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Preface

Conceived within the Erasmus+ Blended Intensive Programme Nature, Culture, Landscape at Trnava University in Trnava, this open-access volume is intended as a compact, research-informed introduction to environmental stress and resilience in antiquity. The topic is necessarily interdisciplinary and methodologically demanding: reconstructing climate and hazards, tracing long-term ecological change, and studying epidemic disease all require the careful combination of heterogeneous evidence and distinct standards of inference. For that reason, the book does not aim at exhaustive coverage of every region and period; instead it offers readers a coherent conceptual vocabulary, methodological orientation, and pathways into the specialist literature. Throughout the volume I have aimed to balance synthesis with evidential caution. Environmental explanations in ancient history can easily slide into determinism; conversely, the fragmentary character of the evidence can invite an unproductive scepticism that treats complexity as a reason to avoid causal questions altogether. By foregrounding how arguments are assembled – through the triangulation of textual testimony, archaeological contexts, and scientific proxies, and through explicit attention to chronology, scale, and uncertainty – the chapters are designed to support discussion and to help readers assess claims on methodological as well as narrative grounds. I am grateful to the reviewers for their careful reading and constructive criticism. I also thank Trnava University in Trnava and the Erasmus+ Programme for supporting the preparation and publication of this work. Any remaining errors and omissions are my responsibility.

Introduction

In contemporary debates about climate risk, disaster, ecological loss, and emerging disease, the past is often invoked either as warning or as reassurance. Antiquity, however, resists both uses. The ancient Mediterranean and its wider connected worlds were shaped by environmental pressures that were real and sometimes severe, yet they unfolded within social, economic, and technological settings unlike those of the present. To treat ancient experience as a storehouse of straightforward lessons is to flatten contingency and to mistake analogy for explanation. At the same time, to dismiss antiquity as irrelevant is to forfeit one of the richest long-term baselines available for understanding how human societies have navigated shocks and slow pressures in the absence of modern infrastructure and global governance. The value of antiquity lies in its time depth and diversity. It offers a laboratory-imperfect, partial, and ethically distant, yet analytically powerful-in which responses to drought and flood, earthquake and eruption, ecological change and epidemic, can be observed across generations and across markedly different political forms. That long view does not give us prediction. It gives us proportion, comparative range, and a disciplined scepticism towards mono-causal stories.

Resilience is the lens that allows these interactions to be analysed without slipping into deterministic narratives. In everyday speech resilience is often imagined as bouncing back, a return to what existed before a shock. In contemporary research, resilience has a broader and more demanding meaning. It refers to the capacity of a system to absorb disturbance and maintain core functions, to adjust through learning and adaptation, and, when existing arrangements become untenable, to transform while still sustaining some continuity of purpose. Resilience is not equivalent to stability (*Holling 1973, 1 – 23*). Systems may appear stable because they dampen variability and absorb minor disturbances, yet this apparent stability can conceal the accumulation of latent risk and lead to brittle failure once critical thresholds are crossed. By contrast, resilient systems often endure by changing: by diversifying, by altering feedbacks, by reconfiguring institutions, and by reorganising relationships between people, resources, and environments. For the historical sciences this is particularly important. Ancient societies rarely returned to a previous equilibrium after disruption. They repaired, improvised, reallocated, migrated, re-legitimised, and sometimes abandoned and rebuilt (*Fachard and*

Harris 2021). Resilience, in this book, names the structured capacity behind such patterns of persistence and change.

Several distinctions are essential if resilience is to remain analytically sharp. Robustness usually denotes resistance to disturbance: the ability to withstand stress with minimal change. Robustness can be valuable, especially where life depends on continuous service, yet robust arrangements may also inhibit flexibility and accumulate risk. Vulnerability refers to susceptibility to harm and a limited capacity to cope, shaped by exposure, resources, social position, and access to support. Risk is not a property of hazards alone; it emerges where hazards meet exposure and vulnerability, and it changes as settlement, infrastructure, and political economy change. Sustainability is a normative orientation towards maintaining valued conditions over time, often with an explicit ethical horizon that includes intergenerational justice. Resilience overlaps with sustainability but is not the same (*Manyena 2006, 433 – 450*). A society can be resilient in ways that are ethically troubling or ecologically damaging, and sustainable outcomes can depend on transformations that are disruptive in the short term. Adaptation refers to adjustment to actual or expected conditions—shifts in practice, technology, or institutions that reduce harm or exploit new opportunities. Adaptation is often one component of resilience, but resilience also includes the capacity to learn, to reorganise, and to transform when incremental adjustment is no longer enough (*Walker et al. 2004*). In short, resilience is a family of capacities—persistence, adaptation, learning, and transformability—rather than a single outcome.

