RESEARCH ARTICLE

VOLCANICA

Eldgjá and Laki: Two large Icelandic fissure eruptions and a historical-critical approach for interdisciplinary researchers working on past nature-induced disasters

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Abstract

The integration of archives of societies with archives of nature has led to collaborations between the natural sciences and the humanities. Not all those involved consider these archives equal, which led to some studies featuring explanations promoting nature as the prime agent in history. The field of the history of climate and society is currently experiencing a shift away from monocausal explanations. Cultural factors must be considered and their contribution to disasters must be examined. This paper introduces an easy-to-use step-by-step approach composed of crucial questions that need to be considered to analyze the entanglement of nature and society in relation to nature-induced disasters. The approach was developed by examining two large Icelandic fissure eruptions, Eldgjá (939–940 CE) and Laki (1783–1784 CE). The approach presented in this paper offers increased understanding across disciplinary cultures from the perspective of historians and is intended as a thought-provoking impulse for future studies.

Résumé

L'intégration des archives sociétales et des archives naturelles a favorisé la collaboration entre les sciences naturelles et les sciences humaines. Cependant, toutes les approches ne considèrent pas ces archives comme égales, ce qui a mené à la publication d'études où la nature est présentée comme l'agent principal de l'histoire. Actuellement, le domaine de l'histoire du climat et des sociétés connaît une évolution qui s'éloigne des explications monocausales. Les facteurs culturels doivent être pris en compte, tout comme leur rôle dans les catastrophes. Cet article propose une méthode simple, en plusieurs étapes, comprenant des questions essentielles à poser pour analyser les intrications entre la nature et la société lors de catastrophes d'origine naturelle. Cette approche s'appuie sur l'examen des grandes éruptions fissurales islandaises, Eldgjá (939–940) et Laki (1783–1784). L'objectif de cet article est d'améliorer la compréhension entre les différentes disciplines du point de vue des historiens et de susciter de nouvelles pistes de recherche.

Keywords: Early Middle Ages; Early Modern Period; Environmental History; Geology; Paleoclimatology; Volcanoes.

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1 Introduction

In July 1893, geologist Thorvaldur Thoroddsen traveled through southern Iceland on horseback. During this trip, he came across evidence of volcanic eruptions that had occurred in the past—Eldgjá and Laki [Thoroddsen 1925]. Both volcanoes are fissures located above the Iceland mantle plume in the Eastern Volcanic Zone [Thordarson and Larsen 2007; Brugnatelli and Tibaldi 2020]. The two eruptions are comparable in their eruption style and consequences. Large amounts of lava, tephra, and SO_2 were emitted, which had serious consequences for weather in the short term, climate in the long term, and societies near and far. These included winter cooling, famine, and a rise in mortality. Due to the volcanic aerosols in the atmosphere, remarkable celestial phenomena were observed in the aftermath of both eruptions [McCarthy and Breen 1997; Stothers 1998; McCormick et al. 2007; Oppenheimer et al. 2018; Brugnatelli and Tibaldi 2020]. The relationship between cause and effect can, in these examples, be described as teleconnections—a meteorological term often used in the context of climate anomalies that are related to one another, although they occur in distant regions. Recently, historians have adopted the concept of societal teleconnections to study "direct and indirect causal links between historical phenomena of climatic and societal change," even if the perpetrating event is unknown to the contemporaries [Bauch 2020]. This allows for the study of the impacts of natural events that occur far away from their source [Moser and Hart 2015]. For example, the Laki eruption was responsible for the dry fog, blood-red sunsets, and sulfuric odor that were perceived in Europe, but beyond its physical consequences, the eruption evoked emotional and intellectual responses that only manifested with a time lag in regions far away from Iceland, which is characteristic for (societal) teleconnections [Kleemann 2023].

As natural stressors, Eldgjá and Laki had the potential to endanger historical societies and produce a disaster. We define disaster as an extreme event that poses an existential threat to a society. While both Eldgjá and Laki are large fissure eruptions, producing large volumes of lava over several months, that originated in a specific geographic region (Iceland) albeit with large-scale effects on other parts of (mostly) the northern hemisphere, these are different from other eruption styles and other kinds of nature-induced disasters. High intensity explosive eruptions with a short duration, such as the 1257 Samalas

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or 1815 Tambora eruptions, would, for instance, affect the climate, possibly on a global scale, for a longer duration [Lavigne et al. 2013; Raible et al. 2016]. Other recent scholarship has focused on the sequences of events and cascades of local physical, social, and political impacts and responses for smaller eruptions in Middle America [Hutchison et al. 2016; Barclay et al. 2022]. Nevertheless, the insights these two case studies (Eldgjá and Laki) produce are, in our opinion, suitable for generalization for developing the approach presented here.

To this day, a widely used interdisciplinary approach to identify a volcanic event involves using evidence (from the erupted products, ice cores, tree rings, etc.) gathered by scientists and then using historiographical evidence in the next step to support the evidence of a volcanic event during a certain time frame. This has led to new insights that point to "nature" as an agent in history [Wozniak 2020]. It has also created an interdisciplinary discourse that goes beyond traditional boundaries. Frameworks have been developed, for example, to study the local impacts of past volcanic eruptions on human societies [Riede 2019]. Using findings from the archives of nature and looking for their possible impacts on society, however, links social distress primarily to natural factors. This heuristic step seemed initially logical and in the field of historical studies, in medieval studies in particular, it was an important door opener [McCormick et al. 2007]. Here, however, we would like to take a more combining approach that not only seeks for natural impacts, but equally includes human-made factors in an attempt to overcome the artificiality of the nature-culture divide in academia.

When natural scientists and historians come together, there is potential for an extensive analysis that also takes into account anthropogenic (human-made) factors aggravating or mitigating natural factors. This can help to provide an even more nuanced picture of past interactions between humans and nature, an approach that has been encouraged lately [van Bavel et al. 2019]. The approach suggested in this paper is, therefore, integrative.

