Latifundia’ that owned more than 125 hectares of land (Spurr 2016).

2.2 Paleoclimatic data

We used marine core data from the Gulf of Taranto (Zonneveld et al. 2024) and tree ring data from Central Europe (Büntgen et al. 2011) to reconstruct daily temperature and precipitation from 200 BCE to 600 CE. This paleoclimatic data was selected for its proximity to the study areas, and its consistency with broader regional trends in temperature and precipitation (Zonneveld et al. 2024). These two reconstructions were the only proxies suitable for our analysis, as they provide continuous coverage from 200 BCE–600 CE, offer annual or near-annual resolution necessary for yield modeling, and represent Italy or its immediate climatic surroundings. Other available Italian or Mediterranean paleoclimate records are either too coarse, or geographically too broad and thus cannot be used for our purposes.

The marine sediment record from the Gulf of Taranto presented by Zonneveld et al. (2024) provides a high-resolution reconstruction of late Holocene climate in southern Italy based on fossil dinoflagellate cyst assemblages. These proxies capture late summer to autumn conditions at a temporal resolution of roughly one sample every three years.

Study areas

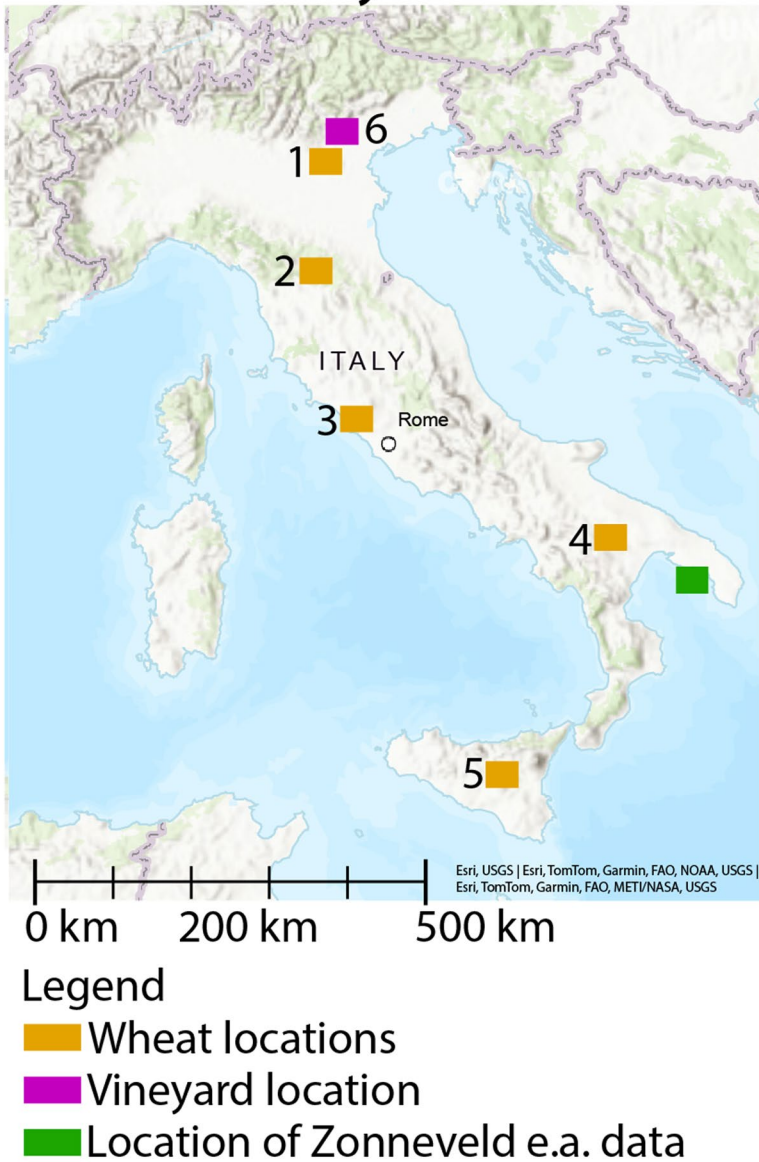


Fig. 1 Map of the six studied areas to simulate wheat and grape yields. Also included the location where the paleoclimatic data of Zonneveld et al. (2024) was sourced

Although locally constrained, the site integrates upstream hydrological input from northern Italy, reflecting both regional and extra-regional influences. The dataset's main strengths are its high resolution, the highest currently available for Roman Italy, and its ability to track temperature and precipitation variability at sub-decadal scale. Limitations include the

seasonal bias toward late summer/autumn, the lack of year-round coverage, and the indirect nature of precipitation reconstructions based on nutrient and salinity proxies.

Complementing this marine record, Büntgen et al. (2011) developed a tree-ring dataset of 7,284 oak series from subfossil, archaeological, historical, and living material across Central Europe, producing annual reconstructions of April–June precipitation and June–August temperature over the past 2,500 years. Anchored by cross-dating techniques, the dataset correlates strongly with instrumental records and allows identification of seasonal extremes such as droughts and wet summers of historical significance. Yet it too has limitations: it may overestimate low-frequency trends due to methodological constraints and uneven sample distribution (Ludescher et al. 2020), captures only specific seasonal windows, and anthropogenic land use affected sample availability and continuity. Together, the Zonneveld and Büntgen records provide regionally constrained, high-resolution reconstructions that complement each other while illustrating the strengths and limitations of different paleoclimate proxies.

2.3 Modern climatic data

From the CMIP6 CMCC-CM2–HR4 model we extracted daily temperature, precipitation, and wind speed data (Scoccimarro et al. 2017) for the years 1850–2014 to run the LINTUL-2 and STICS models. We extracted this data for our study areas to assure local weather patterns were preserved. Daily solar radiation was derived from the Italian Solar Radiation Atlas (ENEA 2022). Our approach involved running the models for all these modern years. We compared annual paleoclimatic data with our modern data to identify which ancient years had similar temperature and precipitation patterns as modern years. These modern years with daily values served as representatives for certain ancient years. By linking together modern years and their corresponding yields that matched the temperature and precipitation range of a specific period, we created what we called the yield envelopes for that climatic period.

Long-term weather station records in Italy generally do not provide all required variables and rarely extend back to the mid-nineteenth century, which is necessary for our simulations beginning around 1850 in order to capture a sufficiently wide range of climate years for comparison with the Roman-period data. We therefore used the CMIP6 model to provide spatially and temporally continuous daily weather input. To evaluate whether the model adequately represents observed variability, we compared simulated daily temperature with NOAA GHCN station data for 1974–2014 (NCEI NOAA 2026). Daily temperature correlations across the five sites ranged between 0.58 and 0.74, with the lowest value at the mountainous Monte Cimone site (96 km from the corresponding grid cell, and the nearest available station to that cell), where greater spatial heterogeneity is expected. Full results are provided in supplementary material table S1.

2.4 Adapting the models

We selected landraces of wheat that were historically cultivated in Italy (Calvi et al. 2023; Frankin et al. 2021; Jaradat 2013) and a grape variety comparable to what the Romans cultivated (De Lorenzis et al. 2019; Purcell 1985; Ramos-Madrigal et al. 2019). For wheat, bread wheat (*Triticum aestivum*) and durum (*Triticum durum*) were chosen. During Roman times,

the predominant wheat variety cultivated in the northern regions of the country was *Triticum aestivum*, while in the southern regions, *Triticum durum* was the primary choice (Calvi et al. 2023). For grapes, *Vitis vinifera* ‘Syrah’ was selected due to its identified genetic similarities with ancient grape varieties (Ramos-Madrigal et al. 2019). However, since Roman grape varieties are lost to history, simulating these exact varieties remains impossible.