Resilience in antiquity must therefore be framed as social–ecological. The book’s domains—climate, hazards, biodiversity, and epidemics—are not separate environments that societies merely encountered from the outside. Ancient communities lived within landscapes of soils, waters, plants, animals, and microbes that were already shaped by cultivation, grazing, extraction, and political control. The concept of social–ecological systems, developed within resilience scholarship, offers a way to describe this entanglement without reducing culture to ecology or treating nature as a passive stage (*Adger 2000, Walker et al. 2004, Folke 2006, Cote and Nightingale 2012*). It foregrounds feedbacks: how land use changes hydrology and soil stability; how urban density reshapes exposure to fire and disease; how trade networks redistribute risk as well as resources; how political extraction alters subsistence strategies and thus ecological pressure.

It also foregrounds scale. Historical evidence forces us to think in nested levels: households and neighbourhoods, villages and cities, regions and imperial networks; local ecologies and long-distance provisioning; immediate hazard impacts and long aftermaths of repair and demographic change. What appears resilient at one scale may be fragile at another, and what is adaptive locally may be maladaptive for a wider system.

The concepts of the adaptive cycle and panarchy provide one interpretive grammar for this multiscale view. The adaptive cycle describes recurrent phases through which systems can move: expansion and accumulation, consolidation and rigidity, release under disturbance, and reorganisation in which new combinations emerge. Panarchy extends this by emphasising that such cycles occur at multiple scales and interact across them (*Gunderson and Holling 2002*). Slow-moving structures—land tenure regimes, irrigation networks, administrative routines, cultural norms—create memory that can stabilise recovery after shocks; at the same time, they can constrain innovation and lock systems into vulnerable pathways. Fast-moving disturbances—earthquakes, eruptions, epidemics, sudden military defeats—can trigger release that forces reorganisation, sometimes enabling transformation that was previously impossible. The value of this framework is not that it imposes a universal cycle on the past, but that it encourages attention to dynamics: to how resilience is built through diversity and redundancy, how it is undermined by overconnection and rigidity, and how cross-scale interactions can either buffer or amplify crisis. It also encourages precision about temporalities. Some adjustments occur within weeks or seasons; others unfold across lifetimes; still others become visible only in the *longue durée* of settlement change and institutional evolution (*Fachard and Harris 2021*).

The critical question, however, is always resilience for whom, to what, and at what cost? Resilience research in the social sciences has insisted that resilience is not an unqualified good. It is shaped by power, and it is often achieved through unequal distributions of burden (*Folke, 2006, 253 – 267*). In antiquity, survival and recovery were conditioned by social position, legal status, gendered labour, and access to land, credit, and protection. The ability of a city to rebuild monumental infrastructure after an earthquake could coexist with intensified extraction from the countryside. The maintenance of imperial supply systems under drought could depend on coercive requisitioning, forced mobility, or the displacement of risk onto fron-

tier communities. Even within a single urban space, resilience was unevenly distributed: elites could retreat, purchase substitutes, or mobilise patronage; the poor were more exposed to food price shocks, unsafe housing, and epidemic mortality. A historically minded resilience perspective therefore treats recovery not only as a technical process of rebuilding, but also as a political process of allocation, legitimacy, and contestation.

This distributive lens also clarifies the phenomenon of maladaptive or undesirable resilience. Systems can become resilient in ways that entrench damaging trajectories. Short-term buffering can be achieved by intensifying exploitation of forests and soils, by expanding cultivation into marginal lands, or by concentrating population in economically productive but hazardous locations. Such strategies may maintain output and political order for a time, yet they can erode ecological resilience and increase exposure to future hazards (*Walker et al. 2004*). Institutions too can be resilient in troubling ways. Extractive fiscal regimes, coercive labour systems, and violent forms of frontier control can persist precisely because they are buffered by force and by ideological normalisation; their resilience can amplify vulnerability among subordinated groups and degrade the ecological conditions on which wider society depends. The analytic task is therefore not to celebrate resilience, but to specify what exactly persists, what changes, who benefits, and which costs are deferred or displaced.

