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Volcanoes, Climate, and Society

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Abstract

This review examines the societal ramifications of large volcanic eruptions—not the proximal impacts of lava, ash, pumice, and gaseous emissions but rather the consequences of the climate forcing triggered by dispersal of volcanic sulfate aerosol in the stratosphere. Using ice core records of volcanism and tree-ring data of summer temperature anomalies, we analyze 38 preindustrial eruptions that injected an estimated 6 Tg or more of sulfur into the stratosphere. We then explore more than 100 works that consider the volcanism-climate-society nexus, teasing out the key elements of their arguments for or against the role of volcanically forced climate change in far-field societal impacts. As well as summarizing and interrogating the history of ideas and state of the art on this topic, we hope to stimulate further holistic, interdisciplinary approaches to assess the broader implications of volcanic eruptions, particularly for global food security—both in the past and in the future.

- There are compelling arguments to consider the role of volcanically forced climate change in explanations of history.
- Such research requires integration of geographical, ecological, demographic, econometric, and other data with historical sources and narratives, and therefore demands cross-disciplinary conversation.
- Statistical evidence is needed to attribute weather and climate extremes to volcanic forcing, and agricultural and pastoral responses to climate anomalies must be reconstructed at high spatiotemporal resolution.
- Several prominent climate forcing eruptions in circa 304, 1182, 1345, and 1453 CE have hitherto received comparatively little attention.

1. INTRODUCTION

1.1. Volcanic Eruptions and Climate Responses

Benjamin Franklin (1706–1790) has been credited as the first person to suggest a relationship between volcanism and climate (Franklin 1785). While he hinted that sightings of "dry fog" in summer might herald a severe winter, he was uncertain of the origin of such hazes. Later studies reported observations of the radiative effects of airborne volcanic dust following the eruptions of Krakatau (Indonesia, 1883), Santa Maria (Guatemala, 1902), and Katmai (Alaska, 1912) (Abbot & Fowle 1913, Wexler 1951), and as early as 1913, the meteorologist William Humphreys (1862–1949) linked agricultural productivity to volcanically forced climate change (Humphreys 1913). More generally, the influences of climate variability on society have been discussed for more than a century (Huntington 1915; Degroot et al. 2021, 2022; Ljungqvist et al. 2021, 2024). Another meteorologist and a pioneer of historical climatology, Hubert Lamb (1913–1997), was the first person to attempt quantification of the climate forcing of volcanic eruptions, proposing a "dust veil index" (Lamb 1970). This soon influenced climate modeling (Schneider & Mass 1975).

A large body of empirical and model-derived evidence, mostly amassed since the 1991 eruption of Pinatubo (Philippines) (Minnis et al. 1993), now underpins our understanding of the impacts of large volcanic eruptions on the atmosphere, weather, and climate via radiative forcing and dynamical interactions (Marshall et al. 2022). These include multi-year summer cooling of the Northern Hemisphere (NH) continental regions and boreal winter warming (Zambri et al. 2017, Tejedor et al. 2024). For eruptions before the instrumental era, tree-ring-based reconstructions have been widely used to reveal climate responses to volcanic forcing (Briffa et al. 1998, Schneider et al. 2015, Sigl et al. 2015, Stoffel et al. 2015, Wilson et al. 2016, Anchukaitis et al. 2017, Toohey et al. 2019, Büntgen et al. 2020). Studies of the consequences of volcanic eruptions on climate and thereby on society offer an especially powerful lens on human ecology and resilience owing to the strong and impulsive forcing that large eruptions may cause.

1.2. The Volcano-Climate-Society Nexus

Stimulated by the bicentenary of the 1815 eruption of Tambora, Indonesia (Brönnimann et al. 2015, Luterbacher & Pfister 2015, Oppenheimer 2015, Brönnimann & Krämer 2016), the past decade has seen a surge in volcano-climate-society (VCS) research, including gatherings of the Volcanic Impacts on Climate and Society working group of the Past Global Changes network

(Sigl et al. 2023). While results have stimulated fresh insights into regional and world history (Campbell 2016, Harper 2017, Parker 2013), they also have foregrounded the challenges of integrating science and history. Likewise, the complexity of both human agency and the climate system ensures that it is difficult to pin down any role of volcanism in far-field societal impacts.

Drawing on expertise spanning the natural and social sciences and humanities (**Supplemental Figure 1**), here we take stock of where we are in understanding the role of volcanism in global affairs. We begin by reviewing ice core records of global volcanism alongside paleoclimate proxy reconstructions, with a focus on the preindustrial Common Era (1–1900 CE) for which volcanic stratospheric sulfur injection (VSSI) and radiative forcing timeseries [*eVolv2k* (Toohey & Sigl 2017)] and tree-ring chronologies are most reliable (Büntgen et al. 2020, 2021; Esper et al. 2024). We compare VSSI estimates against NH extratropical summer temperatures, quantify temperature responses for spatiotemporal subsets of volcanic eruptions, and explore temperature variations at multi-decadal timescales that may reflect the cumulative forcing effects of clustered, sulfur-rich eruptions. We conclude with an interrogation of a large body of VCS work published over the past century, aimed at characterizing the arguments for (and against) connecting volcanic forcing with societal change.

2. ICE CORE EVIDENCE FOR VOLCANIC ERUPTIONS

Several databases of global volcanism, sulfur yields, and forcing estimates exist. We focus here on the *eVolv2k_v3* dataset (Toohey & Sigl 2017) as it provides the most robust estimates of VSSI based on multiple Antarctic and Arctic ice core glaciochemical timeseries (Sigl et al. 2022). Our reassessment indicates 38 volcanic eruptions between 1 and 1900 CE with estimated VSSI equal to or exceeding 6 Tg [1 Tg is 10^{12} g and equivalent to 1 MMT (**Figure 1*a***)]. This threshold is comparable with the sulfur yield of the 1991 eruption of Pinatubo (Minnis et al. 1993, Dhomse et al. 2020), and we take it as a suitable benchmark to identify eruptions likely to trigger a climate response detectable against internal variability. For simplicity, we overlook the significant uncertainties in VSSI estimates, which reflect, among other factors, weak constraints on source latitude and eruption season. From the *HolVol* database, which is derived from a smaller set of bipolar ice core records (Sigl et al. 2022), eruptions of Agung (Indonesia) in 1963–1964 and Pinatubo (Philippines) in 1991 also meet the 6-Tg stratospheric sulfur threshold, and the Katmai 1912 CE eruption comes close. However, alternative estimates of sulfur yields of these twentieth-century eruptions suggest only Pinatubo yielded in excess of 6 Tg of sulfur to the stratosphere (Stothers 1996a, Dhomse et al. 2020). These discrepancies highlight uncertainties in all estimates of volcanic sulfur yields to the stratosphere, whether by direct or indirect observations, petrologic methods, or extrapolation of ice core signals (Scaillet & Oppenheimer 2024).

The largest estimated VSSI in the period 1–1900 CE is 59 Tg for 1258 CE, followed by 33 and 32 Tg for 1458 and 540 CE, respectively. Consideration of all 38 eruptions passing the teragram threshold reveals a mean/median return interval of 50/45 years between an unidentified eruption in 87 CE and the eruption of Krakatau in 1883 CE. The longest interlude in which no VSSI estimate reaches or surpasses the threshold is around 130 years, between two unknown eruptions in 304 and 433 CE, and notably coinciding with the economic and political zenith of the Roman Empire (Harper 2017). The most intense temporal cluster, consisting of at least five large eruptions—namely 1783–1784 (Laki, Iceland), 1809 (unidentified), 1815 (Tambora, Indonesia), 1831 (Zavaritskii, Kuril Islands), and 1835 CE (Cosiguina, Nicaragua)—not only marks the culmination of the Little Ice Age (LIA) (Matthes 1939) but also was likely one of the coldest phases of the entire Holocene (Wanner et al. 2008, Essell et al. 2023).