To simulate ancient crop yields, we calibrated LINTUL-2 and STICS using historical data. Wheat yields were calibrated to represent ancient harvests using the yield estimates of ancient agricultural writer Columella. For winter wheat this was about 1.2 ton per hectare (Columella 1941; Evans 1981), achieved in LINTUL-2 by setting the Light Use Efficiency (LUE) to 2.1 g DM per MJ intercepted Photosynthetically Active Radiation (PAR) and the Harvest Index (HI) to 36%. A lower LUE means a lower biomass production per unit of absorbed radiation, which is partly the consequence of lower atmospheric CO₂ concentrations (see below). A reduced HI means that a smaller fraction of the plant is seed grains, fitting with tall old wheat varieties (Pourazari et al. 2015; Sargun and Mohan 2020). Calibration was done for location 3, where Columella resided, and both calibrated parameters were then applied for all winter wheat locations. We calibrated the model using the modern year 1855, identified as the most representative year for the RCO based on comparisons with marine core summer temperature data from 200 B.C.E. to 600 C.E (Zonneveld et al. 2024). Precipitation levels in 1855 were also comparable to the RCO. To assess uncertainty, we analyzed the five years most similar to the RCO, including 1855. Yield predictions taking any of these years as the calibration year, resulted in a standard deviation for yield of ± 0.2 tons per hectare. Ensuring consistency in spring temperature and precipitation levels with summer data was essential, as spring is the growing season for wheat (OECD 2006). Winter wheat yields were simulated using Columella’s planting and harvest dates as guides, sowing on the 24th of October and harvest before the 26th of July. Durum yielded approximately 1.5 tons per hectare at the beginning of the first century (Romagosa et al. 1999), the LUE for durum was set to 2.15 g per MJ, with a HI of 36%. For LINTUL-2, we adjusted sand parameters to mimic sandy soil found in Italy. The LINTUL-2 model was run for each location from 1850 to 2014 to simulate rain-fed winter wheat yields for locations 1, 2 and 3 and durum wheat for locations 4 and 5.

Grape yields were calibrated to Columella’s historical records of 8.23 ton per hectare (Bernigaud et al. 2021; Columella 1941; Robinson et al. 2006). We adapted the following parameters in the STICS model for Syrah grapes to match the yields observed in Columella’s farms. For the soil parameters, we adapted the clay content using Soilgrids data for the specific study area coordinates (ISRIC-World Soil n.d.), and adjusting albedo based on the mean values from NASA’s January and July 2023 data (NASA 2023). We also customized the soil pH values for the specific location (Panagos et al. 2022). We assumed soil types in Roman times were similar to the present, as no historical soil data is available (in this case as elsewhere, future simulation could explore more complex scenarios). Further, in our STICS grape model, we changed the harvest decision criterion from water content to physiological maturity to align with ancient Roman practices. We specified the elevation. In the model, our CO₂ levels were set to 278 ppm to represent the late Holocene. These CO₂ levels remained relatively stable from the 2nd century BCE to the 6th century CE (Brovkin et al. 2019). We increased the ‘afuitpot’ fruit weight parameter from 1.12 to 5 to match the yields observed in Columella’s farms. The STICS model was run with these parameters from 1850 to 2014 to calculate potential rain-fed yields for the Syrah grape variety.

2.5 Comparing ancient agricultural writers

A number of Roman authors comment on agricultural productivity, including Cicero, Varro, Pliny the Elder, and Columella, all of whom provide figures for wheat yields in Italy. Among these, Columella is generally regarded as the most systematic and reliable source (Evans 1981; Goodchild 2007), therefore, his data are often used as the basis for modern reconstructions (Bernigaud et al. 2024). At the same time, it has been suggested that Columella may have emphasized the profitability of viticulture at the expense of arable farming, and that yields with a return of 6:1 or 8:1 could be achieved (Goodchild 2007), a perspective that should be kept in mind when interpreting Columella's yields. Table S2 in the supplementary material summarizes the reported return yields from each of these writers, alongside the regions of Italy to which their observations apply.

2.6 Creating colder weather data

The CMIP6 CMCC-CM2–HR4 climate model shows a bias toward earlier onset of summer-like temperatures in some years, resulting in spring temperatures that exceed observed values. To correct for this, modeled spring temperatures were compared to the most recent high spring temperatures of the exceptionally warm year of 2018 (Scoccimarro et al. 2017), and years exceeding these thresholds were removed. Furthermore, none of the years in the modern weather data from 1850 to 2014 represents the extraordinary cold temperatures of the LALIA. To reflect the colder climate of the LALIA, we duplicated each year, keeping all climatic values exactly the same but reducing daily temperatures by lowering values in the following way. We used normal distributions to adjust temperatures seasonally: for each season, we generated a normal distribution with a specific mean and a standard deviation of 1 °C. For each daily temperature value, we then selected a value from this distribution, effectively lowering the temperatures while preserving daily variability. For the meteorological summer, we used a mean of −3.74 °C, as derived from the difference between the 10 warmest RCO summers and the 10 coldest LALIA summers (Büntgen et al. 2011). For the meteorological winter, we set the mean to −5.74 °C, subtracting an extra 2 degrees to account for historical seasonal differences, as in the Little Ice Age winters were an extra 2 degrees colder on average (Camuffo et al. 2014). For the meteorological spring we set it to −5.74 °C to correct for the excessively high spring temperatures in the modern data. The mean for the meteorological autumn was set to −4.74 °C (Camuffo et al. 2014; Wanner et al. 2022). Using these means, we adjusted each day of the duplicated years to have lower temperatures while keeping all other climate data the same. This method maintains seasonal variability but lowers overall temperatures, ensuring that the modified data accurately represents LALIA conditions.

2.7 Testing LINTUL-2 and STICS

To evaluate the impact of changing temperature and precipitation on wheat and grape yields, model tests were run. Variables such as solar radiance, wind speed, and vapor pressure remained constant, while either temperature or precipitation increased annually. Daily values were stable. We ran the LINTUL-2 and STICS models with this test data to observe how temperature and precipitation affected yield predictions by the models.

2.8 Yield envelopes

Running these models produced crop yields for all years from 1850 to 2014, from which we created yield envelopes representing Roman times by identifying yields corresponding to warmer RCO years and colder years. We used marine core paleo data from the Gulf of Taranto to find temperature and precipitation ranges matching the Roman late summer climate periods, comparing this data with recent data from the Gulf of Taranto area. Additionally, modern spring climate data were compared to Roman spring climate using a proxy, indicating that Lombardy's spring temperatures during the RCO are comparable to those of the last decade of the twentieth century (Büntgen et al. 2011; Leonelli et al. 2017). We standardized the average yearly spring (for wheat) and summer (for grapes) values of temperature and precipitation data for each location and crop by converting them into z-scores, which indicate how many standard deviations an observation is from the mean. Each of these temperature and precipitation values is linked to a corresponding yield value for that year. We then grouped temperature and precipitation, with the corresponding yields, into 0.5 z-score intervals, ranging from -3 to 3 , to compare how these intervals corresponded to climatic periods like the RCO and LALIA. We chose the four following climatic periods. The RCO, 160–180 C.E., 245–275 C.E., and the LALIA.