To connect these concepts to antiquity requires a methodological bridge attentive to the character of historical evidence. This book works across historical texts, archaeology, and the natural sciences not to produce a seamless master narrative, but to practise consilience in the stricter sense, and triangulation in the historical sciences: the convergence of independent lines of evidence on the most plausible reconstruction. Texts record perceptions, explanations, and institutional responses, yet they are shaped by genre conventions, rhetorical aims, and uneven survival. Archaeological deposits reveal settlement patterns, destruction horizons, repair practices, and shifts in material culture, yet they can time-average events and blur sequences (*Karkanas 2021, 34–49*). Palaeoclimate and palaeoenvironmental proxies provide independent constraints on hydroclimatic regimes, vegetation change, and extreme events, yet they vary in spatial representativeness and chronological precision (*Finné et al. 2019, 847–863*). Bioarchaeology adds direct evidence of diet, stress, health, and

mobility; biomolecular methods—ancient DNA, proteomics, and related approaches—extend the evidential range into pathogens, domestication histories, and the circulation of species (*Cappellini et al. 2018*). Each line of evidence carries uncertainty. The task is to handle that uncertainty explicitly: to distinguish correlation from causation, to avoid forcing alignment where chronologies do not permit it, and to recognise that complex systems can display delayed and indirect responses.

These methodological commitments are especially important because environmental history is prone to mono-causal explanations. Climatic variability can reshape harvest reliability, water access, and migration pressures, but its consequences depend on land tenure, storage capacity, market integration, taxation, and political legitimacy (*Hakenbeck and Büntgen 2022*). Natural hazards can destroy infrastructure and housing, yet whether they become systemic crises depends on building practices, emergency response, resource mobilisation, and long-term repair. Biodiversity change can alter ecosystem functions and disease ecologies, but its social meaning depends on subsistence strategies, property regimes, and cultural valuation of species and landscapes. Epidemics can produce severe mortality and labour disruption, but their trajectories are shaped by mobility networks, urban density, nutrition, and the capacity of institutions to maintain care and provisioning. The historical record is full of cases in which severe environmental stress did not produce collapse, and of cases in which political fragmentation occurred without obvious environmental triggers. Resilience provides a vocabulary for analysing these outcomes as system dynamics rather than as simple chains of cause.

The chapter on climate establishes the broad environmental background in which other stressors operate and clarifies why variability matters more than average conditions for historical societies. It examines the mechanisms through which climate influences water regimes and agricultural reliability, and it shows how hydroclimate can be reconstructed from diverse archives such as lake sediments, speleothems, tree rings, and marine records. Because proxy signals are spatially heterogeneous and chronologically constrained, the chapter emphasises methodological care: the need to interpret reconstructions at appropriate scales, to avoid overconfident precision, and to attend to the difference between regional patterns and local lived experience. It also explains why volcanism matters, not as a dramatic

anecdote but as a physical mechanism of volcanic forcing through which aerosol pulses can produce short-lived cooling and hydroclimatic perturbations that may nonetheless have large social effects. Finally, it explores the relationship between climatic stress and movement of people. Environmental migration is treated not as an automatic response to drought or cold, but as a contingent outcome shaped by political opportunity, violence, household resources, and the permeability of frontiers.

The chapter on natural hazards shifts attention from slow pressures to sudden events and to the difference between hazard and disaster. Earthquakes, tsunamis, floods, eruptions, and fires are physical processes with their own rhythms and probabilities (*Guidoboni and Ebel 2009, De Boer and Sanders 2005*), but their social consequences are produced by exposure and vulnerability: where people build, how infrastructures are maintained, and how resources are distributed. The chapter uses ancient cities as a focal point because urban environments concentrate risk while also concentrating capacities for recovery. Cities may amplify hazard impacts through density, complex water systems, and heavy architecture, yet they also host administrative tools, specialised labour, and fiscal and social networks that can enable rapid repair (*Bresson 2021, Borsch 2023*). In a resilience perspective, the crucial questions concern not only destruction but the sequences that follow: evacuation and return, reconstruction and redesign, the politics of aid and taxation, and the role of memory in shaping future preparedness (*Meerow, Newell and Stults 2016*). The chapter also highlights a methodological challenge central to hazard history: dating. Reliable reconstructions depend on aligning textual chronologies, stratigraphic sequences, and, where possible, scientific dating methods that can constrain the timing and magnitude of events.