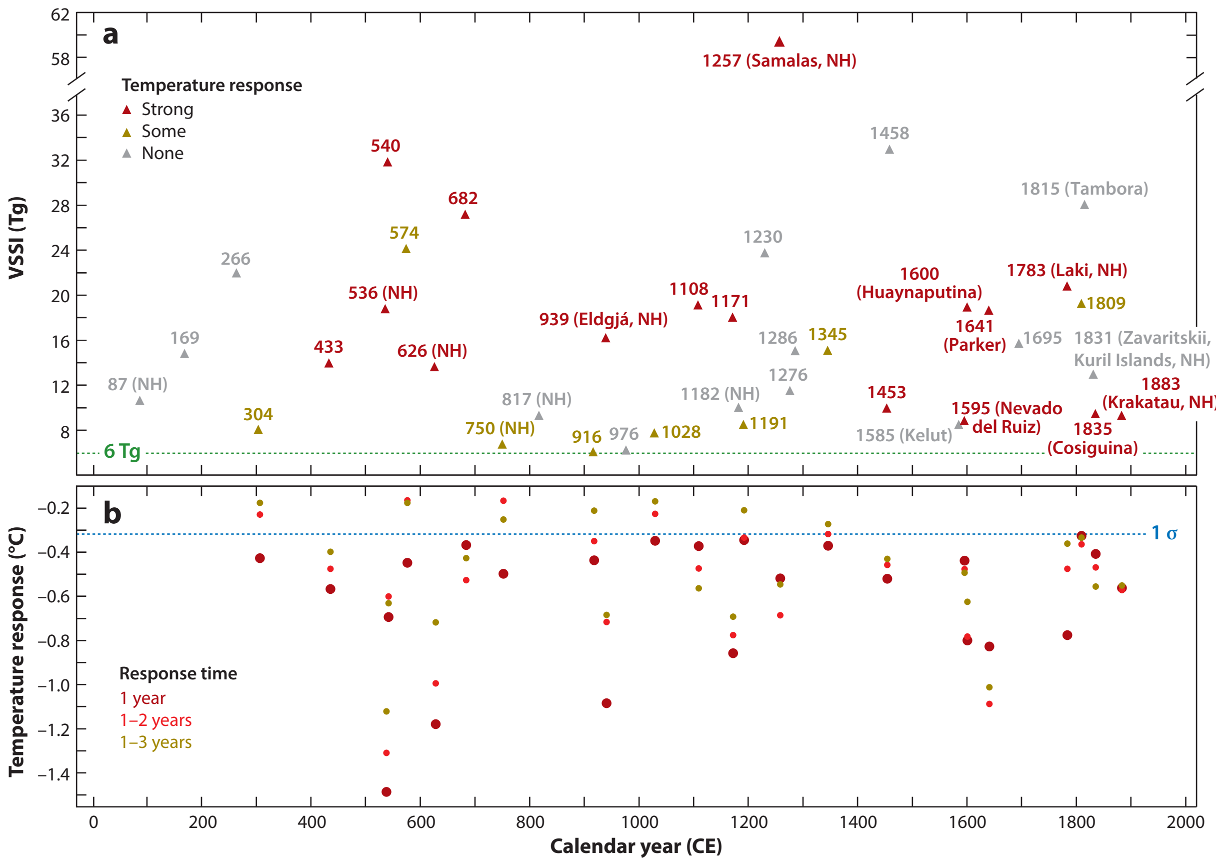


Figure 1

Volcanic eruptions and temperature responses. (*a*) Temporal distribution of volcanic stratospheric sulfur injection (VSSI) derived from analyses of ice cores from Antarctica and Greenland (*eVolv2k_v3*; Toohey & Sigl 2017) expressed in teragrams (1 Tg = 10^{12} g). Colored triangles refer to 38 eruptions with VSSI ≥ 6 Tg (*dashed green line*), comparable with the yield of the 1991 Pinatubo eruption (Dhomse et al. 2020). (*b*) Short-term response of Northern Hemisphere (NH) extratropical summer temperatures calculated for one, two, and three years following each of the 38 sulfur-rich eruptions shown in panel *a*. The dashed blue line indicates one standard deviation from the reconstructed Common Era mean summer temperature.

The 38 eruptions represent just 18% of the 210 records of preindustrial Common Era eruptions in the *eVolv2k_v3* database (**Supplemental Figure 2**). Most eruptions are unidentified, and 9 are located in the NH extratropics A mystery eruption in 1809 (Timmreck et al. 2021, Leland et al. 2023) and the case of 1831 (Garrison et al. 2018, Plunkett et al. 2023, Hutchinson et al. 2025) reinforce how little is known about some of the largest volcanic eruptions of the past. The search for source volcanoes is challenged by the scant historical knowledge of global volcanism (Siebert et al. 2015), leaving geochemical fingerprinting of tephra glass shards as a primary means for linking a volcanic layer in a polar ice core to the volcano responsible (Plunkett et al. 2022, 2023). While powerful, this latter method remains limited by the scarcity within ice cores of tephra glass shards of sufficient size for analysis, the nonunique geochemical signatures that are often encountered, the occurrence of multiple geochemical populations in the same ice horizon (Hutchison et al. 2024), and the fragmentary nature of the global tephra database (i.e., the characterization of potential sources).

The eruptions of Eldgjá (Iceland) in 939–940 (Oppenheimer et al. 2018) and of Samalas (Indonesia) in 1257 CE (Lavigne et al. 2013, Büntgen et al. 2022b) are among the earliest dated VCS cases reliably associated with an identified volcano. Further dated eruptions linked to prominent ice core sulfur anomalies include 1585 (Kelut, Indonesia), 1595 (Nevado del Ruiz, Colombia), 1600 (Huaynaputina, Peru), 1641 (Parker, Philippines, and Koma-ga-take, Japan), 1783–1784 (Laki), 1815 (Tambora), 1831 (Zavaritskii), 1835 (Cosiguina), and 1883 (Krakatau). However, the possibility remains that some of these, along with other historically attested eruptions, are only partly responsible, or not responsible at all, for the large sulfur anomalies in ice core records to which they have been attributed.

3. TEMPERATURE RESPONSES TO VOLCANIC ERUPTIONS

Comparison of the ice core record against reconstructed temperatures shows that only 24 out of the 38 VSSI $\geq$ 6 Tg eruptions coincide with summer cooling amounting to at least −0.33°C, i.e., exceeding one standard deviation of Common Era variability (**Figure 1*b***; **Supplemental Figure 3**). Of these, 17 evidently caused distinct cooling in the first, the first two, and the first three summers. The strongest response patterns of −1.49, −1.31, and −1.12°C followed the unidentified eruption in circa 536 CE at the onset of the Late Antique Little Ice Age (LALIA), the marked cold phase from 536 to circa 660 CE (Büntgen et al. 2016, van Dijk et al. 2022). Severe summer cooling can be further associated with eruptions in circa 626 (unknown), 939–940 (Eldgjá), 1171 (unknown), 1600 (Huaynaputina), and 1641 (Parker and/or Koma-ga-take). Interestingly, the Tambora eruption in April 1815, widely associated with the so-called year without a summer in 1816 across large parts of central Europe and North America (Oppenheimer 2003, Luterbacher & Pfister 2015), did not cause substantial summer cooling when averaged over the NH extratropics (**Figure 1*b***), though we note it is among a handful of special cases of eruption doublets (536/540, 1453/1458, and 1809/1815 CE). Moreover, there are only five sulfur-rich eruptions that can be attributed to synchronous growth depressions in all seven of the most temperature-sensitive regional tree-ring chronologies from North America and Eurasia (**Supplemental Figure 4**): 536 (unknown), 1453 (unknown), 1641 (Parker and/or Koma-ga-take), 1783–1784 (Laki), and 1883 (Krakatau).

We applied superposed epoch analysis (Chree 1913) to stack the signal of the NH extratropical summer temperature responses to sulfur-rich eruptions and reduced the background noise of internal variability (**Figure 2**). Timeseries were therefore aligned by selected event years (i.e., the first summer temperature drop associated with volcanic forcing). Mean/median cooling related to all 38 eruptions with VSSI $\geq$ 6 Tg is −0.72/−0.62°C (**Figure 2*a***), and the negative response accumulates to −0.79/−0.73 and −0.85/−0.75°C for the subsets of 24 and 17 eruptions with highest VSSI. The coldest summers were aligned with the year of peak volcanic forcing. A closer look into the behavior of the individual temperature reconstructions reveals that in each of the 20 years before and after peak forcing (i.e., year zero in the superposed epoch analysis), about half of the timeseries exhibit positive and negative deviations from the long-term mean (**Supplemental Figure 5**). However, more than 93% of the timeseries, that is 142 out of 152, are likely synchronized by eruptions and therefore contribute to the observed rapid cooling patterns.

Intriguingly, it takes more than two decades for temperatures to reach pre-eruption levels. While this slow recovery rate might partly reflect biological memory of tree growth (Esper et al. 2015) or an active adaptation strategy of trees to prevent damage from abiotic stressors (Gessler et al. 2020, Martinez del Castillo et al. 2024), a direct temperature signal likely accounts for most of the observed anomalies because the selected large-scale reconstructions perform robustly during

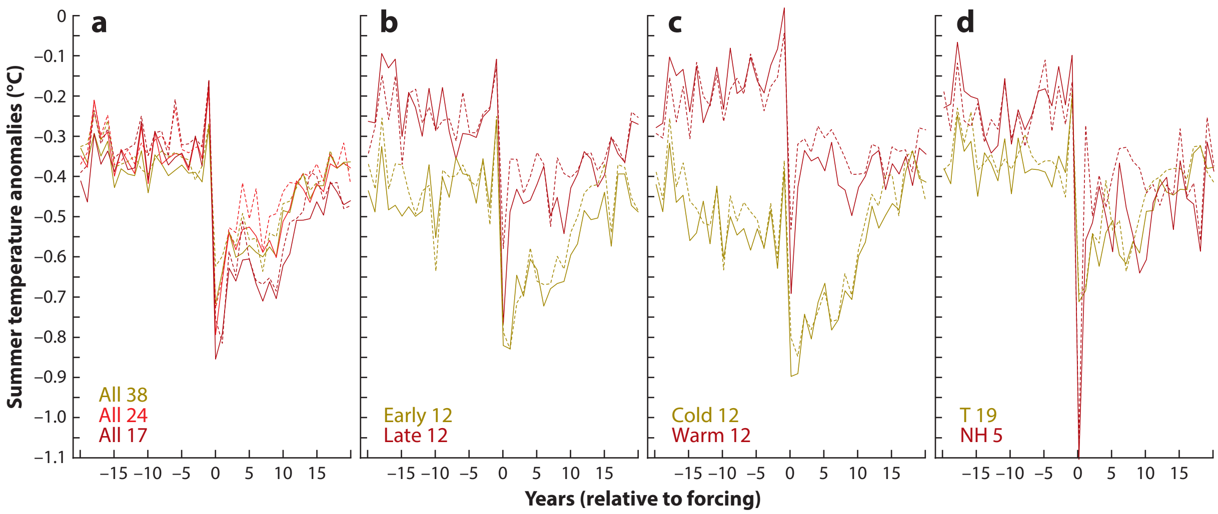


Figure 2

Volcanically forced abrupt summer cooling. (*a*) Superposed epoch analysis (Chree 1913) of the mean (median; *dashed lines*) extratropical summer temperature response of four tree-ring-based Northern Hemisphere (NH) reconstructions to 38 eruptions with volcanic stratospheric sulfur injection (VSSI) ≥ 6 Tg (*yellow*), as well as using subsets of 24 and 17 eruptions (*red* and *dark red*, respectively) with the highest VSSI. The following graphics are as in panel *a* but dividing the 24 eruptions into (*b*) 12 cases before and 12 after 1150 CE, (*c*) 12 that occurred during relatively warm and 12 during relatively cold periods, and (*d*) 5 and 19 eruptions that occurred in the NH and tropics (T), respectively.

the instrumental calibration period (Büntgen et al. 2020, 2021; Esper et al. 2024). Further to their climatological interpretation, the delayed recovery hints at a hitherto neglected aspect of the functioning and productivity of forest ecosystems. Research on global carbon cycle dynamics might reveal if terrestrial carbon stocks shift from sinks to sources after large volcanic eruptions (Krakauer & Randerson 2003).