2.9 Adaptive strategies and sensitivity analysis

To assess the potential for adaptive management by ancient farmers, we ran a sensitivity analysis focused on sowing dates. While the primary LINTUL simulations do not incorporate the possibility for intercropping or social adaptations, historical accounts suggest that Roman farmers employed a wide range of strategies to mitigate climatic stress. These included crop and variety selection, adjusting sowing times, managing water availability, practicing mixed or rotational cropping, maintaining soil fertility through fallowing and grazing, and using windbreaks or hedges (Heinrich et al. 2021). Such practices would have enhanced both short-term flexibility in response to droughts, frosts, or floods, and long-term resilience under gradual climatic change.

To understand the influence of flexible sowing dates on our model, we performed a sensitivity experiment varying winter wheat sowing dates within the historical range reported by Roman agronomists. Columella recommends sowing around 24 October, but notes that in colder and wetter regions sowing should occur before the start of October (Columella 1941), whereas in warmer southern areas sowing could extend into late November (EU Science Hub 2024). Based on these accounts, we ran the sensitivity analysis for the year 1855. Sowing dates varied from 23 September to 22 November. The analysis was run for the three winter wheat locations, which differ in mean spring temperature and precipitation.

2.10 Irrigation sensitivity test

To explore irrigation as a potential adaptive strategy ancient farmers might have employed, we conducted a simplified sensitivity experiment for location 1 (Po Valley), where irrigation could be facilitated by the extensive river system of the Po River (Dermody et al. 2014). Because LINTUL-2 treats irrigation as a binary factor (rain-fed vs. full modern irrigation and alleviation of water stress), we tested a scenario in which precipitation in all climatic

periods was set to RCO-level values, thereby isolating the effect of temperature under constant water supply. Specifically, we replaced the daily precipitation of each simulated year with that of 1916, a year in which precipitation closely matches reconstructed RCO conditions at this site, while retaining the original temperature series and all other meteorological variables for each respective year. Yields were then grouped according to temperature z-value classes, and detailed results are provided in the supplementary material table S3.

3 Results

We present average yields for four periods of Roman history (Fig. 2): the Roman Climate Optimum (200 BCE–100 CE), a period of presumed favorable climate; the decades 160–180 CE, the end of the stable period; the years 245–275 CE, a period of notable climatic and social instability; and the Late Antique Little Ice Age (here 530–600CE), a period of volcanically forced anomalous cooling. On average wheat yields in the LALIA declined by 52% compared to the yields during the RCO. In location 1 wheat yield dropped from 2.66 to 1.97 t/ha, in location 2 from 2.50 to 1.21 t/ha, in location 3 from 0.75 to 0.46 t/ha. Location 4 saw wheat yield drop from 1.18 to 0.43 t/ha, location 5 declined from 0.39 to 0.08 t/ha. The largest declines were in the most southern regions; 64 and 79% respectively for regions 4 and 5 (Table 1). During both 245–275 C.E. and the LALIA period our crop regions became significantly cooler and drier, resulting in significant crop losses. Grape yield in northern Italy was 74% lower during the LALIA period than during the RCO. With yields dropping from 2.15 t/ha to 0.56 t/ha. These declines of 52 and 74% for wheat and grapes, respectively, are comparing the average RCO yields to the average LALIA yields (Büntgen et al. 2011). These LALIA yields represent the lowest-bound temperatures of the time period studied from 200 BCE to 600 CE. The yield values reported represent mean estimates for each region and time period.

To account for uncertainty in these estimates, we provide 95% confidence intervals for each crop, location, and climatic period. For grapes, the confidence intervals are notably wider, reflecting the smaller number of yield observations available in the warmer periods due to the cooler climatic conditions at this site. To test the sensitivity of these results to assumptions about baseline productivity, we repeated the winter wheat simulations for location 5 using Cicero's higher harvest-to-seed ratio (8:1) as a calibration target (Table 1). While absolute yields increased, the temporal pattern and relative magnitude of yield decline toward the LALIA remained unchanged. Yields for all locations using Cicero's yields as calibration can be found in the supplementary materials, tables S4–S9.

The 0.00 t/ha reported for durum at location 5 in 245–275 CE reflects rounding of extremely low (but non-zero) simulated yields. This period represents the driest spring conditions in our study, and because durum was modeled as a spring crop, winter sowing would likely have produced higher yields as precipitation is higher in winter.

Yields for winter wheat and durum (Fig. 3) responded to spring precipitation (May), aligning with the end of the vegetative stage for *Triticum Aestivum* (OECD 2006), confirming that spring precipitation was a significant factor influencing wheat yields. At locations 1, 2, 4 and 5 average yields increased with higher precipitation. This influence is less apparent at location 3. For grape yield the influence of summer precipitation (August and September) was less apparent. The study area for grapes is located in a colder region where grapes