At the intersection of the history of climate and society, interdisciplinary collaboration between historians and scientists is quite common, however, this is not without its challenges. As historian Kristina Sessa [2019] points out, both historians and scientists use radically different types of evidence and methods of analysis, which is rarely addressed and can, in examples of unequal collaborations between historians and scientists, lead to the analysis of historical sources seemingly "to constitute little more than searching for textual references [...], highlighting primarily, if not exclusively, positive 'matches' between the science and the history." This can also lead to premature findings that overestimate natural impacts [Ebert 2016; Sessa 2019]. In an article authored by historian John Haldon and an interdisciplinary team of co-authors, they write "scientists seek to reduce causality to simple terms, such as temporal coincidence or statistical correlation, whereas historians deal with complex processes and are wary of oversimplification" [Haldon et al. 2014]. Sessa [2019] concludes that a working model is needed to integrate different forms of knowledge, from the archives of societies and the archives of nature. This paper is a response to this call for a working model in an interdisciplinary setting: The historical-critical approach offers an easy-to-use step-by-step tool composed of crucial questions that need to be considered to analyze the entanglement of nature and society in relation to nature-induced disasters.

While the historiographic methods detailed in this paper are well-known to historians, the natural scientists that historians seek to collaborate with are not necessarily familiar with them. This paper intends to lay a good foundation for mutual understanding in an interdisciplinary setting, which will ideally produce equal collaborations between historians and scientists. Overall, the historical-critical approach presented here is intended as a thought-provoking impulse for future interdisciplinary studies on past nature-induced disasters to test and challenge the steps laid out in this paper.

2 Background: The Volcanic Eruptions—State of Research

2.1 Eldgjá

Eldgjá is a 75 km-long fissure associated with the Katla volcanic system [Oppenheimer et al. 2018]. Its eruption was the largest volcanic event of the Katla system in the Common Era. It produced 19.7 km^3 of lava, 1.3 km^3 of tephra and 232 megatons of SO_2 [Thordarson et al. 2001; Brugnatelli and Tibaldi 2020]. The eruption has been dated to between spring 939 and autumn 940 CE [Sigl et al. 2015; Oppenheimer et al. 2018; Hutchison et al. 2024].

The climatic response to the eruption has been examined via tree-ring-based reconstructions which reveal northern hemisphere summer land temperatures for the months of June, July, and August (JJA) of the pertinent year. The reconstructions indicate a possible cooling of ~1.1 °C (with respect to 1961–1990 CE) after the Eldgjá eruption; a similar cooling occurred after the Laki eruption (~1.2 °C) [Oppenheimer et al. 2018]. Regions affected by the temperature decline include central Europe, Scandinavia, the Canadian Rockies, Alaska, and central Asia [Fei and Zhou 2006; Oppenheimer et al. 2018]. The tree-ring reconstructions gave no indication of multi-annual cooling effects. According to dendrochronological data, it was the summer of 940 that was most affected by this volcanic event [Luterbacher et al. 2016; Oppenheimer et al. 2018].

Pre-modern agrarian societies were highly sensitive to meteorological variations. In central Europe, the growing season for crops lasts from early spring to June and August [BMEL 2019]. Environmental conditions during this period affect the quality and quantity of a given harvest. Pre-modern societies lived on a subsistence economy, having limited access to grain imports. Therefore, cooling effects in the aftermath of the Eldgjá eruption could have easily led to harvest shortfalls and famine. Because of their relevance to societies, such hazards were well documented, as were celestial phenomena. According to medieval understanding, observations in the atmosphere could be interpreted as portents of calamitous events to come, such as the death of a king, a change of rulership, an epidemic, or war [Beda Venerabilis 1862; Isidore 1862]. The sky was therefore watched with great interest. High-latitude volcanic eruptions, such as Eldgjá, based on the Greenland

ice-core data, likely generated stratospheric aerosol veils that dimmed and reddened the sun [Stothers 1998]. In medieval writings, such phenomena were described as dry fogs, reddish skies, or an unusual brightness. Medieval manuscripts continue to be scoured by multiple scholars for possible responses to the Eldgjá eruption [McCarthy and Breen 1997; Stothers 1998; McCormick et al. 2007; Newfield 2010; Kostick and Ludlow 2015; Sigl et al. 2015; Oppenheimer et al. 2018; Brugnatelli and Tibaldi 2020; Wozniak 2020; Ebert 2021; Newfield and Oppenheimer 2021]. Although Iceland was settled from Norway around 870, there is no written evidence from the tenth century from Iceland itself. During the time of the Eldgjá eruption, the island was ruled by independent chieftains (*goðar*) who met in the Althing (*alþingi*) from 930 where political and social decisions were made [Stefánsson 1991]. On a European scope, however, mentions of hard winters, solar eclipses, observations of a blood-red sun, comets, floods, and famines do appear in writings from the late 930s and early 940s. Concerning western and central Europe, 29 sources are available [Ebert 2021]. This is a remarkable number for a time known to medievalists as "the dark tenth century" due to the relative scarcity of sources [Lubich 2010]. Hence, it seems likely that the societal impact of Eldgjá was considerable. It might have helped to stimulate the Christianization of Iceland, as Oppenheimer et al. [2018] suggest.

2.2 Laki

Between 8 June 1783 and 7 February 1784 CE, another fissure eruption took place in Iceland. Activity at the Grímsvötn volcanic system, located underneath Vatnajökull, precipitated the Laki eruption. Some scientists regard the Laki eruption as part of a larger eruptive episode at Grímsvötn, that lasted from May 1783 to May 1785 [Thordarson and Self 1993; Thordarson 2003; Thordarson and Self 2003]. Throughout its eight-month-long eruption, the Laki fissure reached a length of 27 kilometers. It produced 14.7 km^3 of lava, covering an area of 599 km^2 [Thordarson and Self 1993].

The eruption devastated Iceland, particularly the southeast. Lava flows damaged and destroyed farmsteads and churches, changed the landscape, and rerouted rivers. In addition, tephra fall and volcanic gases, such as sulfur dioxide and fluorine, poisoned the fields, meadows, and ponds. The animals, too, fell victim to the toxic ejecta, which in turn affected the human population [Larsen and Thórdarson 1984; Pétursson et al. 1984; Steingrímsson 1998]. Malnutrition and disease were rife, and ultimately many succumbed to starvation. By 1785, approximately one-fifth of the Icelandic population had perished. The Icelanders remember the aftermath of the Laki eruption as *móðuharðindin* ("the famine of the mist"); the worst disaster in Icelandic history [Gunnarsson 1984; Vasey 1991; Riede 2019; Gunnarsdóttir 2022].