Dividing the 24 eruptions that most likely induced rapid summer cooling into 12 cases before and 12 after 1150 CE reveals mean/median temperature reductions of −0.77/−0.58 and −0.82/−0.78°C, respectively (**Figure 2*b***). While the rate of cooling is comparable between the early and late periods, pre-eruption summers during the first half of the CE were substantially colder than those of the second millennium CE. Dividing the eruptions into 12 that occurred during relatively warm and 12 during relatively cold periods reveals mean/median temperature reductions of −0.69/−0.53 and −0.90/−0.80°C, respectively (**Figure 2*c***). Although the absolute cooling is greater during cold periods, the first-year drop is larger during warm periods. More striking is the slower recovery when volcanoes erupt during colder phases, such as the LALIA, or the LIA between medieval and recent warming episodes, possibly due to stronger ocean–sea ice feedback (van Dijk et al. 2024).

As predicted (Toohey et al. 2019), the largest mean/median NH summer temperature reduction of −1.1°C is associated with the 5 volcanoes situated in the NH extratropics (**Figure 2*d***), compared with the 19 putative tropical eruptions whose corresponding boreal mean/median summer temperature anomalies amount to −0.71/−0.69°C. The extent of volcanically induced summer cooling in the tropics at lower latitudes remains largely unknown owing to the scarcity of high-resolution, multi-millennial temperature records and the complexity of internal climate dynamics (Cobb et al. 2003, Wilson et al. 2010, Emile-Geay et al. 2013, Timmermann et al. 2018, Henley et al. 2024).

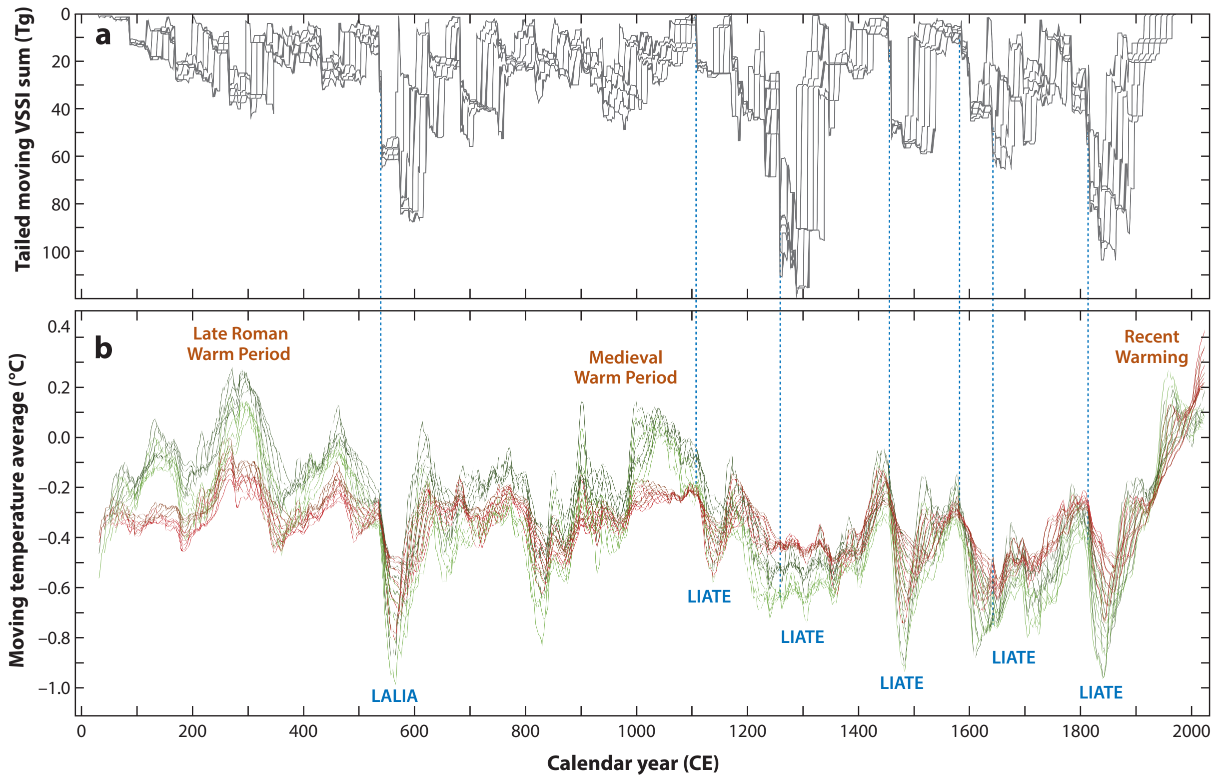


Figure 3

Volcanically forced long-term temperature changes. (*a*) Cumulative volcanic stratospheric sulfur injection (VSSI) calculated over 30-, 40-, 50-, 60-, 70-, and 80-year one-tailed windows (for raw data, see **Supplemental Figure 1**). (*b*) Average summer temperature anomalies calculated over 30-, 40-, 50-, 60-, 70-, and 80-year one-tailed windows (for raw data, see **Supplemental Figure 2**). Dashed vertical lines show volcanically forced tipping points in Northern Hemisphere (NH) extratropical summer temperatures, including the Late Antique Little Ice Age (LALIA) (Büntgen et al. 2016) and five Little Ice Age Type Events (LIATE) (Wanner et al. 2000).

Further to the abrupt cold spells following sulfur-rich eruptions (**Figure 2**), we find evidence for cumulative volcanic forcing of long-term temperature changes (**Figure 3**). Tipping points in Earth's climate system follow clusters of eruptions, and the one-tailed, smoothed volcanic forcing and summer temperature timeseries exhibit a grand average correlation of −0.5, with a range of −0.4 to −0.6 for the individual records ($p < 0.001$; 81–1920 CE). The LALIA (Büntgen et al. 2016) and the various Little Ice Age Type Events (LIATE) (Wanner et al. 2000) follow clusters of eruptions. Further, the late Roman, medieval, and recent warm periods all coincide with prolonged intervals of comparatively weak volcanic forcing (Büntgen et al. 2020). Volcanism must therefore be considered a key driver of multi-decadal and even centennial-scale climate variability in addition to interannual change, at least for summer temperatures in the NH extratropics (**Figure 3**), with expected implications for teleconnection patterns. The paucity of high-resolution, high-quality proxy data for the Southern Hemisphere precludes a global assessment.

Because VSSI is only one of many factors that dictate radiative forcing, we do not expect a simple relationship between VSSI and temperature anomalies (Timmreck 2012; Marshall et al. 2021, 2022). Despite having the largest estimated VSSI of 59 Tg, the NH extratropical summer temperature response associated with the 1257 CE Samalas eruption appears modest (**Figure 4*a***).

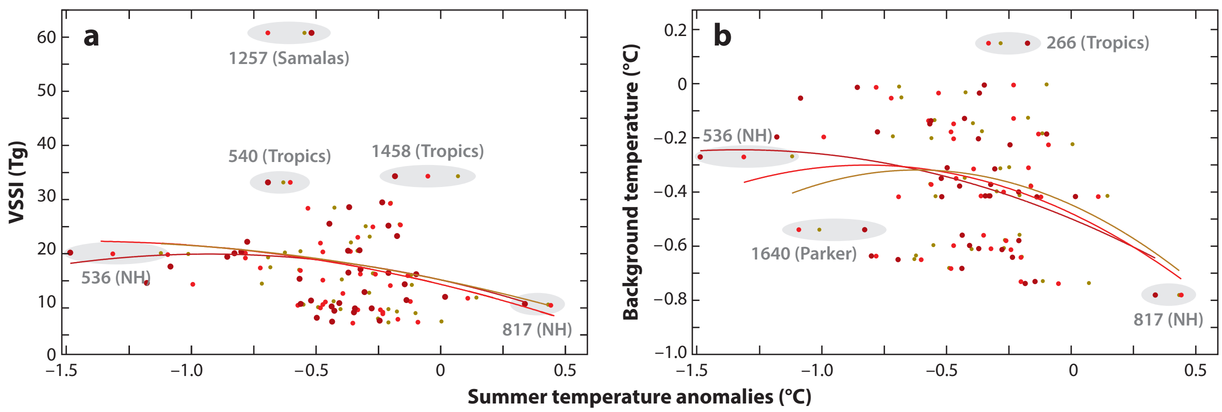


Figure 4

Volcanic forcing and temperature responses. (*a*) Relationship between the amount of volcanic stratospheric sulfur injection (for VSSI ≥ 6 Tg eruptions) and Northern Hemisphere (NH) extratropical summer temperature responses during the first (*dark red*), two (*red*), and three (*orange*) years after eruptions (see **Figure 1**). Curves are second-order polynomial trends, and gray shadings depict example eruptions. (*b*) As in panel *a* but using background temperatures instead.