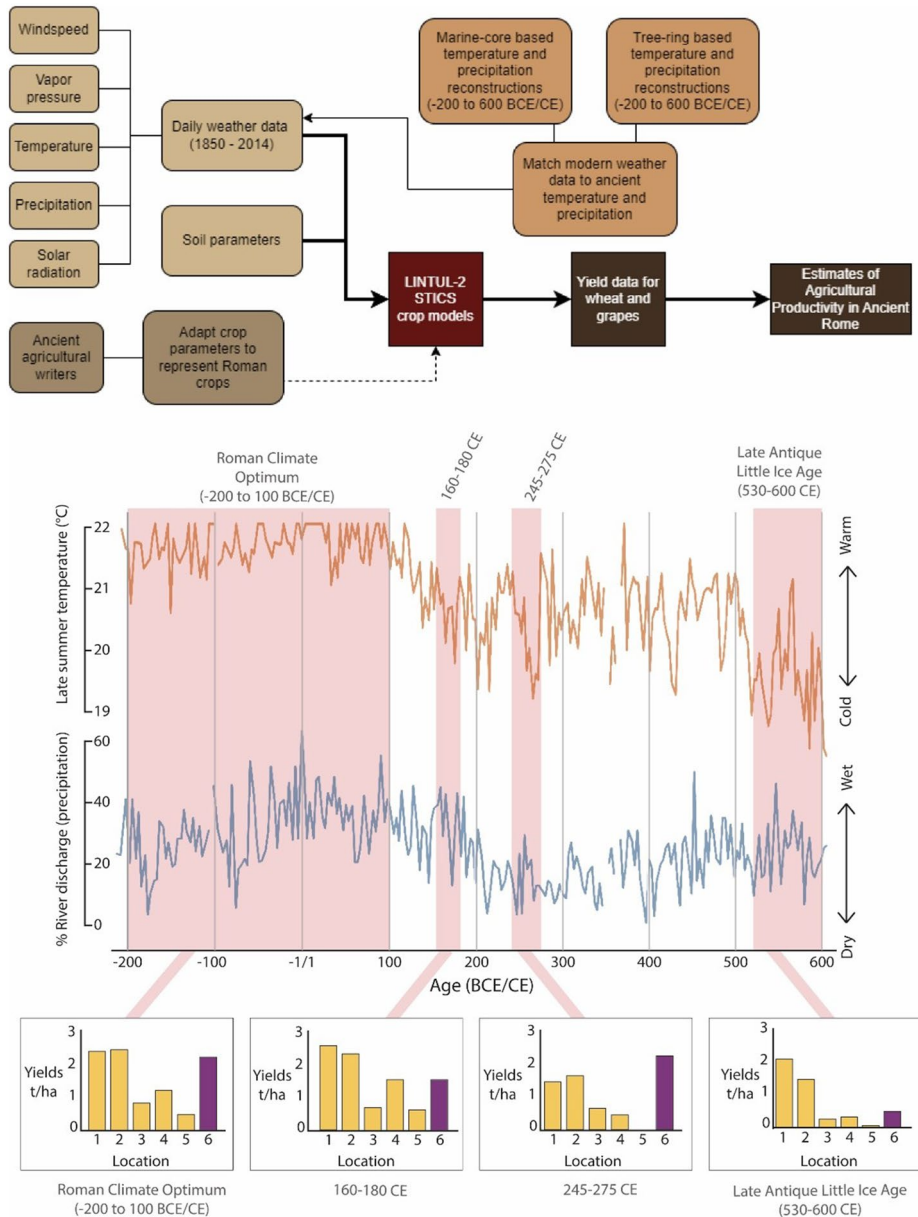


Fig. 2 Figure illustrating the method used, yield decline and paleoclimatic reconstructions used. The top panel shows a flowchart illustrating model inputs, outputs, and calibration parameters, including the method for aligning modern weather data with ancient paleoclimate records. Further depicted are marine-core temperature and precipitation reconstructions by Zonneveld et al. (2024), the four study periods (shaded), along with average wheat and grape yield declines between the RCO and LALIA. The percentage river discharge refers to a percentage of dinoflagellate species that reflect river nutrient runoff and hence precipitation

Table 1 Average winter wheat, durum and Syrah grape yields (t/ha) for different climatic periods. Climatic periods (e.g., RCO, etc.) were defined based on the key growing-season temperatures: spring temperature and precipitation for wheat, and summer temperature and precipitation for grapes, reflecting the stages when these crops develop. Values in parentheses indicate the 95% confidence interval for yields at each location during the corresponding climatic period. Winter wheat locations 1–5, durum wheat locations 4–5, and grapes location 6 are calibrated using Columella’s yield ratios, except for the row “durum location 5, calibrated with Cicero’s yields,” which uses Cicero’s higher yield ratios. This row provides a sensitivity check to demonstrate the effect of an alternative historical yield baseline

	RCO average yield (200 BCE– 100 CE)	160–180 CE average yield	245–275 CE average yield	LALIA yield (530–600 CE)
Winter wheat location 1	2.66 [1.90–3.42]	2.26 [1.14–3.38]	1.35 [1.09–1.61]	1.97 [1.35–2.60]
Winter wheat location 2	2.50 [1.61–3.39]	1.86 [1.13–2.59]	1.50 [1.01–1.99]	1.21 [0.84–1.60]
Winter wheat location 3	0.75 [0.55–0.95]	0.62 [0–1.25]	0.70 [0.48–0.93]	0.46 [0.22–0.70]
Durum wheat location 4	1.18 [0.61–1.75]	1.70 [0.93–2.47]	0.53 [0.23–0.83]	0.43 [0.19–0.68]
Durum wheat location 5	0.39 [0–0.85]	0.07 [NA]	0.00 [0–0.01]	0.08 [0–0.17]
Durum location 5, calibrated with Cicero’s yields	0.61 [0–1.25]	0.16 [NA]	0.00 [0–0]	0.12 [0.02–0.30]
Grapes location 6	2.15 [0–4.88]	1.43 [0–3.25]	2.14 [0–4.53]	0.56 [0–1.66]

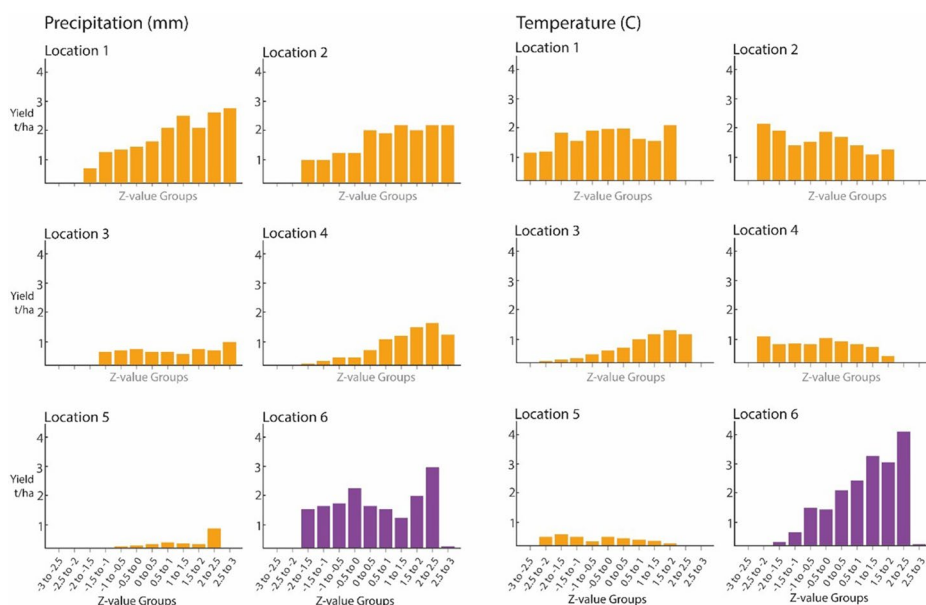


Fig. 3 Average yields (ton/ha) per z-value group for precipitation and temperature at six locations for winter wheat, durum and Syrah grapes. Locations are shown in Fig. 1. The x-axis displays z-value groups. We divided the yields by location and crop for both precipitation and temperature into z-value groups of 0.5, ranging from -3 to 3 . This approach allowed us to assess the yield variations between specific z-value intervals. The y-axis displays the yield in ton per hectare

develop later in the season, compared to the usual late spring budbreak, early flowering, and ripening characteristics of Syrah (Robinson et al. 2006). The yields did not significantly correspond to precipitation.

For wheat locations 1, 2, 4 and 5, spring temperatures did not significantly influence yields (Fig. 3). At location 3, temperature did influence yields. This is due to the specific microclimatic properties of this region, where winter temperatures and wind speed are relatively high, and vapor pressure is stable throughout the year. Grape yield showed a strong link with temperature. In this region, summer temperatures play a crucial role in influencing yields. During extremely cold years, such as those in the LALIA when volcanic eruptions caused temperatures to drop, it was too cold for the grapes to develop, leading to failed yields in the simulation. In contrast, during the RCO, temperatures were sufficiently high to support successful grape development.

3.1 Sensitivity analysis on sowing dates

The sensitivity analysis showed that sowing date influenced simulated wheat yields, though the magnitude and direction varied by location. Table S10 in the supplementary material displays the yield per location for different sowing days. In location 2, the coolest and wettest site, yields showed a consistent increase as sowing was delayed. In location 3, corresponding to Columella's farm region, optimal yields occurred near his recommended sowing date, with minor improvement (+0.4t/ha) when sowing was delayed by up to ten days. In the warmest and driest site of location 1, yields showed only minor variation (0.5 t/ha) between late-September and late-November sowing dates.