The eruption produced 122 megatons of sulfur dioxide and other gases. Roughly 60 percent of these were released within the first month of the eruption, between 8 June and 8 July 1783 [Grattan and Brayshay 1995]. These gases reached far beyond Iceland and formed a dry fog visible in large parts of the northern hemisphere (from Labrador in today's Canada to the Altai mountains in central Asia) for much of the summer of 1783 [Stothers 1996; Demarée et al. 1998; Demarée and Ogilvie 2008]. This fog was sometimes referred to as a mist; today, it is commonly called the Laki haze. In western and central Europe, the dry fog—in varying intensities—lasted until autumn 1783. In addition to the dry fog, which at times had a sulfurous odor, the "blood-red" color of the sun concerned contemporaries. This unusual weather inspired much debate among the naturalists of the day across Europe, mainly because the origins of these phenomena were unknown [Grattan and Brayshay 1995; Kleemann 2019b; 2022b; 2023].

In 1783, Iceland was a Danish dependency. Due to a trade monopoly, only certain Danish merchants were allowed to do business there. Usually, the merchants traveled to Iceland in the spring and returned to Denmark in the late summer [Karlsson 2000; Oslund 2011]. This is why the news of an Icelandic eruption only reached Copenhagen—and subsequently the rest of Europe—in early September of 1783. However, by that point, the dry fog had largely vanished. Although naturalists discussed an Icelandic volcanic eruption as a potential source of the fog, this remained just one theory among many [Demarée and Ogilvie 2001; Kleemann 2019a; b].

The Icelandic naturalist Sveinn Pálsson discovered the Laki fissure in 1794 [Pálsson 1945; 2004]. His findings—detailed in his manuscript—remained obscure, and unappreciated until the 1880s, when the Norwegian geologist Amund Helland stumbled across Pálsson's manuscript in Copenhagen and published parts of it [Helland 1881; 1886]. Upon the suggestion of Thorvaldur Thoroddsen, Helland visited the Laki fissure in 1881 [Thoroddsen 1925]. When Krakatau erupted in the Dutch East Indies in 1883, news of the event spread around the world within days due to the recent invention of telegraphy. Scientists realized that volcanic eruptions could have far-reaching effects. Due to this realization and the almost simultaneous rediscovery of the Laki fissure by Helland and Thoroddsen, the connection between the Laki eruption and the dry fog of 1783 was finally established [Kleemann 2020; 2023].

While the summer of 1783 was very warm in western Europe, it was colder than average in eastern and southern Europe. Recently, Zambri et al. [2019a,b] have modeled this hot summer and found that it was a consequence of natural climatic variability due to the presence of an anticyclone in western Europe. Additionally, they conclude that without the eruption, it would likely have been warmer still. The winter of 1783/1784 was much colder than expected in Europe and North America [Ludlum 1966; Ogilvie 1986; Wood 1992; Thordarson 2005; Glaser 2008; Brázdil et al. 2010].

2.3 Summary

Both Eldgjá and Laki were fissure eruptions in southern Iceland that released exceptionally large volumes of lava and volcanic gases. In their respective millennia, both produced the largest volumes of lava on planet Earth. They are, therefore, comparable with each other. Their consequences within Iceland were substantial, be it through lava flows that changed the landscape (Eldgjá and Laki) or poisoning gases and debris that affected agriculture (Laki). Both eruptions' effects were not limited to Iceland; larger parts of the northern hemisphere

were also affected. This paper focuses on the eruptions' consequences for western and central Europe.

3 Methods and Results: The Historical-Critical Procedure

3.1 The approach

As Degroot et al. [2021] demonstrated, much of the work in the field of the "history of climate and society" (HCS) is produced by scholars from different disciplines. White et al. [2022] published an overview of recent scholarship in the growing and diverse field of historical climatology. Often in interdisciplinary collaborations between natural scientists and historians, difficulties arise when dealing with the specifics of the sources for both disciplines. Sources, in this context, are original materials from the past. Regarding the archives of nature, this can include studying the physical deposits at the eruption site, volcanic material captured in ice cores (e.g. ash, tephra), pollen found in lake sediments, or evidence gleaned from tree rings, to name but a few. The archives of societies can be documents written during the time in question, such as chronicles, newspaper articles, administrative literature, poetry, egodocuments, and weather records. Flood marks on bridges, dikes, or buildings and epitaphs are also considered part of the archives of societies. It is important to note that the archives of society to which we refer here relate to historical times, i.e. times from which written evidence has been preserved. For pre-historic societies or those with strong oral history traditions, the approach would have to integrate other disciplines, such as archaeology, in order to compensate for the lack of written records. As far as patterns of perception and measures taken are concerned, however, definitive answers will probably remain very limited in this case.

Every type of source has its particular strengths and weaknesses [Nash et al. 2021]. This paper will draw on existing studies rather than performing scientific reconstructions. The historical-critical approach presented here analyzes relevant information from scientific studies and historical records. It focuses, in particular, on historical material and classifies the information contained therein in terms of the question of nature-induced extreme events in the past. Recently, scholarship in the field of disaster research has moved away from the previously used notion of "natural" disasters and has now adopted the term "nature-induced disaster" [Kleemann and Mseba 2024]. It highlights additional (e.g. human-made) factors besides proxies that allow for a more differentiated picture of historical processes in the context of natural events [van Bavel et al. 2019]. The approach unveils the complexities of both nature and society in the past.

The approach is divided into five stages (cf. Figure 1). It is important to note that not all of the stages will be applicable in every case study. Due to gaps in both the archives of nature and society, in certain cases it may be impossible to answer some of the questions. However, the questions of all five stages should be taken into consideration during the process of analysis. The discussion of these questions will make the potential but also the limitations of each case study transparent. If it is impossible, for example, to narrow down the precise date of a volcanic eruption because the given data relies solely on ice cores (in cases in which the volcano responsible for an eruption is unknown) or the historiography is vague, or seems to be exaggerated for literary purposes, a discussion of these relevant aspects helps to illustrate the complexity of analyses of the entanglement between nature and culture. The benefit of an open discussion of the individual questions is the disclosure of the heuristic steps, which contributes to the transparency of different working methods, particularly in an interdisciplinary context. No attempt was made to measure or evaluate individual stages. This is for two reasons: First, events in the more recent past would automatically receive better values due to the greater availability of data. Second, indices developed in historical climate research are available, which can be used to classify the severity of events from from −3 "extremely cold" to 3 "extremely mild" [Pfister 1984; Camenisch 2015]; they are only suitable for use from about the late Middle Ages onwards due to the state of documentation, so that events further back in time (e.g. in antiquity or the early Middle Ages) should also be excluded from this analysis [Wozniak 2020]. The Eldgjá eruption, for example, could not be covered by these indices.