Likewise, two as-yet-unidentified tropical eruptions in 540 [possibly Ilopango in El Salvador (Dull et al. 2019)] and 1458 CE (possibly Kuwae in Vanuatu) have substantial VSSI of 32 and 33 Tg, respectively, but comparatively muted temperature signals. On the other hand, the mystery eruption in circa 536 CE, with a VSSI of ∼19 Tg, contributed to the coldest summer of the past 2,000 years (Büntgen et al. 2020, 2021; Esper et al. 2024). The nonlinear relationship between VSSI and subsequent summer cooling prolongs the debate around proxy-model discrepancies (Anchukaitis et al. 2012, Mann et al. 2012, Esper et al. 2013). Moreover, there seems to be no simple effect of background climate variability on the forcing intensity of volcanism (**Figure 4*b***). The eruptions in circa 817 (9.3 Tg, NH midlatitudes) and 266 CE (22 Tg, tropical), for instance, were preceded by the coldest and warmest decades (relative to all 38 eruptions), but neither had an extreme impact on summer temperatures.

4. VOLCANOES, CLIMATE, AND SOCIETY

Our literature review identified 103 scholarly publications (**Table 1**; **Supplemental Inventory**) that discuss direct and indirect impacts of volcanically forced climate variability on human society (**Figures 5**, **6**). While it is not exhaustive, we are confident that our collection captures the depth and breadth of argumentation for VCS linkages (**Supplemental Figure 6**). Included studies had to at least partly concern the potential connections between volcanically influenced climate change and human experience—this results in the inclusion of works that are more descriptive and derivative, in addition to more investigative studies. We began by gathering works known among the authors and searching online bibliographic resources for further germane studies. We recursively searched reference lists of selected works for deeper inroads into the literature. In line with our interrogation of ice core and tree-ring data, we restricted our literature review to the Common Era, thereby excluding a few examples, such as the eruption of Okmok (Alaska) in 43 BCE and its possible climatological and societal responses (McConnell et al. 2020), as well as the studies of suppressed Nile summer flooding linked to volcanic forcing and associated with unrest and conflict in ancient Egypt (Manning et al. 2017, Singh et al. 2023). We also neglected synthetic works on climate and history, such as books by Ellsworth Huntington (1876–1947), Hubert Lamb (1913–1997), Emmanuel Le Roy Ladurie (1929–2023), and Christian Pfister (1944–). More

Table 1 Scholarly publications that discuss direct and indirect impacts of volcanically forced climate variability on human society (Supplemental Inventory)

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Imamura 1947	626, 1815, 1883, and others	Unknown, Tambora, Krakatau	Japan	Warm winter; cool summer, reduced radiation, lower air temperature; cold spring, wheat reduced, famine; cool and rainy summer, harvest failure, famine, storm, flood
Mussey 1949	1815	Tambora	North America	Frost, cold, crop failure, migration, theodicy
Arakawa 1957	1782–1787, 1833–1839, 1866–1869	Asama, Laki	Japan	Excessive cold and rain in summer linked to poor rice harvests and potentially to volcanic dust in the atmosphere
Post 1977	1815	Tambora	North America, Europe	Harvest failure, food crisis, riots, political repression, mortality, migration
Pfister 1978	1750–1800	Laki	Switzerland	Severe winter; wet, cold summer; poor harvest; famine; population decline
Stommel & Stommel 1979	1815	Tambora	New England, Canada, and western Europe	Cold, frosts, crop failures, severe summer weather, wind, soaring prices of grain, food shortage, famine, migration, morality, riots, disease (cholera)
Stommel & Stommel 1983	1815	Tambora	North America, Europe	Food crisis, famine, migration, disease
Stothers 1984a	536	Unknown	Middle East	Severe winter, poor harvests, fruits killed
Stothers 1984b	1815	Tambora	North America and Europe	Cold summer, crops failed, famine, disease, social distress
Rampino et al. 1988	536, 1815	Unknown, Tambora	Western Europe	Cold, crop failures, food shortages, severe winter, chilling winds and frost, famine
Harington 1992	1815	Tambora	Global	Edited volume mostly on meteorological phenomena but with some references to food security
de Jong Boers 1995	1815	Tambora	North America, Europe, India	Cold summers, food shortages, famine, cholera in India
Stothers 1996b	1783/1784	Laki	Europe	Summer heat, severe winter, crop losses, societal turmoil
Stothers 1998	934/939	Eldgjá	Europe and Middle East	Severe winter, famine, pestilence, floods, snow, wet weather, disease, cattle die-off, pandemic
Jacoby et al. 1999	1783/1784	Laki	Northwest Alaska	Population decrease/migration due to famine; abandonment; severely cold summer; starvation; mortality; strong northerlies; rivers and lakes frozen over; frozen ground preventing hunting, fishing, and collection of plant foods; herbivore game also declined
Stothers 1999	536, 626, 934, 1258, 1783, 1815	Unknowns, Eldgjá, El Chichon?, Laki, Tambora	Europe and Middle East	Severe winter; poor harvest; famine; pandemic; hungry rats driven from fields to grain piles, bringing contact with people
Stothers 2000	1258	Samalas	Europe and Middle East	Severe winter, famine, livestock disease, pestilence and religious manifestations, e.g., flagellants

(*Continued*)

Table 1 (*Continued*)

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Atwell 2001	1225–1233, 1256–1262, 1444–1465, 1584–1610, 1636–1644	Unknown	Global	Cold and wet summers in western Europe and North America; low temperatures in northern Japan linked to famine; windstorms; excessive rain damaging or spoiling crops (rot); drought; low temperatures in summer resulting in famine and food shortages; floods; crop pests (locusts); severe winters; heavy snow; in western and central Europe, poor harvests attributed to "prolonged cold spells in spring and cool and wet summers, especially during the harvest season, when such conditions may cause the grains to rot in the fields"; impoverishment; starvation; water shortages; plague; disease epidemic; peasant revolts; uprisings
Grattan et al. 2003	1783/1784	Laki	Europe	Environmental damage, alarm and panic, heat, thunderstorms, crop damage, mortality
Oppenheimer 2003	1815	Tambora	North America and Europe	Cold weather, short growing season, killing frosts, snow, high rainfall, crop failures, livestock mortality, famine, emigration and epidemic typhus, civil unrest, riots
Arjava 2005	536	Unknown	Mediterranean, Egypt, Eurasia	Cooling, famine, plague
Witham & Oppenheimer 2004	1783/1784	Laki	England	Severe winter; increase in infection rates of communicable diseases, pneumonia, etc.
Fei & Zhou 2006	934/939	Eldgjá	China	Cold, summer snow, severe winter, drought and locusts 939–942 followed by famine, starvation, migration, demise of Later Jin Empire
Fei et al. 2007	626	Unknown	China and Mongolia	Unseasonal snow, frost, sheep and horse mortality, famine and human mortality, collapse of Eastern Turk Empire, early frosts, summer snow
McCormick et al. 2007	757, 827, 859, 876, 939	Unknown, Eldgjá	Central and western Europe	Severe winter; loss of livestock; famine; mortality; environmental, societal, political, and economic crisis
Shen et al. 2007	1586–1589, 1638–1641, 1965–1966	Kelut, Parker, Agung	China	Eastern China exceptional droughts, famine, peasant rebellion, collapse of Ming Dynasty, weak summer monsoon, shift of subtropical high to south
Parker 2008	Seventeenth century CE	Unspecified	Global	Cooling, agricultural productivity, disease
Fei & Zhou 2009	1600	Huaynaputina	China	Wind and frost ruining crops, poor harvests, famine, cannibalism
Woods 2010	536	Unknown	British Isles	Call for repentance, religious reaction

(*Continued*)

Table 1 (*Continued*)

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Oppenheimer 2011	Several	several	Global	Harvest failure, food crisis, riots, political repression, mortality, migration
Cao et al. 2012	1815	Tambora	China	Cold winds, severe frost, cold, wet, summer snow and frost, failed crops, Yunnan famine
Gräslund & Price 2012	536	Unknown	Scandinavia	Harvest failures, myth, cultural memory, population decline, abandonment, religious transformations, social unrest, agrarian decline, poetry, symbolism
Arrhenius 2013	536	Unknown	Sweden	Cultural memory, archeological perspectives, change in ritual practices, food shortage, abandonment
Klingaman & Klingaman 2013	1815	Tambora	Global	Food crisis, hunger, migration
Bondeson & Bondesson 2014	536	Unknown	Scandinavia	Extreme weather, ergotism, mortality, migration, religious reactions
Tvauri 2014	536	Unknown	Estonia, Baltics	Food crisis, famine, disruption of trade networks, power relations, settlement structures, world views, material culture, migration, development of agriculture
Wood 2014	1815	Tambora	Ireland, Europe, India, China	Harvest failure, famine, epidemic, economic depression, literary response
Luterbacher & Pfister 2015	1815	Tambora	Europe	Low pressure systems, persistent cold, heavy rainfall, storms shifted southward, cold and wet attributed to weakening of Asian and African summer monsoons, biomass production and water availability, crops rotted, poor quality and reduced yields, grain process soared, undernourishment, lowered fertility, famine, charity, emigration
Newfield 2015	940	Eldgjá	Europe	Livestock mortality from cattle plague—movement of live animals with human migrants during famine periods diffused plague
Oppenheimer 2015	1815	Tambora	North America and Europe	Cold summer, short growing season, crop failures, high grain prices, epidemic, famine, social unrest, upsurge in conservatism and repression
Price & Gräslund 2015	536	Unknown	Scandinavia	Food crisis, migration and abandonment, sociocultural impact
Puma et al. 2015	1226, 1231, 1257, 1314, 1452, 1600, 1783, 1815	Reykjanes, Zao, Samalas, Tarawera, Kuwae, Huaynaputina, Laki, Tambora	Global	Harvest failure, food shortage, famine