3.2 Irrigation sensitivity results

To test irrigation as a potential adaptive strategy, we fixed precipitation at RCO-level values for all climatic periods at location 1. Even under these conditions of constant high water availability, yields declined with colder temperatures. Average yields were 2.73 t/ha for RCO-like temperatures, 2.51 t/ha for intermediate periods (160–180 CE and 245–275 CE), and 2.49 t/ha for LALIA-like temperatures. Yields dropped by 9% when precipitation was at RCO-level, compared to 25% for rain-fed wheat in this location between the RCO and LALIA. Although absolute yields were higher than in rain-fed LALIA simulations, colder conditions still resulted in substantial reductions (Supplementary material table S3).

4 Discussion

The value of using the full power of crop models lies in the potential to display the complexity of ancient agricultural systems in their sensitivity to climate change within Italy, as well as the boundaries of human strategies of resilience. Agriculture is highly variable regionally and complicated by differences in soil types, irrigation, cultivation choices and multi-cropping strategies. Our analysis underscores the importance of regional variability and deepens our understanding of it. Variations in regional response to lower temperatures and precipitation provide deeper insights into the resilience and vulnerability of these regions

between the RCO to LALIA. Additionally, crop models can help to specify most significant climatic factors influencing yields.

The novelty of our approach lies in the integration of modern daily weather data and paleoclimatic records to reconstruct past crop yields using the power of computerized crop models. Unlike traditional approaches that rely on generalized climate reconstructions, our method acquires daily weather data by comparing modern daily weather patterns with comparable years from paleoclimatic records. This allows us to preserve local weather characteristics while identifying realistic daily conditions from centuries ago.

Of course, using modern daily values as a comparison to annual paleoclimatic averages introduces uncertainty. While we have aimed to reduce this uncertainty by using local modern daily weather data to maintain regional weather patterns, it remains an imperfect proxy. Additionally, differences in atmospheric composition, land use, and vegetation cover between ancient and modern times could affect the accuracy of our reconstructions. Despite these limitations, our approach offers a novel way to approximate daily weather conditions that would otherwise be inaccessible, providing insights into ancient agricultural productivity.

While the focus of this study is on the direct impact of climate change on crop production, it is essential to consider the adaptive measures in Roman Italy that may have lessened the effects of climate fluctuations. Notably, the grain supply system was crucial in ensuring food security during times of shortage (Linn 2012). Additionally, the Romans cultivated a diverse range of crops (Bosi et al., 2020; Ragno 2023), which could have helped reduce vulnerability to climate change. However, this study concentrates on yield outcomes, and further research is needed to better understand how these environmental shifts may have affected social structures.

Our models indicate that wheat yields are heavily influenced by spring precipitation, with northern locations showing higher yields compared to southern locations. This finding aligns with previous research, which highlights the significant impact of precipitation on wheat yield variability (Basso et al. 2009; Dalla Marta et al. 2015; Erdkamp 2012; Yu et al. 2014). Spring temperature also affects yields, aligning with research by Dermody et al. and Yu et al. (Dermody et al. 2014; Yu et al. 2014), shown particularly in location 3. Our irrigation sensitivity experiment, where water was set to RCO conditions for all years, shows that temperature alone can produce substantial reductions under colder conditions.

For grape yields realized in the northern location we studied, our findings suggest that summer temperature affects yields, while summer precipitation had no significant effect on yield. Potopová et al. (Potopová et al. 2015) also reported minimal influence of summer precipitation on grape yields. High spring temperatures shorten the time from flowering until ripeness in grapes (Leeuwen and Darriet 2016). Conversely, lower spring temperatures would prolong the dormancy period in grapevines (Camargo-Alvarez et al. 2020), thereby delaying the onset of grape development and making summer temperatures more influential on yields, as observed in this colder northern location.

Because absolute yield levels in antiquity are uncertain and depend on the choice of historical baseline, we conducted a sensitivity analysis using alternative harvest-to-seed ratios reported by Roman agricultural writers. While Columella's 4:1 ratio was used for the primary calibration due to its systematic character and widespread acceptance, we repeated the winter wheat simulations using Cicero's higher 8:1 ratio, recalibrating the LINTUL-2 model by increasing light use efficiency (LUE from 2.1 to 2.8 g DM MJ⁻¹ PAR, and 2.85 for

durum) to match Cicero's reported productivity in Sicily. This recalibration was applied to location 5, Sicily. As expected, this higher baseline productivity resulted in increased absolute yields across all climatic periods. However, the relative response of yields to climatic deterioration remained robust: the magnitude and direction of yield decline from the RCO to the LALIA closely mirror those obtained under the Columella calibration. In other words, adopting Cicero's higher productivity assumptions moderates the absolute severity of yield loss but does not alter the overall pattern of climate-driven decline. This result confirms that our central finding, namely substantial agricultural vulnerability under colder and drier conditions, does not depend on the choice of a single historical yield ratio, but instead reflects the underlying sensitivity of crop growth to climate variability.

There remains a challenge in determining whether Syrah accurately represents ancient grape varieties grown in Italy. The uncertainty arises from the lack of historical information about the cultivation of this variety in ancient times, as much of the historical information regarding the modern-day descendants of Roman grapes has been lost. The LINTUL-2 crop model, used for modeling durum and bread wheat, simplifies the complexity of these crops by focusing mainly on Light Use Efficiency and Harvest Index to adapt modern crops to ancient varieties.

Spring temperatures were used to assess the climate's influence on wheat yields, but the potential impacts of early spring or late winter on yields might have been overlooked. This could explain instances where similar precipitation and temperature resulted in different yields. This shows the limitation of using average temperature and precipitation data for either spring or summer to display yields, without considering the influence of other months.

Wheat and grapes were essential subsistence crops in ancient Rome with cereals being the dominant staple food, and large grain estates served as key economic assets for the Roman elite (Erdkamp 2012). Grape cultivation, driven by the economic importance of wine production, was equally vital (Purcell 1985). The success of both crops was closely tied to weather conditions, particularly in Southern Italy, where minimal annual rainfall was closer to the lower bound to support grain cultivation. Droughts and early onset of summer led to harvest failures, prompting ancient Romans to adapt crop diversification strategies, including planting various grains and legumes (Erdkamp 2012).

In our main simulations for wheat, we applied a fixed sowing date. However, historical evidence suggests that farmers were unlikely to adhere rigidly to a single calendar date. As noted by Heinrich and Hansen (2021), Roman farmers demonstrated considerable adaptability, adjusting their management practices, which included sowing dates, to local conditions and seasonal cues. Our sensitivity analysis showed that variation in sowing date can influence yields through its interaction with temperature and precipitation during early crop development. Sowing timing likely served as an important adaptive mechanism. Consequently, while our main analysis relies on a single sowing date for comparability, actual yields in antiquity may have differed depending on how farmers responded to local weather patterns. Recognizing this adaptive behavior is essential when interpreting the modeled results, as it underscores the dynamic decision-making that contributed to the resilience of Roman agricultural systems.