The chapter on biodiversity decline extends resilience thinking into the living systems that underpin subsistence, material culture, and health. It defines biodiversity broadly, encompassing not only species richness but also genetic diversity, functional traits, and ecological interactions. This matters for resilience because ecosystem functions—pollination, soil formation, pest regulation, and the stability of food webs—depend on diversity and on the redundancy of ecological roles (*Cardinale et al. 2012*). The chapter traces domestication, exploitation, and species dispersal as long-run processes through which human societies reconfigured landscapes and biotic

communities. These processes produced benefits—greater food supply, labour power, transport capacity—but also new vulnerabilities: habitat simplification, reliance on a narrower range of crops and animals, and altered interfaces between humans, domesticates, and wild species. The chapter thus treats biodiversity change not merely as loss, but as a reorganisation of social–ecological relations with feedbacks for productivity, disease, and the capacity to recover from shocks.

The chapter on epidemics draws these threads into the sphere where social and biological processes are most visibly intertwined. It shows how the study of ancient epidemics now depends on a deliberate combination of methods: close reading of texts attentive to genre and symptom description, archaeological analysis of burial practice and mortality patterns, bioarchaeological reconstruction of stress and health, and biomolecular detection of pathogens where preservation allows. Patterns of spread are approached through connectivity and ecology rather than through retrospective certainty. Epidemics move along routes of trade, pilgrimage, military mobilisation, and migration; they find favourable conditions where urban density, nutrition stress, and disrupted sanitation increase susceptibility and transmission (*Harper 2021*). The chapter also emphasises that epidemics are not only biological events but social shocks. They test institutions of care, religious explanation, fiscal extraction, and military recruitment, and they can reshape labour relations and settlement patterns. In resilience terms, the question is not simply whether societies survived, but how they reorganised—whether recovery restored previous arrangements, produced adaptation, or forced transformation.

Across these domains, a unifying idea is compound and cascading stress. Many of the most consequential crises arise not from single hazards but from interactions among pressures, whether simultaneous or sequential (*Knapp and Manning 2016*). A climatic anomaly can lower harvest reliability and weaken nutrition (*Vidal-Cordasco and Nuevo-López 2021*); weakened nutrition can increase susceptibility to disease; disease can disrupt labour and provisioning; disrupted provisioning can intensify migration and conflict; and conflict can further degrade ecological conditions and governance capacity. An earthquake can damage aqueducts and housing, increase crowding, and accelerate disease transmission through compromised water quality and displacement. Such cascades are not inevitable, but they become more likely when systems are tightly coupled and when safety margins

have been eroded by inequality, ecological degradation, or political instability (*Hakenbeck and Büntgen 2022*). Connectivity is central to this analysis and is historically distinctive in the ancient Mediterranean. Roads, ports, and imperial supply systems could buffer shocks by enabling import, redistribution, and the movement of specialised labour and knowledge. The same corridors could transmit crisis, carrying pathogens, invasive species, and political instability from one node to another. Resilience, in this sense, is inseparable from the ambivalence of connection.

The organisation of the book follows this integrated logic. It begins with climate because climatic regimes and hydroclimatic variability shape the background probabilities within which other stressors unfold, and because reconstructing that background requires careful methodological discussion. It then turns to natural hazards, where the contrast between event and aftermath makes resilience visible in practice through evacuation, rebuilding, and institutional learning. The discussion of biodiversity deepens the temporal frame, demonstrating how long-run ecological transformations can either enhance or diminish the capacity to absorb shocks, and how human–animal relations form part of the infrastructure of resilience (*Cardinale et al. 2012, 59–67*). The exploration of epidemics then brings the analysis into the domain where environmental stress becomes embodied, and where the coupling of mobility, urbanism, and biology produces shocks that are simultaneously demographic, economic, and cultural (*Harper 2021*). Read together, the chapters build an argument about interacting stressors and system dynamics rather than about isolated causes.