As the historical-critical approach targets mainly natural scientists, the *first stage* uses the archives of nature, rather than historical sources. The aim in the first stage is to search for traces of significant events in the proxy data. In order to identify the right type and location of proxies, one needs to know the eruption style of the volcano in question, examples of sources for such data include tree rings and ice cores. Interdisciplinary teams can conduct independent research to corroborate this data; however, the use of previously published studies is just as valid. In this paper, the latter approach is used to confirm the data (see above).

The archives of societies are the primary source for the *second stage*. Here, the reliability of the historical documents is considered based on specific criteria, which derive from the basic method of source criticism in the discipline of history: Works that are translations of manuscripts are less significant than publications offering the original language and a translation, for example. Critical editions informing readers about the status of the manuscripts (for example, documents that have been altered or added to later, evidence of which would be dissimilar handwriting throughout the manuscript) are also afforded more significance. A critical edition allows the reader a chance to establish if a report of extreme weather is likely authentic. Sometimes these reports were embellished, or the words were merely copied from a report from another area. Inserts added years after a given document was initially written only become apparent if a critical edition points them out, or when looking at the original archival material. The critical edition of Widukind of Corvey's writing—a key author for the Eldgjá case, for example—provides background information on the text, its origin, and the author in the foreword, which is also relevant for the third stage (see below). In the footnotes, details are given about what celestial phenomena might be described in the historical text if the report itself is rather vague like *prodigia monstrata sunt* ("prodigies were seen") and how the phenomena can be dated, which passages of the text are taken from other authorities like—in Widukind's

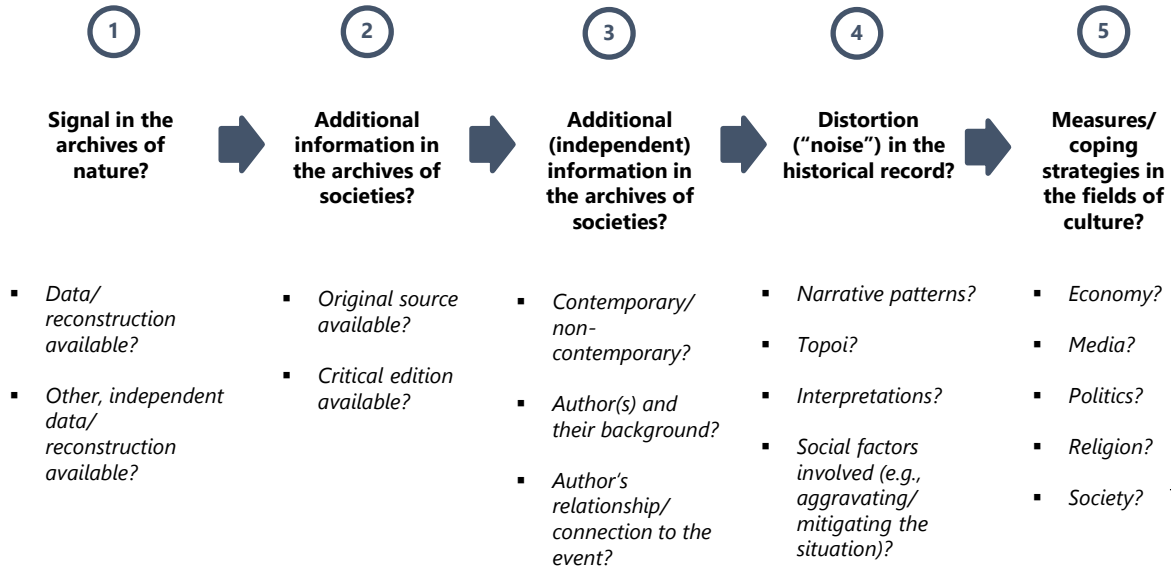

Figure 1: The historical-critical approach for interdisciplinary researchers.

case—the Roman historiographer Sallust, and how historians reviewed certain passages in Widukind's manuscript in terms of authenticity [Hirsch and Lohmann 1935]. Critical editions are, therefore, especially useful for the pre-modern period, as they can help to better understand the historical context. The most reliable are the original documents themselves. Unfortunately, in some cases, critical editions or original documents may not be available for a given event. Some manuscripts did not stand the test of time and are lost forever, and some are still waiting to be critically edited. The document used needs to be evaluated when looking for historical evidence; this information should be made transparent in discussions in order to illustrate the validity of the historical evidence for the purpose of the research question.

This process is also necessary for the historical texts addressed in the *third stage*. It is important to know the period in which the text was written, the writers' motivation, and their relationship to the subject matter. A writer to the royal court, for example, is unlikely to criticize the regent's leadership, whereas commissioned texts from a succeeding monarch may well seem to be overly critical. Therefore, the following questions must be broached: When was the text written? What is known about the author(s)? What was their intellectual background (what knowledge was available to them)? Where did the authors reside at the time of the documented event? An educated abbot writing a letter to his king informing him about poor provisions in his monastery due to a bad harvest related to unfavorable weather conditions is a considerably more reliable informant than an anonymous monk writing about rumors he heard of some misery in a distant region. This is why historians seek "contemporary" evidence. "Contemporary" means that the author and/or the historical document, as well as the events described, belong to the same time period in the past (at best, a text written by an eyewitness of an event, during a said event or soon after the fact). Historical writings can sometimes seem to corroborate one another when, in fact, they do not. Through clerical connections, for example, information written in one monastery can appear in accounts written in another region. This cannot be considered as two pieces of independent information—one is simply a copy of the other. Overall, the purpose of this stage is to determine the reliability of the sources in terms of their significance with respect to a nature-induced event.

In the *fourth stage*, this approach focuses on aspects that can distort the data. Here, the term "noise" is used; it is a term often used in reconstructions from the natural sciences. This stage is challenging because it examines historical texts for factors embedded in culture. We are therefore concerned with references that may be anchored in the politics and religion as well as the social and economic structure of the time, plus evidence from art and material culture. For historical times, references to this can usually be found in past writings. However, the information in these writings may well be distorted, because of the author(s) intentions and rhetorical techniques. These include, for example, narrative patterns and rhetorical themes (topoi), as well as perceptual patterns and interpretations, which play a particularly large role in narrative sources. Historical documents—especially chronicles and similar literature—are rarely "fact reports". Information was often adjusted to suit the whims and affiliations of the author(s). Culture and religious beliefs play an important role too. There is evidence that, in some instances, writers fabricated natural

events or spun real events in a certain way simply for dramatic purposes [Wozniak 2020]. Topoi and narrative motifs are frequently used when describing extreme events or documenting social unrest [Nünning 2013; Schellbach 2021]. The use of topoi such as Biblical motifs, for example, swarms of locusts or cannibalism, are indicative more of the storytellers' perception of an event and their desire to emphasize the significance of an event or their desire to dramatize an event than their desire to document what actually happened [Stathakopoulos 2016]. It is necessary to consider such things when looking for accurate and honest reports of nature-induced disasters in the archives of societies.