Our irrigation sensitivity experiment represents a simplified approximation of Roman water management. Because LINTUL-2 treats irrigation as a binary condition and does not simulate partial or seasonal irrigation practices, we approximated irrigation by fixing precipitation at RCO-level values for all climatic periods. Even under these conditions of

high water availability, yields declined under colder temperature regimes, demonstrating that temperature remained a limiting factor. Higher water availability would therefore likely have mitigated yield losses but could not fully offset the effects of sustained cooling. The experiment thus illustrates the potential buffering capacity of water management, while also highlighting the continued sensitivity of crop growth to temperature variability. Accordingly, this experiment should not be interpreted as a faithful simulation of Roman irrigation, but as a sensitivity experiment, underscoring the importance of future research incorporating nuanced irrigation systems into crop models.

Our research highlights how ancient agricultural systems may have been impacted by extreme climatic events, particularly during the Late Antique Little Ice Age, a period marked by significant cooling due to volcanic activity. Modeling the LALIA years, characterized by low temperatures following volcanic eruptions, we observe substantial decreases in wheat and grape yields of 52 and 74% respectively, compared to the average yields in the Roman Climate Optimum. It should be noted that our results were modelled to represent yields for the average LALIA temperatures, the yields are not representative for the most extreme years where factors as extremely low solar radiation due to eruptions would have had a profound impact on yields.

The impact of climate change on Roman agriculture was multifaceted. Long-term climatic shifts during the Holocene, particularly from 200 BCE to 600 CE, reveal a gradual shift toward cooler and drier conditions, which resulted in a decline of agricultural yields. In contrast, short-term extremes, such as the decadal cooling following multiple volcanic eruptions at the onset of the LALIA, resulted in more immediate and dramatic declines in yields. These short-term extremes likely placed considerable strain on Roman society by reducing food production.

A promising avenue for future work would be to situate the simulated Roman-era wheat yields within a broader empirical framework, drawing on pre-modern data that reflect harvest variability under comparable climatic conditions. In particular, long-term grain price series from early modern Italy (Galloway 1988; Malanima 2021) offer indirect evidence of how yields responded to weather fluctuations in a low-input agricultural regime. By linking paleoclimatic reconstructions of temperature and precipitation with these historical price data, it would be possible to identify eighteenth-century years that experienced similar climatic stresses to those modeled for the Roman period. Such parallels could help to validate and contextualize the simulated patterns of yield variability.

Overall, our results indicate that climate change in Roman times led to agricultural yield losses. In the Roman world, climate-induced agricultural stress plausibly contributed to economic stagnation, conflict and epidemic disease (Harper 2019). Simulating the response of plant biology to realistic climate variation allows, for the first time, insight into the primary mechanism connecting the climate system and these social effects, and future study can build on these methods and results to explore the dynamics of resilience and vulnerability in complex social systems strained by climatic perturbations.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-026-04195-4>.

Acknowledgements We thank Dr. Christian Gary for his valuable insights and an informative discussion on grape yields and the STICS model. We are very grateful to the reviewers for their thoughtful and constructive feedback. Their insightful comments have greatly helped us to improve the clarity, depth, and overall quality of the manuscript.

Author contributions Kyle Harper, Kirsten de Beurs and Marthe Deij designed research; Marthe Deij and Ep Heuvelink performed research; Marthe Deij, Kirsten de Beurs and Ep Heuvelink analyzed data; All authors wrote the paper.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability Analysis code and created data can be found at: <https://git.wur.nl/deij002/romancimatechange> <https://github.com/mdeij/RomanClimateChange>

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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References

- Ahlfeldt J (2020) Digital atlas of the roman empire. <https://imperium.ahlfeldt.se/>
- Basso B, Cammarano D, Chen D, Cafiero G, Amato M, Bitella G, Rossi R, Basso F (2009) Landscape position and precipitation effects on spatial variability of wheat yield and grain protein in southern Italy. *J Agronomy Crop Sci* 195(4):301–312. <https://doi.org/10.1111/j.1439-037X.2008.00351.x>
- Amato V (2007) Map of the main Italian areas of wine production. ResearchGate. https://www.researchgate.net/figure/Map-of-the-main-Italian-areas-of-wine-production-green-areas-original-drawing-by_fig1_318019596
- Bernard S, McConnell J, Di Rita F, Michelangeli F, Magri D, Sadori L, Masi A, Zanchetta G, Bini M, Celant A, Trentacoste A, Lodwick L, Samuels JT, Lippi MM, Bellini C, Paparella C, Peralta D-EP, Tan J, van Dommelen P, ... De Giorgi AU, Cheung C (2023) An environmental and climate history of the Roman expansion in Italy. *J Interdiscip Hist* 54(1):1–41. https://doi.org/10.1162/jinh_a_01971
- Bernigaud N, Bondeau A, Guiot J (2021) Understanding the development of viticulture in Roman Gaul during and after the Roman climate optimum: the contribution of spatial analysis and agro-ecosystem modeling. *J Archaeol Sci Rep* 38:103099. <https://doi.org/10.1016/j.jasrep.2021.103099>
- Bernigaud N, Bondeau A, Guiot J, Bertoncello F, Ouriachi M-J, Bouby L, Leveau P, Bernard L, Isoardi D (2024) The impact of climate change on the agriculture and the economy of Southern Gaul: new perspectives of agent-based modelling. *PLoS One* 19(3):e0298895. <https://doi.org/10.1371/journal.pone.0298895>
- Bini M, Zanchetta G, Regattieri E, Isola I, Drysdale RN, Fabiani F, Genovesi S, Hellstrom JC (2020) Hydrological changes during the Roman climatic Optimum in Northern Tuscany (Central Italy) as evidenced by speleothem records and archaeological data. *J Quaternary Sci* 35(6):791–802. <https://doi.org/10.1002/jqs.3224>
- Bosi G, Castiglioni E, Rinaldi R, Mazzanti M, Marchesini M, Tottoli M (2020) Archaeobotanical evidence of food plants in northern Italy during the Roman period. *Veget Hist Archaeobot* 29(6):681–679 <https://doi.org/10.1007/s00334-020-00772-4>
- Brisson N, Gary C, Justes E, Roche R, Mary B, Ripoche D, Zimmer D, Sierra J, Bertuzzi P, Burger P, Busière F, Cabidoche YM, Cellier P, Debaeke P, Gaudillère JP, Hénault C, Maraux F, Seguin B, Sinoquet H (2003) An overview of the crop model Stics. *Eur J Criminol Agronomy, Modell Cropping Syst: Sci, Softw Appl* 18(3–4):309–332. [https://doi.org/10.1016/S1161-0301\(02\)00110-7](https://doi.org/10.1016/S1161-0301(02)00110-7)
- Brovkin V, Lorenz S, Raddatz T, Ilyina T, Stenmler I, Toohey M, Claussen M (2019) What was the source of the atmospheric CO₂ increase during the Holocene? *Biogeosciences* 16(13):2543–2555. <https://doi.org/10.5194/bg-16-2543-2019>