(*Continued*)

Table 1 (*Continued*)

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Brázdil et al. 2016	1815	Tambora	Czech Lands, central Europe	Historical climatology and hydrology; climate variability and climate change; hydrometeorological extremes and their impacts; statistical analysis and homogenization of instrumental meteorological series; synthesis of some historical data—mentions crop pests (caterpillars, rye rust), flooding, and agricultural damage during wet, cold summer in 1815
Breeze 2016	536	Unknown	Scotland	Cold, famine, crisis, warfare
Brönnimann & Krämer 2016	1815	Tambora	Central Europe, Switzerland, China, India	Reduced monsoonal rains, drought, cooling, poor harvests, famine, crop pests, rot, transport disruption, pandemic disease, malnutrition, inflation, rationing, migration, civil unrest, differential impacts, adaptations, mortality, reduced birthrate, riots, innovation, modernization, political movement, literature, culture, knowledge
Büntgen et al. 2016	536	Unknown	Eurasia	Crop failure, famine and plague, political and societal turmoil, Justinianic plague, decline of eastern Roman Empire, shorter growing seasons and malnutrition linked to large-scale pastoral movements toward China
Camenisch et al. 2016	1430	Unknown	Northwest and central Europe	Cold and wet conditions in spring, summer, and autumn impact grain, vine, diary, and forage; exceptionally cold and/or long winter reduces ecosystem productivity (cold injury, alterations of the energy and water balance, and advanced/retarded phenology); late frosts can devastate grain production; frozen rivers and lakes disrupt transport and food processing
Fei & Zhou 2016	934/939	Eldgjá	China	Drought and locusts 939–942 CE followed by famine, starvation, migration, demise of Later Jin Empire—volcanic forcing of El Niño, drought in Yellow River basin, decline of Later Jin, invasion by Khitan
Fei et al. 2016	1600/1601	Huaynaputina	China and Korea	Cold summer, hot autumn 1601; severe frost; drought; epidemic disease in China, Korea
Toohey et al. 2016	536, 540	Unknown, Ilopango?	Europe and Scandinavia	Summer cooling, reduced growing degree days, food shortages, famine, collapse of society, abandonment, sacrificial practices
Alexander et al. 2017	1815	Tambora	New England, Gulf of Maine	Crop failures intensified fishing pressure, declines in some species resulting from cooling and changes on spawning and feeding forced focus on mackerel—resource switching
Behringer 2017	1815	Tambora	Germany, Europe	Food crisis, hunger, emigration, unrest, sociopolitical and religious transformations

(*Continued*)

Table 1 ***(Continued)***

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Brázdil et al. 2017	1783/1784, 1815	Laki, Tambora	Czech Lands	Meteorological observations of thunderstorms and lightning hazard after Laki; flooding impacts on haymaking and harvest, rust; restructuring of trade—imports from Silesia, flour made from acorns, beggars after Tambora
Büntgen et al. 2017	822	Katla	Europe	Subsistence and demographic crises affecting parts of Europe; excessive rain, flooding, unusual humidity, a cool growing season, poor harvests, animal plague in 820 CE; severe winters, food shortages in 823 CE; drought, hailstorms, damaged crops, disease, frozen lakes and rivers, harvest failure, food shortage, epidemic disease, exceptionally low temperatures in China between 821 and 826; freezing events, substantial snowfalls, unusual hailstorms, devastating crop failures
Campbell 2017	1257	Samalas	England	Starvation and famine-related diseases; food shortages; flooding; harvest failure; grain price increases; wind, frost, snow killed sheep; heavy rain damaged crops; destitution; relief supplies from Germany; migration to London where many died; mass graves; eruption compounded effects of back-to-back ruined harvests in 1256 and 1257
Di Cosmo et al. 2017	626	Unknown	China and Mongolia	Summer cooling, snow and severe frosts, reduced vegetation growth and livestock mortality, famine, vulnerability of nomadic populations, economic emergency triggers political crisis, snow cover prevents grazing, animals suffer hypothermia and starvation, drought followed by frost and snowfalls, impacts on malnourished livestock, early frosts damaged crops, drought, locusts, rebellion, migration
Flückiger et al. 2017	1815	Tambora	Switzerland	Cloud cover influences temperature, waterlogging, phenology, crop yield; crop development rate driven by temperature; yields influenced by intercepted radiation—low temperature and low solar irradiance limited growth and yields; model does not account for waterlogging, fungal disease, etc.; harvest failure; food shortage; subsistence crisis
Gao et al. 2017	1815	Tambora	China	Cold, drought, snow, famine, mortality, plague, cold the overriding factor

(*Continued*)

Table 1 (*Continued*)

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Glaser et al. 2017	1815	Tambora	Southwest Germany	Interaction between weather and phenology; severe winters; vernalization; sowing dates; food security; prices; emigration; spring cold; very cold and wet summer; crop failures; granaries depleted after Napoleonic Wars; large areas uncultivated; forage production failed due to cold and wet, leading to animal diseases; livestock sold off before winter; migration
Guillet et al. 2017	1257	Samalas	England, Europe, and Japan	Cooling; delayed harvests; in Japan, wet, cold summer, heavy rain, and strong winds, damaging rice fields; food shortages; subsistence crisis; high prices in London; Shoga famine in Japan; volcanic forcing aggravated rather than triggered subsistence crisis
Huhtamaa & Helama 2017	1600/1601	Huaynaputina	Finland	Summer cooling, agricultural crisis, impoverishment, hunger, reduced ability to pay taxes, famine and mortality, poor harvest can reduce seed bank for next year's sowing, tithes used as a proxy for grain production, begging, eating bark, vagrancy, food shortage and malnourishment, mortality, desertion of farms
Damodaran et al. 2018	1783/1784	Laki	India, Australia, Japan, Northeast Africa	Cool summer weather and harvest failures (clouds and rain), Chalisa and Tenmei famines, migration, pandemics; Nile—low flow, famine and plague, violence
Harper & McCormick 2018	266, 536	Unknown	Mediterranean	Climate extremes, stable/favorable vs. unfavorable climate, agriculture, food production
Helama et al. 2018	536, 540	Unknown, Ilopango?	Mediterranean	Irradiance decrease and cooling; crop failures, demographic catastrophe, disruption of settlement, population displacement; in Mediterranean-type environments, solar radiation dictates growing season length and hence crop production; exceptionally cool weather of 541 CE beneficial to rat survival and flea reproduction, plague; malnutrition and vitamin D deficiency
Moreland 2018	536	Unknown	Europe, Mediterranean, Sweden	Critical review of 536 case from archeological perspective, with focus on Sweden
Newfield 2018b	536	Unknown	Mediterranean, Near East, Japan, China, Korea	Cooling, grain shortage, disease, temperature drop, food security, shorter growing season, limiting arable land, harvest failure, dearth, malnutrition, abandonment, ergotism, plague pandemic drought, migration, spread of pathogen, cold promoted pneumonic plague, accelerated pace of agricultural and demographic transformation

(*Continued*)

Table 1 ***(Continued)***

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Newfield 2018a	536/537	Unknown	Europe	Climate events trigger subsistence crises, resulting in malnutrition and compromised immune function, as well as migration for food and work; migrations with animals included fostered wider transmission of disease within or between humans and domesticates; overcrowding in cities favored spread of human pathogens as well as water-borne diseases associated with poor sanitation; climate change disrupts plague reservoir, allowing bacterium to spread beyond usual range; food shortages provoke malnutrition, increasing susceptibility to infection and provoking migration, facilitating spread of plague; food shortages also trigger hoarding, which can increase commensal rat populations; changing temperature and precipitation may cause decline in rodents and fleas looking for alternative hosts
Oppenheimer et al. 2018	939	Eldgjá	Eurasia, Middle East	Dearth, harvest failures, food crisis, severe winter, food shortages, subsistence crisis, flooding, locusts, cattle plague, mortality
Pfister & White 2018	1815	Tambora	Global	Cooling, crisis, disease
Behringer 2019	1815	Tambora	Global	Failed crops, hunger, criminality, unrest, conflict, migration, emergence of meteorology, soup kitchens, literature, paintings
Hubbard 2019	1815	Tambora	Northern Europe	Signatures of year without a summer in European art
Maraschi 2019	536	Unknown	Scandinavia	Cold, wet summers, myth, cultural memory, poetry
Marshall et al. 2019	1815	Tambora	Europe	Literature, dismisses easy links between Tambora and Frankenstein
Pinke et al. 2019	1815	Tambora	Ganges-Brahmaputra Delta region of modern India and Bangladesh	El Niño, warming sea surface temperature, nutrient cycling, plankton blooms that host cholera bacterium, transmission to coastal communities, cholera epidemic
Büntgen et al. 2020	Common Era	Multiple	Northern Hemisphere	Multi-decadal- to multi-centennial-scale impacts—summer warmth promotes changes in sea ice extent and ocean current dynamics, societal prosperity, and political stability in parts of Europe and China (Norse expansion, voyages of discovery); volcanic forcing leading to abrupt summer cooling, cooler summers; temperature instability coincides with conflict and economic decline; demographic contraction, political turmoil, migration, disease, cultural and religious change in Eurasia

(*Continued*)