In disaster studies, the concepts of vulnerability and resilience are used to describe a multi-causal structure of external and internal factors that can exacerbate or alleviate the social impacts of natural hazards. This applies to both "slow" processes like famine or "sudden" events like volcanic eruptions. In order to appreciate the dimensions of an extreme event, one must understand the social structures it collides with; therefore, researchers need to examine social stressors that could have aggravated the situation in question, such as political conflicts or failing infrastructure. This process will also help to identify multiple causes and cascading effects [Pescaroli and Alexander 2015]. For example, by looking for other factors possibly involved in an existential threat, this approach may help to highlight orders of impacts such as biophysical, cultural, socio-economic ones. When arguing for an event that was most likely caused by nature in the first place, these stressors need to be evaluated and ruled out.

To ascertain how past societies were impacted by and responded to shocks, an understanding of their coping strategies is necessary: this is the focus in the *fifth stage*. This step identifies particular measures related to a certain natural event (e.g. drought, heavy precipitation, volcanic cooling) and sheds light on how people interact(ed) with their environment more generally. It is important to note that the way people react to certain events depends on how they interpret them [Schenk 2010]. At this point, the fifth stage is closely linked to the fourth stage. An analysis of the connection between the interpretation of a natural event and the measures taken to mitigate its impact will provide a deeper understanding of how past societies responded to nature-induced disasters. Research in cultural anthropology, for example, has pointed to the various strategies that societies that have lived near volcanoes for centuries have developed. On the Indonesian island Flores, for instance, the observation of animal behavior is an important method for the early detection of a volcanic eruption [Frömming 2006]. Opening up our approach to humanistic reflections offers surplus potential and takes local adaptation strategies into account. Of course, measures taken can differ over time—be it because of local traditions, learning effects, or different world views. In slow-onset disasters a lessons-learned from similar events can play a role. Here, however, the time aspect is not listed separately because the cases are of limited duration and substantial recurrence period. With sufficient historical sources of a certain standard, all elements deriving from culture can be examined and accounted for in the fifth stage: the economy, political, social, and media landscapes. Here, Eldgjá and Laki will be used as two case studies of how to implement the approach during research, this will shed more light on the steps that are to be taken in each stage.

3.2 Eldgjá

The eruption of Eldgjá from spring 939 to autumn 940 CE and a cooling effect in the aftermath of the volcanic event have been identified by various independent researchers using different approaches, as mentioned in Section 2.1 (see above). Hence, the signal in the archives of nature covers relevant aspects addressed in the *first stage* of the approach.

Getting to the *second stage*: original sources mentioning phenomena that can be related to a volcanic event are available—most of them even in critical editions of the *Monumenta Germaniae Historica* [Ebert 2021]. This makes it rather easy to discuss the elements of the *third stage*.

A substantial number of surviving records are copies of original records (many of which are now lost) that were made centuries later. These records depend on each other. However, contemporary and independent manuscripts from Europe are available (Ebert 2021), particularly from the historical regions of *Lotharingia*, *Saxony*, *Swabia*, and the eastern borders of *West Francia* as well as northern Italy and the monastery of Montecassino (Italy). While these manuscripts mostly describe hard winters, famines, cattle mortality, comets, or a solar eclipse, four medieval texts (contemporary and noncontemporary), have been used to date and explain volcanic impacts on climate and society in the tenth century: The *Chronicum Scotorum* (a compilation of Irish annals from the 1700s based on earlier manuscripts) (Hennessy 1866), the *Res gestae Saxonicae* ("Deeds of the Saxons") by the Saxon chronicler Widukind of Corvey (written ca. 967–973) [Hirsch and Lohmann 1935], the Icelandic *Landnámabók* ("Book of Settlements," written in the 1200s), and the *Codex Regius* which contains the Poetic Edda (written ca. 1270). The *Landnámabók* and the *Codex Regius* must be described as noncontemporary because of their significant temporal distance. They may refer to a volcanic event, but the information given is too vague to be assigned to Eldgjá. Writing more than 250 years after the eruption, the scribes might have included experiences and reports of other volcanic events in their descriptions [Ebert 2021]. Current assumptions based on the *Codex Regius* suggesting the Christianization of Iceland was stimulated by Eldgjá are therefore questionable [Oppenheimer et al. 2018]. They rather indicate that writers in the 1200s had an interest in linking a historical eruption to their story. At this point, the advantage of our approach becomes apparent, as it takes research further by not only focusing on the potential impact of a volcanic eruption on society, but also by taking the historical context into account. The picture that emerges becomes more accurate as a result. The value of the *Chronicum Scotorum* is ambiguous. Due to its substantial temporal distance, the source could be excluded from the analysis. Studies on the *Chronicum Scotorum*, however, have put its distorted chronology in order so that dating phenomena described in the text is possible (McCarthy 1998, 2005). In earlier studies, the *Chronicum Scotorum* was used to link observations of a blood-red sun for one and a half days to the

Eldgjá event [McCarthy and Breen 1997]. Yet, this occurrence cannot be attributed to Eldgjá because of the short duration of its continuance and the fact that the subsequent line in the chronicle refers to the siege of the fortification Ailech by "the heathens" [Chronicum Scotorum, a. 939; Ebert 2016]. This is important information in the context of the aspects of the *fourth stage* of the approach.