- Büntgen U, Arseneault D, Boucher É, Churakova O, Gennaretti F, Crivellaro A, Hughes MK, Kirilyanov AV, Klippel L, Krusic PJ, Linderholm HW, Ljungqvist FC, Ludescher J, McCormick M, Myglan VS, Nicolussi K, Piermattei A, Oppenheimer C, Reinig F, Sigl M, Vaganov EA, Esper J (2020) Prominent role of volcanism in common Era climate variability and human history. *Dendrochronologia* 64:125757. <https://doi.org/10.1016/j.dendro.2020.125757>
- Büntgen U, Tegel W, Nicolussi K, McCormick M, Frank D, Trouet V, Kaplan JO, Herzig F, Heussner K-U, Wanner H, Luterbacher J, Esper J (2011) 2500 years of European climate variability and human susceptibility. *Science* 331(6017):578–582. <https://doi.org/10.1126/science.1197175>
- Calvi A, Preiti G, Gastl M, Poiana M, Zarnkow M (2023) Malting process optimization of an Italian common wheat landrace (*triticum aestivum* L.) through response surface methodology and desirability approach. *LWT* 173:114242. <https://doi.org/10.1016/j.lwt.2022.114242>
- Camargo-Alvarez H, Salazar-Gutiérrez M, Keller M, Hoogenboom G (2020) Modeling the effect of temperature on bud dormancy of grapevines. *Agri For Meteorol* 280:107782. <https://doi.org/10.1016/j.agrformet.2019.107782>
- Camuffo D, Bertolin C, Schenal P, Craievich A, Granziero R (2014) The Little Ice Age in Italy from documentary proxies and early instrumental records. *mediterranea* 122), Article 122. 17–30. <https://doi.org/10.4000/mediterranea.7005>
- Columella LJM (H. B. Ash (Trans) (1941) *Columella on agriculture books 1-4*. Harvard University Press. (Original work published 65
- Contreras DA, Hiriart E, Bondeau A, Kirman A, Guiot J, Bernard L, Suarez R, Leeuw SVD (2018) Regional paleoclimates and local consequences: integrating GIS analysis of diachronic settlement patterns and process-based agroecosystem modeling of potential agricultural productivity in Provence (France). *PLoS One* 13(12):e0207622. <https://doi.org/10.1371/journal.pone.0207622>
- Dalla Marta A, Orlando F, Mancini M, Guasconi F, Motha R, Qu J, Orlandini S (2015) A simplified index for an early estimation of durum wheat yield in Tuscany (Central Italy). *Field Crops Res* 170:1–6. <https://doi.org/10.1016/j.fcr.2014.09.018>
- De Lorenzis G, Mercati F, Bergamini C, Cardone MF, Lupini A, Mauceri A, Caputo AR, Abbate L, Barbagallo MG, Antonacci D, Sunseri F, Brancadoro L (2019) Snp genotyping elucidates the genetic Diversity of Magna Graecia Grapevine Germplasm and its historical origin and dissemination. *BMC Plant Biol* 19(1), Article 1. <https://doi.org/10.1186/s12870-018-1576-y>
- Dermody BJ, van Beek RPH, Meeks E, Klein Goldewijk K, Scheidel W, van der Velde Y, Bierkens MFP, Wassen MJ, Dekker SC (2014) A virtual water network of the Roman World. *Hydrol Earth Syst Sci* 18(12):5025–5040. <https://doi.org/10.5194/hess-18-5025-2014>
- ENEA (2022) ENEA - Solaritaly | table values of solar radiation in Italy. <http://www.solaritaly.enea.it/TabelleRad/TabelleRadEn.php>
- Erdkamp P (2012) *A cultural history of food in antiquity*, vol 1. Berg Publishers
- Erdkamp P (2019) The local grain market in the Roman World. In: Cascio ELIOLO, Bresson ALAIN, Johnson JANE, Maiuro MARCO (eds) *Manuscript for the Oxford Handbook of economies in the classical world*. Oxford University Press (Forthcoming). https://www.academia.edu/75211867/The_Local_Grain_Market_in_the_Roman_World
- Erdkamp P (2021) Climate change and the productive Landscape in the Mediterranean region in the Roman period. In: Erdkamp P, Manning JG, Verboven K (eds) *Climate change and ancient societies in Europe and the Near East: diversity in collapse and resilience*. Springer International Publishing, pp 411–442. https://doi.org/10.1007/978-3-030-81103-7_14
- EU Science Hub (2024) Dry conditions allow sowing campaign to catch up - the joint research. *EU Science Hub, Centre*. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/dry-conditions-allow-sowing-campaign-catch-2024-11-25_en
- Evans JK (1981) Wheat production and its social consequences in the Roman World. *CI Q* 31(2):428–442. <https://doi.org/10.1017/S0009838800009769>
- Frankin S, Roychowdhury R, Nashef K, Abbo S, Bonfil DJ, Ben-David R (2021) In-Field comparative study of landraces vs. Modern wheat genotypes under a Mediterranean climate. *Plants* 10(12):2612. <https://doi.org/10.3390/plants10122612>
- Galloway PR (1988) Basic patterns in annual variations in fertility, Nuptiality, mortality, and prices in pre-industrial Europe. *Popul Stud. (world)*. 42(2):275–303. <https://doi.org/10.1080/0032472031000143366>
- Goodchild H (2007) Modelling Roman agricultural production in the Middle Tiber Valley, Central Italy [University of Birmingham]. <https://etheses.bham.ac.uk/id/eprint/175/1/Goodchild07PhD.pdf>
- Goodchild H (2013) GIS models of Roman agricultural production. *The Roman Agric Economy* 55
- Harper K (2019) *The fate of Rome: climate, disease, and the end of an empire*, 2019th edn. Princeton University Press