Table 1 ***(Continued)***

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Campbell & Ludlow 2020	1182, 1257	Unknown, Samalas	Ireland	Impact of extreme weather (particularly in back-to-back years) on agricultural production, especially arable but also pastoral output (especially when hard winters depressed grass growth); starvation; migration; conflict; disease spread; destitution; theft; rustling; plunder
D'Arrigo et al. 2020	1695	Unknown	Scotland	Extreme cold; late harvests; crop failures; short growing season impacting plant health and growth in spring and summer; cold weather; frosts; hunger and famine in 1696; frost and snow damaged crops; severe and long winter delayed sowing; heat stress and damage to crops; drought ruined pasture and hay crop; excessive rain rotted hay; storms, rain, and cold winds; back-to-back harvest failures; population decline; emigration
Guillet et al. 2020	1108/1109/1110	Unknown	Western Europe	Wet summer and autumn, reduced harvests, excessive rainfall drowned crops, food prices increased, grain hoarding and speculation, famine in some areas especially France, subsistence crisis
Wood 2020	1815	Tambora	Europe	Weather extremes, hunger crisis, literary impact
Corner 2021	1815	Tambora	Europe	Reduction in large-scale symphonic works, innovation in songwriting
Di Cosmo et al. 2021	1257	Samalas	Near East	Colder and wetter climate and feedbacks between carrying capacity for grazing animals, Mongol expansion and warfare
Gao et al. 2021b	1783/1784	Laki	China	Severe drought promoting locust habitats, poor harvests, famine and pestilence, begging, El Niño–Southern Oscillation interactions
Gao et al. 2021a	Multiple	Multiple	China	Dynastic collapse; cold and drought; mild winters and survival of agricultural pests; warfare; food security; severe cold might reduce pests, benefiting yields; mass migrations; epidemic/epizootic diseases; pest outbreaks (bacterial, fungal, insect, rodent); feedbacks with taxation regimes; conflict; volcanically induced drought or cold has greater impact during periods of demographic pressure or when superimposed on longer-term drying or cooling
Gjerpe 2021	536	Unknown	Scandinavia	Archeological perspectives, resilience, material cultural shifts, political networks, crop failures, ergotism, disease, religion, mortuary practice, human agency
Maraschi 2021	536	Unknown	Scandinavia	Myth, cultural memory, poetry

(*Continued*)

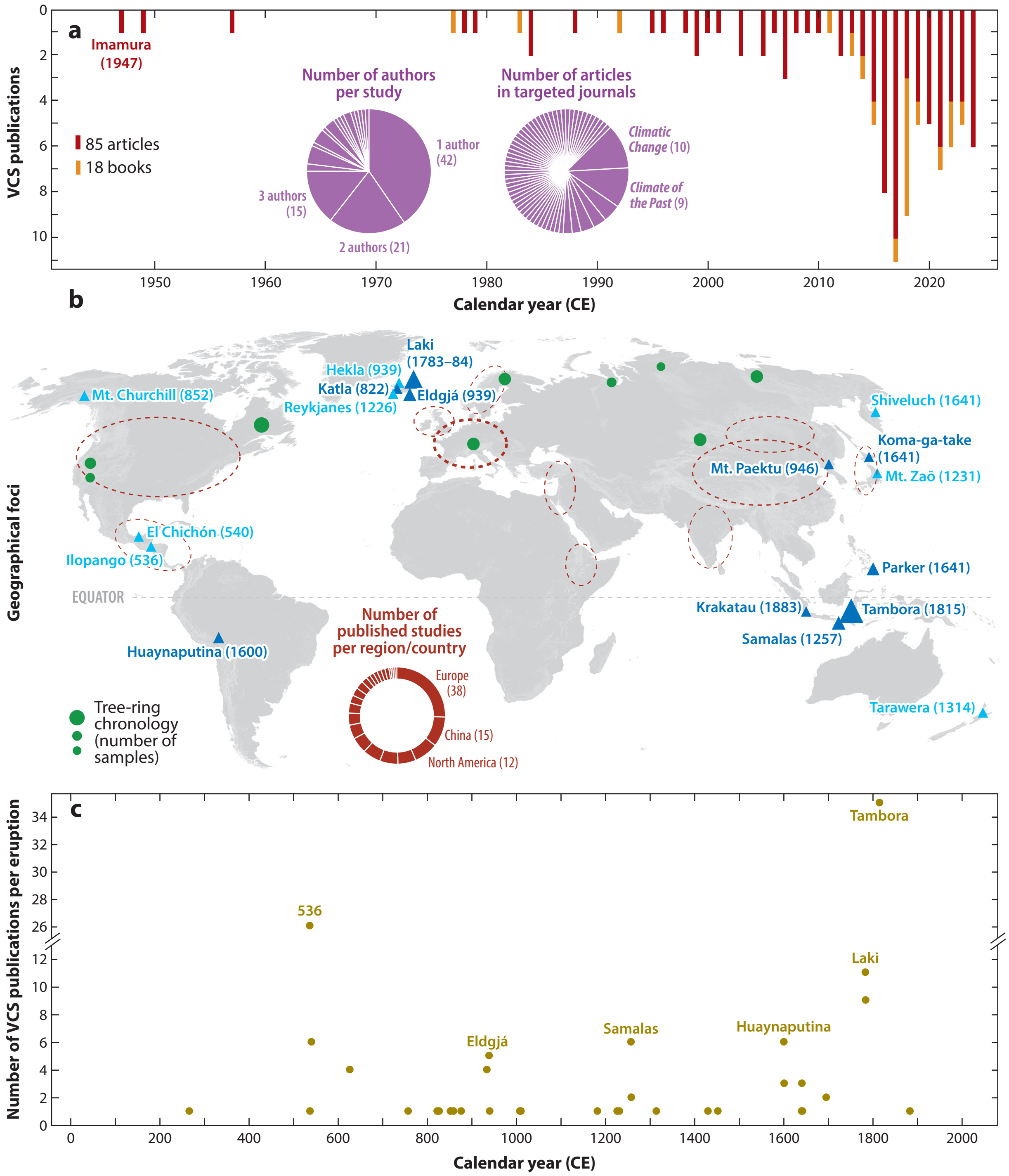
Table 1 ***(Continued)***

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
Pfister & Wanner 2021	1815	Tambora	Europe	Includes a chapter on Tambora—climate stress, harvest failure, hunger, literary response
Drimbe 2022	536	Unknown	Mediterranean, Near East	Hunger, disease, fear, economic downturn, theological dispute, schism in Christianity
Huhtamaa et al. 2022	1600/1601, 1640/1641, 1695	Huaynaputina, Koma-ga-take, Parker, Unknown	Ostrobothnia in northwestern Finland	Focuses on societal vulnerability and resilience
Kostick & Ludlow 2022	Fifth to seventh centuries CE	Unspecified	Ireland	Weather phenomena and extremes, poor or delayed harvest, famine
Mackay et al. 2022	852/853	Churchill	North Atlantic (including Eurasia and northern Africa)	Storms, snowfall, modest climate forcing potential but strong Northern Hemisphere cooling, severe winter, food shortages, equivocal evidence for societal impacts
Stoffel et al. 2022	1641/1642	Parker, Komaga-take, Hekla, Shiveluch	Europe, China, Japan	Cold, poor harvests, war, drought, famine, cold and wet spring and summer, flooding, severe winter, summer frost, ruined vegetables, rain, thunderstorms, early frost, late harvest, grain price increases, severe drought, frozen rivers, heat and drought, autumn frosts, subsistence crisis, crop failure, disease epidemic, hunger, collapse of Ming Dynasty, locusts, widespread famine, pestilence, looting, religious disputes, warfare, abandonment of farms, riots, rebellion, animal pestilence
White et al. 2022	1600	Huaynaputina	North America, North Atlantic, and Europe	Slowdown of subpolar gyre resulted in winter and summer cooling, sea ice, northerlies, severe winter can kill livestock and reduce births, fodder depleted over long winters, reduced dairy production, slaughter of animals, a risk to winter grains through fungi, damaged seedlings under snow, delayed start of growing season, postponed harvest potentially impacted by first autumn frosts, agricultural hardship, sea ice redirected Arctic exploration, whaling, migration
Brázdil et al. 2023	1641	Parker	Central Europe	Harvest failure, food shortage, famines, epidemics, subsistence crises, demographic decline, warfare, epidemic disease, mortality, adaptations in transportation and agriculture
Gooding 2023	1783/1784	Laki	Highland Ethiopia	Argues against significance of volcanism in favor of political instability and weak central authority
Kleemann 2023	1783/1784	Laki	Europe, North America	Volcanic pollution effects, summer heat, thunderstorms, lightning, societal transformation, famine, migration, pandemics

(*Continued*)