The blood-red sun could be a rhetorical theme—a portentous event—indicating that blood will be spilled in the future. The same must be applied to the writing of Widukind of Corvey († after 973). Widukind was a Saxon monk and historian who was well-informed about the royal affairs of the Ottonian dynasty [Warner 2016]. In the second book of the "Deeds of the Saxons," he writes: "Many people were terrified at the sight of the comets, fearing that there would be a great pestilence or at least a change in ruler since great prodigies were seen before the death of King Henry. For example, the light of the sun could hardly be seen outdoors because of the dark sky, but inside sunlight poured red as blood in through the windows of houses" [Hirsch and Lohmann 1935; Bachrach and Bachrach (trans.) 2014]. King Henry I died in 936. Hence, Widukind refers to an event that occurred not later than this year. According to recent research, Eldgjá erupted in 939–940, which allows for the conclusion that the phenomena that Widukind describes were not connected to the Icelandic eruption. Vague information of a distant volcanic eruption could have been spread by merchants or noble travelers along the way from Iceland via England to Saxony where the information was written down later, but there is no historical proof for that [Wozniak 2020; Ebert 2021]. This approach cannot confirm the exact date of the Eldgjá eruption based solely on the historical material, but it does show that relevant natural phenomena were observed around 939 and skillfully inserted into the authors' narratives to fit their literary purpose in line with medieval interpretations such as extraordinary omens (Chronicum Scotorum, Deeds of the Saxons). This may not answer questions regarding Eldgjá's impact on climate, but it describes how nature was perceived and "used" in tenth-century historiography.

Contemporary sources mention hard winters, famines, and pestilences. This could well be connected with volcanic cooling; tree-ring data suggests a decline in temperature during the summer of 940 (see above). In the critical approach's fourth stage, it is necessary to look for factors aggravating or mitigating the harsh winters, famines, and pestilences. This will determine whether the hardship was primarily nature-driven or greatly influenced by other factors ("noise"). Social stressors were considerable during the time in question—especially in *East Francia*, which at the time was ruled by Otto I (912–973). In the years following his coronation in 936, conflicts set in; Otto pursued a new policy that some magnates in his kingdom did not support [Ebert 2021]. War, plunder, looting, and the burning of fields increased greatly. In particular, *Saxony*, *Swabia*, and *Lotharingia* fell victim to this violence. Most of the tenth-century sources come from these very regions [Ebert 2019; 2021, see also the GIS map available at https://arcg.is/rbn5i]. This means that the Eldgjá eruption coincided with a period of military conflicts and political and social instability that severely threatened people's livelihoods. The shadow that the people of this place and time lived under was not entirely nature-induced. Rather, the volcanic event exacerbated an already undesirable situation.

The fifth stage of the approach asks for coping strategies and measures taken in reaction to extreme events. These can be found in administrative documents—an underrepresented genre in studies of climate reconstruction. In the case of Eldgjá, only two administrative documents offer insights into how people might have reacted to environmental stressors. In the first half of the tenth century, a capitulary (royal decree) dealing with famine in 779 was included in a codex compiled in the regions between *Lotharingia* and *West Francia* [Mordek 1995]. The capitulary aimed to overcome hunger with spiritual guidance and food aid (i.e. prayers, almsgiving/pecuniary fees, feeding of paupers, and fasting). These measures only make sense when interpreting changes in the natural and social environment as divine punishment. Although these measures were of a religious nature, they nevertheless considered the agricultural economy and—because religion and power were so closely linked at the time—politics. There is no evidence as to whether people actually followed the measures formulated in the capitulary when Eldgjá erupted. Still, in the event of social turmoil due to natural stressors, monastic communities would have found orientation in such a decree and acted accordingly [Ebert 2021]. The biography of Markswid, the abbess of the Saxon monastery Schildesche (Germany), notes that in 940 she ordered her sisters to participate in an annual rogation to pray for a good harvest and an end to adverse weather [Holder-Egger 1888]. In a social environment in which Christian belief was not yet totally engrained, instructions of this kind helped communicate the appropriate Christian rituals to the populace. Extreme events and the measures taken against them could conceivably said to be a catalyst for the ubiquitous influence of Christianity in everyday life. The historical evidence for this, however, is not sufficient enough to make a strong claim for this point of view in the case of the Eldgjá eruption. While the capitulary fell within the relevant period, the vita of Markswid mentioning the rogation was not written until the thirteenth century. In the tenth century, although there was no press as we understand it today, examples from historiography demonstrate how literate society reported on events related to Eldgjá. Having applied the approach to the Eldgjá case, new insights emerge that can be added to the current research. These include:

1) In terms of interdisciplinary communication, the importance of contemporary and non-contemporary sources as well as topoi when evaluating nature's impact on disasters becomes clear.

2) Cultural patterns/interpretations of processing natural phenomena/topoi can be identified during the time of the Eldgjá eruption (e.g. omens). Due to a lack of sources, however, it is not possible to exclusively link the cultural patterns to Eldgjá. The descriptions, however, are related to natural phenomena, which were woven into the historiography in a very unique way. They, therefore, show how actors in historical

societies wrote about occurrences in the natural world and how these found their way into cultural history.

3) Although the Eldgjá eruption had a high intensity, its impact on western and central European societies was only significant due to an interaction with human-made factors. The Eldgjá eruption occurred during a time of ongoing military conflicts and social insecurity. It can therefore most likely be described as a cascading effect among other correlating anthropogenic factors.

4) Coping strategies are hardly documented, but it seems likely that they drew on religious ideas combining spiritual and nourishing aid. Further research would be necessary to determine whether this aid was handled by the clergy alone or also by lay noblemen and -women.

Using the approach, relevant factors in written sources are analyzed and major cultural aspects that have not been addressed so far emerge. This provides an even more detailed picture of the entanglement of nature and culture around 939.

3.3 Laki

Several independent studies using paleoclimatological reconstructions based on ice-core data and tree rings have identified the Laki eruption and its effects on the environment [Hantemirov et al. 2004; D'Arrigo et al. 2011; Sigl et al. 2015; Edwards et al. 2021; see also the commentary by Kleemann 2022b]. This volcanic eruption left a signal in the archives of nature. Hence, the aspects mentioned in the *first stage* of the approach can be reviewed.

Moving on to the *second stage*, numerous original sources on the Laki eruption have survived to the present day. The effects of the eruption on the local population in Iceland are documented in great detail by the Lutheran priest Jón Steingrímsson, an eyewitness, and, independently, by other contemporaries [Steingrímsson 1998; 2002; Thordarson 2003; Thordarson et al. 2003]. However, in this instance, the focus remains on the eruption's effects on western and central Europe. The Laki eruption precipitated a mysterious haze and generally unusual weather throughout the continent that lasted for months. A wealth of information concerning these phenomena survives in the archives of societies. Different types of historical documents are available, ranging from newspaper articles, weather diaries, scientific journal articles, and monographs, to mention but a few; many were created at a time when the Laki haze and its consequences were observable. These accounts were, therefore, contemporary. Many articles in dozens of newspapers from different parts of central and western Europe mention unusual weather phenomena. At times, however, different newspapers used the same correspondent or copied from one another, which becomes apparent from the phrasing of individual articles. While newspaper articles can be dated exactly, as most newspapers were printed one to six times per week, the identities of the correspondents responsible for penning the articles are rarely known. Nevertheless, the large number of articles regarding the unusual weather in different regions during the summer of 1783 published by dozens of newspapers over the course of several months make the sources independent [Grattan and Brayshay 1995; Kleemann 2022a; 2023].