- Heinrich F, Hansen AM (2021) A hard row to hoe. Ancient climate change from the crop perspective. In: Erdkamp P, Manning JG, Verboven K (eds) *Climate change and ancient societies in Europe and the Near East. Diversity in collapse and resilience*. pp 25–80. https://doi.org/10.1007/978-3-030-81103-7_2
- ISRIC-World Soil (n.d.) *SoilGrids web portal*. SoilGrids Web Portal. <https://soilgrids.org>. September 14, 2023, from
- Jaradat AA (2013) Wheat landraces: a mini review. *Emir J Food Agric* 25(1):20–29. <https://doi.org/10.9755/ejfa.v25i1.15376>
- Joerin UE, Stocker TF, Schlüchter C (2006) Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene* 16(5):697–704. <https://doi.org/10.1191/0959683606hl964rp>
- Kaplan JO, Krumhardt KM, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. *Quaternary Sci Rev* 28(27–28):3016–3034. <https://doi.org/10.1016/j.quascirev.2009.09.028>
- Leeuwen CV, Darriet P (2016) The impact of climate change on viticulture and wine quality. *J Wine Econ* 11(1):150–167. <https://doi.org/10.1017/jwe.2015.21>
- Leffelaar P (2011) LINTUL-2, a simple crop growth Model for both potential and water limited growing conditions | models & data library. <https://models.pps.wur.nl/lintul-2-simple-crop-growth-model-both-potential-and-water-limited-growing-conditions>
- Leonelli G, Coppola A, Salvatore MC, Baroni C, Battipaglia G, Gentilella T, Ripullone F, Borghetti M, Conte E, Tognetti R, Marchetti M, Lombardi F, Brunetti M, Maugeri M, Pelfini M, Cherubini P, Provenzale A, Maggi V (2017) Climate signals in a multispecies tree-ring network from central and southern Italy and reconstruction of the late summer temperatures since the early 1700s. *Clim. Past* 13(11):1451–1471. <https://doi.org/10.5194/cp-13-1451-2017>
- Linn J (2012) The Roman grain supply, 442–455. *Jla* 5(2):298–321. <https://doi.org/10.1353/jla.2012.0015>
- Lo Cascio E, Malanima P (2005) Cycles and stability. Italian Population before the Demographic transition (225 B.C. In: - A.d. 1900, vol 21. *Rivista Di Storia Economica*
- Ludescher J, Bunde A, Büntgen U, Schellnhuber HJ (2020) Setting the tree-ring record straight. *Clim Dyn* 55(11–12):3017–3024. <https://doi.org/10.1007/s00382-020-05433-w>
- Malanima P (2021) Famines, Demographic crises and climate in Italy 1650–1913. In: Erdkamp P, Manning JG, Verboven K (eds) *Climate change and ancient societies in Europe and the Near East: diversity in collapse and resilience*. Springer International Publishing, pp 103–125. https://doi.org/10.1007/978-3-030-81103-7_4
- Marletto V (2009) Cultivated areas for durum wheat and common wheat in Italy. ResearchGate. https://www.researchgate.net/figure/Cultivated-areas-for-durum-wheat-and-common-wheat-in-Italy_fig1_228722411
- McCormick M, Büntgen U, Cane MA, Cook ER, Harper K, Huybers P, Litt T, Manning SW, Mayewski PA, More AFM, Nicolussi K, Tegel W (2012) Climate change during and after the Roman Empire: reconstructing the past from scientific and historical evidence. *J Interdiscip Hist* 43(2):169–220. https://doi.org/10.1162/JINH_a_00379
- NASA (2023 December 7). Global Albedo Monthly [Text.Article]. NASA Earth observations (NEO). Albedo (1 month) | NASA. https://neo.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA%26;date=2023-07-01
- NCEI NOAA (2026) NCEI NOAA climate Data online [Dataset]. <https://www.ncei.noaa.gov/cdo-web/>
- OECD (2006) Safety assessment of Transgenic organisms, volume, 1: oECD consensus documents. Organisation for Economic Co-operation and Development. <https://www.oecd-ilibrary.org/docserver/9789264095380-10-en.pdf?expires=1705505641%26id=id%26accname=guest%26checksum=3ADA271E6017D5FBB0B062BDE42982A9%26text=The%20vegetative%20period%20is%20120,are%20insensitive%20to%20day%20length>
- Panagos P, Van Liedekerke M, Borrelli P, Köninger J, Ballabio C, Orgiazzi A, Lugato E, Liakos L, Hervas J, Jones A, Montanarella L (2022) European soil data centre 2.0: soil data and knowledge in support of the Eu policies. *Eur J Soil Sci* 73(6):e13315. <https://doi.org/10.1111/ejss.13315>
- Paparella C, Bernard S, Bini M, Columbu A, Isola I, Harper K, Post R, Zonneveld K, Zanchetta G (2025) Historical archives from the Roman monarchic and republican periods show human perceptions of environment and climate change in Italy, 753–29 BCE. London, England, Sage UK. <https://doi.org/10.1177/09596836241307302>. *The Holocene*
- Peregrine PN (2020) Climate and social change at the start of the late Antique Little Ice Age. *The Holocene* 30(11):1643–1648. <https://doi.org/10.1177/0959683620941079>
- Potopová V, Štěpánek P, Možný M, Türkott L, Soukup J (2015) Performance of the standardised precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic. *Agri For Meteorol* 202:26–38. <https://doi.org/10.1016/j.agrformet.2014.11.022>
- Pourazari F, Vico G, Ehsanzadeh P, Weih M (2015) Contrasting growth pattern and nitrogen economy in ancient and modern wheat varieties. *Can J Plant Sci* 95(5):851–860. <https://doi.org/10.4141/cjps-2014-260>

- Purcell N (1985) Wine and wealth in ancient Italy. *J Rom Stud* 75:1–19. <https://doi.org/10.2307/300648>
- Ragno R (2023) Cereal farming practices in Italy during the 1st millennium CE: an integrated approach to regionality. *J Archaeol Sci Rep* 52:104287. <https://doi.org/10.1016/j.jasrep.2023.104287>
- Ramos-Madriral J, Runge AKW, Bouby L, Lacombe T, Samaniego Castruita JA, Adam-Blondon A-F, Figueiral I, Hallavant C, Martínez-Zapater JM, Schaal C, Töpfer R, Petersen B, Sicheritz-Pontén T, This P, Bacilieri R, Gilbert MTP, Wales N (2019) Palaeogenomic insights into the origins of French Grapevine Diversity. *Nat Plants* 5(6), Article 6. 595–603. <https://doi.org/10.1038/s41477-019-0437-5>
- Robinson J, Harding J, Vouillamoz J (2006) *The Oxford companion to wine*, 3rd Revised edn. Oxford University Press
- Romagos I, Slafer GA, Araus JL (1999) Durum wheat and barley yields in antiquity estimated from ¹³C discrimination of archaeological grains: a case study from the Western Mediterranean basin. *Australian J Plant Physiol* 26(4):345–352. <https://doi.org/10.1071/pp98141>
- Sargun K, Mohan S (2020) Modeling the crop growth-A review. *MAUSAM* 71(1), Article 1. <https://doi.org/10.54302/mausam.v71i1.10>
- Scoccimarro E, Bellucci A, Peano D (2017) CMCC CMCC-CM2-HR4 model output prepared for CMIP6 HighResMIP. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.1359> [Dataset]
- Spurr MS (2016) Latifundia. *Oxford Res Encycl Classics*. <https://doi.org/10.1093/acrefore/9780199381135.013.3596>
- Steinhilber F, Beer J, Fröhlich C (2009) Total solar irradiance during the Holocene. *Geophys Res Lett* 36(19). <https://doi.org/10.1029/2009GL040142>
- Valdes-Gomez H, Celette F, de Cortazar-Atauri IG, Jara-Rojas F, Ortega-Farias S, Gary C (2009) Modelling soil water content and Grapevine growth and development with the Stics crop-soil model under two different water management strategies. *OENO One* 43(1):13–28. <https://doi.org/10.20870/oeno-one.2009.43.1.806>
- Wanner H, Pfister C, Neukom R (2022) The variable European Little Ice Age. *Quaternary Sci Rev* 287:107531. <https://doi.org/10.1016/j.quascirev.2022.107531>
- Yu Q, Li L, Luo Q, Eamus D, Xu S, Chen C, Wang E, Liu J, Nielsen DC (2014) Year patterns of climate impact on wheat yields. *Intl J Climatol* 34(2):518–528. <https://doi.org/10.1002/joc.3704>
- Zonneveld KAF, Harper K, Klügel A, Chen L, De Lange G, Versteegh GJM (2024) Climate change, society, and pandemic disease in Roman Italy between 200 BCE and 600 CE. *Sci Adv* 10(4):eadk1033. <https://doi.org/10.1126/sciadv.adk1033>

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Authors and Affiliations

E. W. Marthe Deij¹  · Kyle Harper^{2,4}  · Ep Heuvelink³  · Kirsten M. de Beurs¹ 

✉ Kirsten M. de Beurs
kirsten.debeurs@wur.nl

¹ Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, Droevendaalsesteeg 4, Wageningen 6708 PB, The Netherlands

² Department of Classics and Letters, University of Oklahoma, 650 Parrington Oval, Norman, OK CARN 110, USA

³ Wageningen University, Horticulture and Product Physiology, Droevendaalsesteeg 4, Wageningen 6708 PB, The Netherlands

⁴ Santa Fe Institute, Santa FE, NM 87501, USA