Table 1 ***(Continued)***

Reference	Eruption or peak forcing year(s) or period(s) of interest	Source volcano(es)	Geographical focus(es)	Stressors and societal impacts
van Dijk et al. 2023	536, 540	Unknown, Ilopango?	Southern Norway	Cooling in growing season, decreased precipitation, drying and cooling impact harvest, shift to more negative North Atlantic Oscillation, crop reductions, abandonment
Wilson et al. 2023	1815	Tambora	Global	Cooling, food insecurity, riots, disease
Anagnostou et al. 2024	536, 540	Unknown, Ilopango?	Sweden	Agricultural practices and animal husbandry changes, abandonment of agricultural areas and settlements, demographic change, population decline
Arthur et al. 2024	536, 540	Unknown, Ilopango?	Sweden, Norway, Europe	Cold, crop stress, societal decline, adaptation, mobility, resilience
Bauch 2024	1257	Samalas	Europe, England, Germany, Mediterranean	Response to food crisis, grain exports, symbolic emblem
Clavel & Hecht 2024	1815	Tambora	Switzerland, Brazil	Volcanic winter, subsistence crisis, cooling and heavy rain, ruined crops, food prices soar, reduced fertility, increased mortality, disease, colonialism, emigration
Ljungqvist et al. 2024	Mid-sixteenth to early eighteenth century CE	Europe	Multiple	Famines associated with severe winters and cold/wet summers; most large-scale famines preceded by eruptions, wet autumns and winters, cold springs, excessive wet/cold summers; drought a lesser factor in Mediterranean; spring drought and extreme winter more significant, i.e., different climatic stressors in different geographies; short growing seasons at environmental limit of agriculture; too much rain before or during harvest decreased yield; susceptibility to pests (insects, fungi); excessive autumn rainfall affected sowing of winter crops; short growing seasons affected green pastures, impacting haymaking and dairy, meat production; cold springs led to starvation of grazing animals; wet/cold promoted disease in livestock; reduction of draught and manure had knock-on effects; persistently cold climate the main driver as opposed to climate instability
Zonneveld et al. 2024	200 BCE to 600 CE	Unknown	Italy	Climate stress (cooler, drier) amplified risk of epidemic disease outbreak (mediated through societal vulnerability, changes in host/vector populations, migration and conflict, etc.); cites Antonine (∼165–180 CE), Cyprian (251–266 CE), and Justinianic (541–766 CE) plagues; does not argue specifically for volcanic forcing but corroborates Late Antique Little Ice Age



*(Caption for **Figure 5** appears on following page)*

Figure 5 (*Figure appears on preceding page*)

Published evidence for the volcano-climate-society (VCS) nexus. (*a*) Publication dates of 103 VCS studies, separated into 85 articles and 19 books. Purple pie charts show the number of authors per study (*left*) and the journals they targeted (*right*). (*b*) Geographical foci of the VCS studies (*red ellipses*), together with putative and established source volcanoes (*light* and *dark blue*), and the tree-ring chronologies used for summer temperature reconstruction (*green dots*, with their size referring to the number of samples). The circle diagram shows the number of published studies per region and country. (*c*) Distribution of 36 eruption dates mentioned in 103 publications (**Table 1**; **Supplemental Inventory**).

generally, we omitted studies that cite historical documentary sources only as evidence for weather extremes.

Of the 103 VCS studies, 85 are articles in peer-reviewed journals and 18 are book contributions (**Table 1**; **Supplemental Inventory**). Assessment of all titles reveals the prevalence of "climate,"

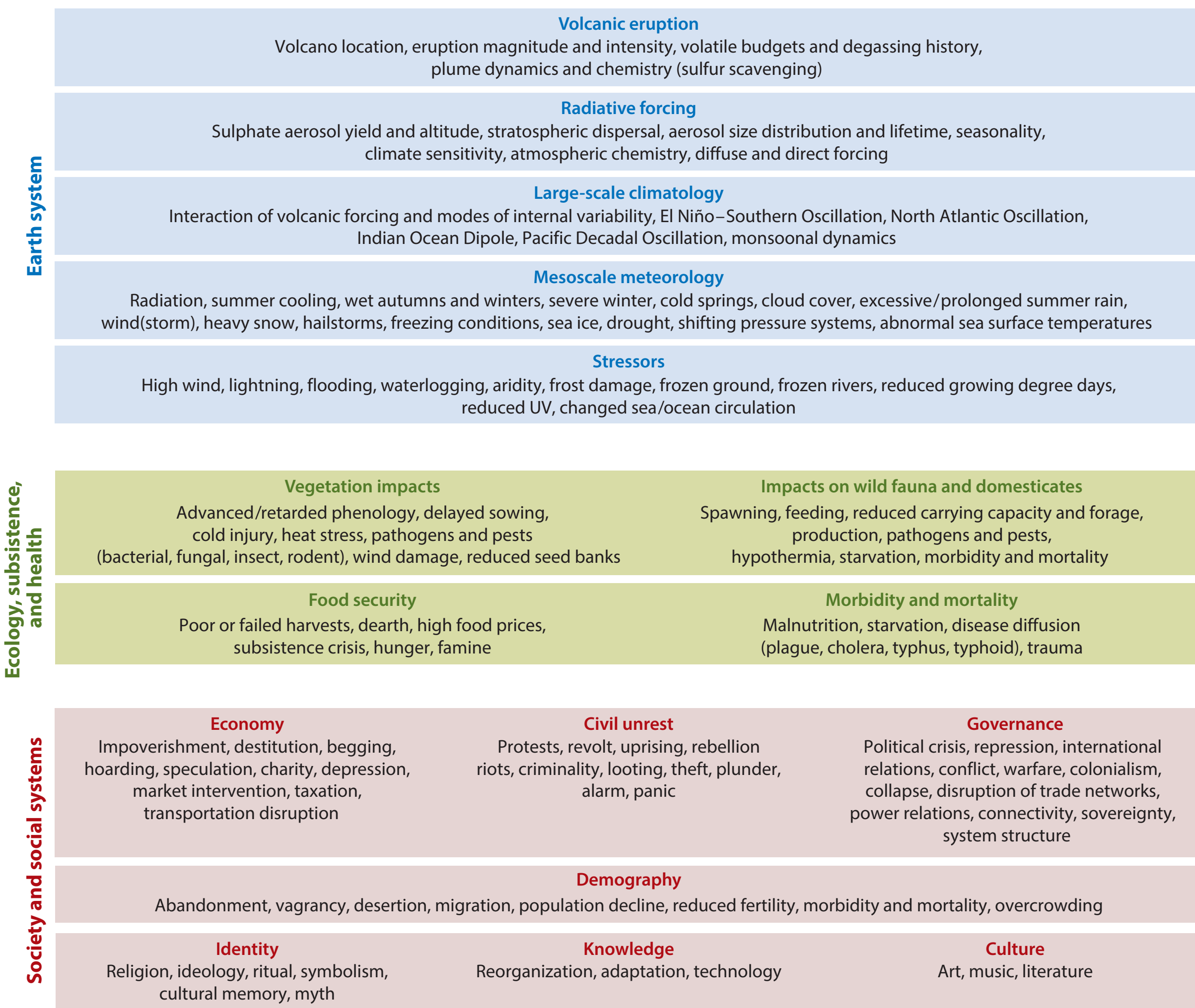


Figure 6

The volcano-climate-society (VCS) nexus. Schematic illustration of arguments made in the reviewed 103 VCS studies to link the volcanically forced weather and climate changes to human affairs. The design is not intended to suggest linear causality but rather the interconnectedness of and feedback loops between the subsystems illustrated. Human agency is acknowledged as a primary driver of history.

"eruption," "volcanic," "Tambora," and "climatic" as terms (**Supplemental Figure 6**). The earliest studies date to the 1940s and 1950s (**Figure 5*a***). The pace in publications gathered from the late 1970s to the early 2010s and sharply increased between 2016 and 2018, reflecting the Tambora bicentenary. Since then, around 5–7 contributions per year have emerged. Of the 85 articles, 42 studies have a single author, the maximum number of authors for an individual contribution is 32, and they appear in 60 different journals (**Figure 5*a***).

Our first publication is a remarkable and apparently hitherto uncited piece by the seismologist Akitune Imamura (1870–1948) (Imamura 1947), who was familiar with William Jackson Humphreys' work. Imamura's study stands out for implicating global volcanism in several historic famines and bad harvests experienced in Japan. Notably, he recognized warm winters and cool summers and observations of dry fog as signatures of distant explosive eruptions. He even linked a famine in 626 CE to a far-off volcano six decades before archival, ice core, and dendroclimatological research would amplify the significance of this year (Fei et al. 2007, Di Cosmo et al. 2017). Considering the ice core record, most of the 20 episodes of famine and poor harvest Imamura identified can now be seen to coincide with years of pronounced volcanic forcing.

Inspired by Hubert Lamb's work, NASA astrophysicist Richard Stothers brought new impetus to the field with six articles published between 1984 and 2000 CE. Stothers' provocative work engaged with the mystery eruption of circa 536 CE (Stothers 1984a), as well as the Eldgjá (Stothers 1998), Samalas (Stothers 2000), Laki (Stothers 1996b), and Tambora (Stothers 1984b) eruptions.

There are nine reported VCS cases for the British Isles, the Middle East, and the Near East; eight for the Mediterranean; seven for Scandinavia; six for Japan; and five for India (**Figure 5*b***). Another 14 countries or regions are mentioned at least once and up to four times (**Supplemental Inventory**). While 36 different eruption dates and 18 possible source volcanoes are mentioned (**Figure 5*b*,*c***), the most detailed evidence presented concerns the eruptions of Tambora in 1815 (35), the mystery eruption of circa 536 CE (26), and Laki in 1783–1784 (11/6) (**Figure 5*c***).

The VCS studies almost exclusively concern the NH, especially Europe (38), China (15), and North America (12). The most commonly described societal responses are poor or failed harvests, food shortages, famines, disease outbreaks, socioeconomic and political turmoil or collapse, and migration (**Supplemental Inventory**).

Figure 6 provides an overview of arguments ventured to connect volcanically forced climate change to societal impact in the 103 articles (**Table 1**; **Supplemental Inventory**). Many of the studies acknowledge the antecedent factors, societal vulnerabilities, and political instabilities that condition responses to environmental change (Mackay et al. 2022, Büntgen et al. 2024). The engagement and interventions of economic and environmental historians, historical epidemiologists, world historians, and historical climatologists, often in collaboration with paleo-scientists, have clearly promoted a more critical stance to investigations of the impacts of food insecurity on health, economy, governance, and demography (**Figure 6**). At the same time, some historians have expressed skepticism and criticism at such collaborative efforts (Strunz & Braeckel 2020).