The authors of the other source types are mostly known to us, which is a vital consideration in the *third stage*. They are often naturalists who recorded the weather regularly, often daily. This is the case, for instance, with the weather diary of British naturalist Gilbert White at Selbourne (England), whose "Naturalist's Journal" manuscript for 1783 and the following years are available at the British Library [White 1783; 1784; 1785]. Several other contemporary naturalists also kept weather diaries, writing about their meteorological observations [Christ 1783; von Beroldingen 1783; Woodforde 1782–1784]. The authors in question could observe this strange weather with their own eyes. These sources are also contemporary and independent [Kleemann 2023].

Concerning the *fourth stage*: regarding the narrative patterns, naturalists responded, for the most part, intellectually to the impacts of the Laki eruption by speculating about the cause of this unusual weather. They gathered data, conducted experiments, and debated in learned societies and through academic journals in an effort to find an answer. Many different theories were in circulation at the time. Some blamed the earthquakes in Calabria, southern Italy. Others suggested that the large-scale introduction of lightning rods had deprived the air of its "fertilizing electricity," which in turn led to the formation of the fog. A few naturalists, as early as the summer of 1783, postulated that an Icelandic volcano, such as Hekla, or the new "burning island" off the coast of Iceland, was to blame. These scientific explanations were published by contemporary newspapers in an effort to calm their readership, which can be seen as a coping strategy. Additionally, newspapers undertook interviews with the elderly, who reassuringly stated good harvests had usually followed similar events in the past. The newspapers also searched chronicles, which corroborated what the elderly interviewees had said, further comforting readers [Kleemann 2019a; b].

At the time, the *Societas Meteorologica Palatina*, a meteorological society with its headquarters in Mannheim (Germany), operated a network of more than thirty weather stations across Europe and beyond. The society's weather observers received standardized instruments and forms with instructions to take note of the instruments' readings at three specific times per day. After the year's end, the forms were sent to Mannheim, where they were compiled into annual compilations called *Ephemerides* [Pappert et al. 2021]. The Ephemerides for 1783 include instrumental data on temperature and pressure and sometimes remarks on *meteora*, unusual observations that include descriptions of the sun setting in a blood-red color [Ephemerides 1785]. The careful application of the scientific method by various weather observers from numerous weather stations in different parts of Europe and the collection of large quantities of data rule out topoi. Social factors did not play a mitigating role in western Europe regarding the Laki haze specifically, as it affected everybody regardless of their social standing [van Swinden 2001]. It is, however, a good example of how this critical approach can stimulate research by adding new aspects to current debates on the interrelation of nature and society.

The coping strategies that European contemporaries developed are the focus of the *fifth stage*. In terms of economy, the hot temperatures and Laki haze did affect vegetation in some parts of western Europe; the crops largely recovered and famine was avoided that year [Grattan and Pyatt 1994; Stothers 1996]. Contemporary newspapers nevertheless offered some practical advice: A newspaper report in the *Königlich-Privilegirte Zeitung*, a Berlin-based newspaper, from 24 July 1783 suggested that vegetables affected by the fog should be washed properly before consumption. The diligent smoking of tobacco was also recommended, as was keeping livestock inside. These recommendations were written by an anonymous correspondent from Hanau (Germany). There is no indication that suggestions like those mentioned above were widely adopted [Kleemann 2023].

The people from these regions suffered from bouts of ill health: those with pre-existing respiratory diseases suffered due to the air pollution caused by the Laki haze; others complained of sore throats and stinging eyes [Brugmans 1783; Santel 1997; van Swinden 2001]. Some regions in England and France experienced increased mortality during the summer and autumn months of 1783. It is, however, not certain that the haze was directly responsible for these bouts of disease. It may be that the haze aggravated pre-existing conditions [Durand and Grattan 2001; Grattan et al. 2003; Witham and Oppenheimer 2004; Garnier 2011]. Further research is needed to establish which other regions within Europe, if any, suffered increased mortality in the second half of 1783.

Newspapers were widely available in 1783 and during that summer, they frequently mentioned the Laki haze. One theory that circulated in the media and was later debunked centered around different fire-spitting volcanoes in Germany, including the Gleichberg, both of which were blamed for the unusual weather. In this case, newspaper articles from different regions within Germany reported that four different mountains of volcanic origin were throwing out stones and seemingly showing signs of an imminent eruption. This story serves as a reminder that it is prudent to be cautious even with historical accounts that seem reliable [Grattan et al. 2000; Kleemann 2022a].

Thunderstorms were widespread in 1783; they were likely triggered by the Laki eruption [Hochadel 2009; Brázdil et al. 2017]. One coping strategy in the German-speaking countries in 1783 was the ringing of church bells (*Wetterläuten*). This practice, which was thought to avert thunderstorms, had its origins in pre-Christian tradition [Meineke et al. 2010]. This ringing of church bells for this purpose was later abolished because of the real danger of electrocution [Kleemann 2023].

Some contemporaries suggested there was a connection between the eruption and the severe winter that followed [Franklin 1785]. Modern natural scientists confirm some of these theories [Hochadel 2009; Zambri et al. 2019a; b]. The cold winter 1783/1784 was interrupted by a sudden thawing and heavy rain, which led to widespread and significant flooding along many rivers in central and western Europe; in some of the affected towns, flood markers show that the 1784 floods were the highest or second-highest to have occurred since at least the fourteenth century [Glaser 2008; Bauch 2020]. While the affected communities had the means to mitigate the dangers and consequences of flooding, (these included using cannons and church bells to warn of imminent risk, churches and monasteries providing aid, and exempting affected citizens from taxation), they found it difficult to deal with the dry fog [Degroot et al. 2021].

When applying the approach to the Laki case, the following new insights emerge:

1) The availability of historical sources with regard to the Laki eruption, both within and outside of Iceland, is extraordinarily rich. The historical sources give us a good idea of what happened in Iceland. In Europe and beyond, the dry fog and other unusual phenomena captivated onlookers and naturalists alike; their observations give us a detailed picture of this nature-induced disaster and its hemispheric teleconnections.

2) The contemporary newspaper accounts of the Gleichberg and other mountains in Germany "throwing out stones" remind us to be cautious even with sources that seem reliable. At the same time, they indicate the diverse (and sometimes misleading) coverage by the media.

3) More interdisciplinary research is needed on the topic of the Laki eruption; this may shed light on the role the eruption played in mortality in 1783.

4) In Europe, the response was primarily of an intellectual nature: The first and foremost concern was data collection. In the dark as to its cause, it was difficult, even for those who had witnessed the fog first-hand, to prepare for a similar event in the future.

4 Discussion

This historical-critical approach is a tool to aid and support the interdisciplinary cooperation and communication between historians and natural scientists from different disciplines. For nature-induced events, this approach provides a guideline with a list of questions in each of the five stages to ensure historical sources are suitable to use as corroborative evidence in conjunction with studies from the natural sciences.

The historical-critical approach enables scientists to select reliable sources to support their studies with data from archives of societies (see Figure 1 and Section 3.1). It serves as a guideline for natural scientists working with historical topics in interdisciplinary settings, introducing them to crucial questions relating to the selection, evaluation, and interpretation of historical sources. However, the first stage of the approach also reminds historians to look beyond the realm of history and to include findings and data from the natural sciences. This is crucial in order to confirm whether an event that is described in historical sources can be cross-referenced by other means, such as geological and paleoclimatological data. The in-depth discussion of "noise" factors in the approach avoids circular reasoning. The historical-critical approach is a powerful and easy-to-use tool for interdisciplinary approaches to historical climatology, historical disaster studies, and, more broadly, environmental history. The proposed approach equally integrates knowledge gained from the natural sciences and history. Thus, current research can yield new

results and a deeper understanding of nature-induced disasters can be attained. This is strengthened by the consilience approach [Haldon et al. 2018] as the methods of the natural sciences and the humanities are epistemically entirely different and independent.

As Sessa [2019] reminds us that "climate [...] has a cultural history that is inextricably interwoven with its physical history" and the consilience approach "cannot be anchored in a system of knowledge that neglects the role of language in the generation of structures of power, identities, and worldviews." She points out that many studies have not integrated the cultural or linguistic turn of recent scholarship. Like proxy records, a historical source is not simply a picture of the past; it needs to be interpreted in the context of its period. As becomes apparent, not every historical source is equally suited to serve as proof of a distant volcanic eruption or another extreme event. A given source is only safe to use if it covers the aspects mentioned in Section 3.1 (see above).

Both Eldgjá and Laki are examples of Icelandic flood basalt volcanic eruptions. Combined they produced more than half of all the lava ejected from Icelandic volcanoes in historical times [Thordarson and Höskuldsson 2014]. These are low-probability but high-impact events [Schmidt et al. 2011]. Applying the historical-critical approach to these two volcanic eruptions and their effects on Europe shows that this approach can be utilized for nature-induced disasters that occurred during periods for which few written sources are available (tenth century) and periods for which the sources are abundant (eighteenth century). Although both eruptions are very similar in geographic origin, eruption style, and volumes of lava and gases released, the consequences were different: While descriptions of the dry fog and the subsequent "blood-red" sunsets feature prominently in sources from the summer of 1783, similar descriptions are few and far between for 939–940. It is, of course, possible that differing conditions at the time of year (e.g. jetstream, wind patterns, high and low-pressure systems) led to less obvious phenomena in 939–940. It is also possible that the contemporary perceptions of the environmental consequences of volcanic eruptions were different. Hence, the historical-critical approach pushes research forward. It offers additional perspectives on large-scale historical eruptions and their teleconnections by asking new questions. For example: How appropriate are the historical sources in terms of the questions that need to be addressed? To what extent are social conflicts connected with natural events? Have natural events been overlooked in the context of social conflicts so far? What was the nature of *local* coping strategies in the regions affected by nature-induced events? Do other factors such as epidemics or historical atmospheric conditions play a significant role?

The approach bolsters interdisciplinary research as it leads to an increased understanding of which historical sources to choose, which to avoid, and offers new perspectives of what *else* can be analyzed to learn more about the interrelation of nature and society. By using this historical-critical approach and discussing the five stages, the results become transparent to the academic audience. This will increase the reliability of the outcomes of these interdisciplinary endeavors and the understanding of the impacts of past nature-induced disasters. While in this case the historical-critical approach has been applied to two large, effusive volcanic eruptions, it is also suitable for the study of other volcanic eruptions of a more-than-local scale and other nature-induced disasters throughout history, such as flooding events, droughts, earthquakes, or even epidemics. Studies in the field of historical pandemics and the history of medicine already show that a determined humanities perspective enriches research [Bauch 2020; Furner-Pardoe et al. 2020].

5 Conclusions

The historical-critical approach is an analytical tool for interdisciplinary studies. It can be used to examine the impact of nature-induced events and to evaluate their contribution to historical disasters. The approach serves as a step-by-step research guideline. The purpose of this approach is to sensibilize scientists to the questions historians are asking to improve interdisciplinary collaborations in the field of the history of climate and society. This approach is intended as a thought-provoking impulse that should be used for future interdisciplinary studies that test and challenge the steps laid out here. At the same time, using this approach on existing studies can enable interdisciplinary research teams to make additional findings. Answering the questions in the five stages simultaneously allows for a reflection on the interpretation of individual research data. Overall, following the historical-critical approach opens new paths of investigation, which—in the end—provides more differentiated results on a specific natural event from the perspective of the disciplines concerned. In this way, a large number of factors that may have been involved in the emergence of a disaster are examined. A reduction of "causality to simple terms" [Haldon et al. 2014], that can be perceived as monocausal explanations, can thus be avoided. If, however, the investigation proves that only one specific factor was decisive, the result is all the more convincing. The use of this historical-critical approach on the examples of Eldgjá and Laki demonstrates that the effects of two comparable volcanic eruptions were different due to natural and human-made factors. In this respect, the approach gives differentiated insights into how past societies were affected by natural impacts and how they dealt with them.

Author Contributions

Both authors contributed equally to the writing of this article, and the study's conception, design, research, and analysis.

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Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to copyright restrictions but are available from the corresponding authors on reason and request.

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