The historical texts quoted in VCS works mainly describe local observations (e.g., of weather, crop health, grain prices, unrest, disease), and most studies assume that the meteorological stressors (temperature, precipitation, wind) acting on food production derive from large-scale radiative forcing and its interactions with modes of internal climate variability. Rather few studies specifically explore the attribution of weather extremes (e.g., severe winters, unseasonal frost and snow, flooding, strong winds, drought, or cold summers with reduced growing degree days) to large-scale climatology (which might help to establish their relationship to large-scale volcanic forcing) (Auchmann et al. 2012, Rössler & Brönnimann 2018). Weather extremes (which might be abrupt and ephemeral in nature as well as represented in anomalous seasonal averages) are held responsible for a range of impacts on vegetation (agricultural crops, pasture) including phenological changes that affect productivity and harvesting, and physical or biological stresses that result in injury (e.g., frost or wind damage, rot). Even for recent decades, it has been shown that interannual climate variation linked to the El Niño–Southern Oscillation (ENSO) and other factors accounts for a significant fraction of variance in crop yields, a pattern evident across spatial scales and crop varieties (Ray et al. 2015). While extrapolation from this finding to evaluate the possible effects of volcanic forcing on preindustrial agriculture and cultivars would be unwise, it seems reasonable to infer that the impacts would have been at least as significant in terms of food production.

Impacts on crops can have knock-on consequences for domesticates (raised for food), for instance via reduced haymaking, malnutrition, starvation, and increased prevalence of disease, with the combined effects provoking food shortages, escalating costs and dearth, and, in many cited cases, famine. One of the studies noted that most of the major famines afflicting medieval and early modern Europe were preceded by significant volcanic eruptions, with persistently cold conditions, rather than climate instability or drought, being the leading environmental driver (Ljungqvist et al. 2024). Responses to food crises that are discussed include civil unrest, conflict, and migration, and many of the studies consider these reactions in light of prevailing socioeconomic and political conditions. In turn, famine, malnutrition, population movements, and ecologically driven changes in host and vector populations can trigger the onset and shape the geography of disease epidemics (**Figure 6**).

After Tambora, the most prominent VCS case concerns the circa 536 CE mystery eruption, argued to have triggered the onset of the LALIA and then quickly amplified by the climate forcing of another eruption in circa 540 CE. Stothers played an important role in drawing attention to the mid-sixth century (Stothers 1984a), as did two popular books published in 1999, one by dendrochronologist Mike Baillie (1944–2023) (Baillie 1999) and the other by journalist David Keys (Keys 1999). Though the timing and source of large eruptions in the 530s and 540s CE remain unclear (Dull et al. 2019, Smith et al. 2020), textual and archeological evidence attests to the coincidence of climate variation and societal transformation across the Mediterranean world as well as within northern and western Europe in this period. Another major eruption occurred in circa 626 CE, associated with one of the coldest summers of the past two millennia (Büntgen et al. 2016). This cooling is argued to have reduced the carrying capacity of Eurasian steppe environments, with the consequent livestock mortality playing a role in the collapse of the Eastern Turk Empire and rise of Tang China (Fei et al. 2007, Di Cosmo et al. 2017).

While many textual sources describe excess, unseasonal, or low precipitation, robust high spatiotemporal resolution proxies of precipitation and drought are scarce. The importance of hydroclimate for both natural and social systems is, however, exemplified by a range of environmental changes following the Samalas eruption that are thought to have facilitated the Mongol invasion of Syria in 1258 CE (Di Cosmo et al. 2021), before contributing to their defeat by the Mamluks at Ayn Jālūt in 1260 CE. Another complicating factor is the possible interplay between volcanic forcing and modes of internal climate variability, such as the ENSO (Dätwyler et al. 2019). Many documentary sources also attest to weather extremes outside of the growing season and thus not captured in tree-ring-based climate reconstructions (although see Tejedor et al. 2024), and there remains a lack of consensus around the boreal winter climate consequences of volcanic forcing. Numerous works invoke early or late frosts and severe winters as hazards to crops and domesticates, sometimes triggering societal crises. Single shocks, for instance widespread loss of livestock in a single winter, can have a far more profound impact than ephemeral or even prolonged summer cooling (or warming). However, proxy-based evidence for out-of-growing season climate is largely absent or at best spatially and temporally restricted (Dobrovolný et al. 2010, Zanchettin et al. 2013, Zambri et al. 2017, Dogar et al. 2023). Even the picture from modeling efforts is equivocal in light of internal variability in the climate system (Dalla Santa & Polvani 2022, Tejedor et al. 2024). Mere coincidences between major historical episodes and summer temperature anomalies need not offer any explanatory power in understanding sociopolitical changes.

Tambora in 1815 is arguably the most emblematic VCS case with research on its climate effects and their potential ramifications for distant societies going back to the 1970s. Among the most notable publications is the 1977 work of economic historian John Post, who combined the themes of volcanism changing climate and climate change impacting society in his book *The Last Great Subsistence Crisis in the Western World* (Post 1977). Post argued that the year without a summer of 1816 conspired with the devastating socioeconomic legacy of the Napoleonic Wars to usher in profound social, demographic, and political change. Post's monograph prefigures many further fine-grained studies of weather, food insecurity, health, and migration (Krämer 2015, Büntgen et al. 2024, Clavel & Hecht 2024) and even conjecture on the eruption's role in shaping European art, literature, and music (Hubbard 2019, Wood 2020, Corner 2021). That contemporary observers drew connections between, for instance, weather extremes and crop health, and between dearth, vagrancy, and disease, elevates arguments for the role of Tambora in world history (Oppenheimer 2011, 2015), ensuring this episode stands as one of the most compelling VCS cases.

5. CONCLUSIONS AND OUTLOOK

High-resolution paleoclimate, environmental, and socioeconomic datasets, as well as collaboration across the natural and social sciences and humanities, are needed for robust understanding of the connections (if any) between large volcanic eruptions, abrupt climate variations, and societal responses. Dendroclimatology offers the great benefit of precise chronologies, which are crucial for comparing with other dated sources. In addition to summer temperature reconstructions, "blue rings," revealed by wood anatomical staining techniques and indicative of a lack of cell wall lignification (Büntgen et al. 2022a) (**Supplemental Figure 7**), might offer even finer temporal resolution on discrete vegetation responses to radiative cooling. However, in our opinion, tree rings cannot capture winter (or out-of-growing season) climatology (for an alternative view, see Tejedor et al. 2024). Given the societal significance of severe winters in both agrarian and pastoral contexts, as well as the uncertainties surrounding the impacts of volcanism on winter climatology (and hydroclimate in general), this represents a major obstacle for VCS argumentation and underlines the importance of historical sources concerning specific events.

One way forward is stronger engagement with disciplines such as ecology, pedology, economics, migration studies, agronomy, and crop science to gain fresh insights into how volcanically forced temperature and hydroclimate variations affect, directly and/or indirectly, the functioning and productivity of natural and agricultural systems, thereby potentially playing a role in food shortages, disease outbreaks, and demographic change (**Figure 6**). For instance, constraints on past land-use/land-cover changes and ecosystem responses would strongly complement investigation of complex human-environmental interaction at various spatiotemporal scales (Frachetti et al. 2023).

While much attention has been paid to the mid-sixth century and the eruptions of Eldgjá, Samalas, Laki, and Tambora, there are several notable volcanic episodes of the Common Era that remain little explored from a VCS perspective. One, in circa 1345 CE (VSSI ~14 Tg), not yet attributed to a source volcano but likely tropical, precedes the Black Death (Fell et al. 2020), the initial phase of the plague pandemic that claimed a large proportion of Europe's human population between 1346 and 1353 CE (Campbell 2016). Coinciding with one of the most pivotal events in European medieval history, exceptional summer cooling in 1345 and 1346 CE is evident from two consecutive blue rings found in a high-elevation tree-ring chronology from the central Spanish Pyrenees (Piermattei et al. 2020). Another prominent case is the eruption doublet of circa 1453 and 1458 CE. The demise of the Byzantine Empire in 1453 CE coincides with significant volcanic forcing (**Figure 1*a***) and with one of the coldest summers of the NH extratropics (**Figure 1*b***). While the fall of Constantinople followed a 53-day siege on May 29, 1453 CE, thus preceding the cool summer reconstructed from tree-ring width and maximum latewood density (Esper et al. 2017), it does not preclude an influence of volcanically forced climate because any weather extremes between the autumn of 1452 and spring of 1453 CE would not be captured in the tree-ring reconstructions (Büntgen & Esper 2024).

Other unidentified eruptions in circa 304 and 1182 and even the 1883 CE eruption of Krakatau could merit deeper research. Such studies, while recognizing the diverse and dynamic mixture of economic, sociopolitical, and cultural influences on different societies and their interactions, might stimulate further development of mechanistic models of the effects of volcanically forced temperature and/or hydroclimate changes on the stability of ecological and agricultural systems, including harvest failures and outbreaks of zoonotic infectious diseases. Understanding the impacts of volcanically forced climate variations on agricultural productivity requires consideration of many variables, such as direct and diffuse radiation, mesoscale meteorology, soil conditions, and crop varieties (Proctor et al. 2018). Such holistic efforts are critical if we are to assess the risks of future very large, sulfur-rich eruptions on global food security (Puma et al. 2015, Stoffel et al. 2024).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

U.B. and C.O. conceived the study, organized and attended six interdisciplinary one-week workshops at the Centre for Interdisciplinary Studies (ZiF) (Bielefeld, Germany), compiled data, performed the analyses, designed all figures, and wrote the review. N.D.C., J.E., M.F., L.K., F.M., and E.R. attended all workshops and contributed to discussions and refinement of the review.

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