A few episodes serve as recurring points of orientation, not as deterministic templates but as analytically rich cases. The eruption of Thera raises questions about how spectacular events are dated, how they disrupt exchange networks, and how their consequences can be mediated through sequences of vulnerability rather than through immediate political rupture. The disruptions that closed the Bronze Age highlight how interdependence can become fragility when multiple pressures converge across trade, warfare, and subsistence, and how reorganisation can take the form of both contraction and innovation (*Knapp and Manning 2016*). Accounts of urban destruction and recovery—whether in earthquake-prone regions or in cities threatened by flood and fire—show how resilience is built through repair cultures, institutional capacity, and social memory, and how reconstruc-

tion can involve both restoration and redesign. Late antique disease shocks, read alongside episodes of climatic stress and volcanic perturbation, illustrate how compound pressures can test imperial supply systems, intensify inequality, and prompt shifts in settlement and governance. In each case, the interpretive aim is not to narrate collapse, but to trace capacities: how societies buffered, adapted, and sometimes transformed under environmental stress.

The book's contribution is therefore twofold. For historical scholarship, it offers a synthesis that treats environmental stress not as an external factor appended to political narrative, but as a set of interacting pressures that shape, and are shaped by, institutions, economies, and cultural practices. For resilience research, it offers temporal depth and evidential complexity. It shows that resilience is not only a matter of rapid response, but also of long-term maintenance, learning, and transformation; that trade-offs between robustness and flexibility can be decisive; and that distributive questions are integral rather than secondary. Antiquity does not tell us what to do. It can, however, sharpen the questions we ask in the present, offering principles rather than prescriptions: how risks are produced through exposure and inequality, how connectivity can both buffer and transmit crisis, how institutions maintain or lose legitimacy under stress, and how adaptation and transformation become possible when established routines fail. In that cautious sense, the deep past becomes a resource for thinking, not a script for action.

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1 Climate

1.1 Climate Variability and Societal Responses

Forecasts of future climate change—at regional as well as global scales—are increasingly described less as a simple rise in average temperature than as a reshaping of variability and of the statistical distribution of extremes. Heatwaves become more probable and more persistent; precipitation regimes are reorganised; the balance between evaporation and rainfall shifts; intense drought episodes recur more often, while short-lived but exceptionally heavy rainfall events also intensify, frequently with flood consequences. These signals do not remain confined to weather. They feed into water availability and water quality, the stability of soil systems, changing fire regimes, accelerating biodiversity loss, and the spatial reordering of ecosystems as habitats move, fragment, or disappear. Contemporary climate change is also distinctive because it unfolds rapidly under strong anthropogenic forcing, and because it takes place in a world already dense with infrastructure, technological dependencies, and tightly coupled social and economic interdependence.

That specificity does not make earlier periods irrelevant; it changes what is sought from them. Archaeology, history, and adjacent fields provide a long temporal baseline for observing how communities and states navigated climatic stressors, hydrological instability, and ecological thresholds in contexts without modern water engineering, fossil energy systems, or globalised markets. Across this baseline, the natural sciences—geosciences and the physical, mathematical, and biological sciences—work to reconstruct mechanisms and drivers of change in the climate system, hydrosphere, and biosphere through proxy archives and modelling. Social and historical sciences, including archaeology, history, and cultural anthropology, examine how environmental shifts were translated into decisions, institutions, inequalities, symbolic orders, economic strategies, and the dynamics of conflict and migration. As human influence on landscapes and on carbon and nitrogen cycles has expanded, and as water regimes have been altered by both climate and direct management, the value of bringing these approaches into sustained conversation has grown

accordingly, especially because social linkages can convert local disturbances into wider systemic crises.

One widely used climatic and chronostratigraphic marker lies at the beginning of the Holocene, about 11,700 years ago, when interglacial conditions stabilised after the last Ice age and following the Younger Dryas episode (*Moravcová 2014, 15 – 16, Kalvová, Mikšovský and Raidl 2009, 284*). This threshold sits close to a sequence of transformations that eventually produced dense settlements, complex economies, and state-level polities in several regions, but the relationship between climatic background and social change is not a straight line. Early Holocene warming and shifts in seasonality did provide a more favourable framework in some settings for increases in productivity and population density, and for the expansion of subsistence strategies that could generate more reliable surpluses (*Bar-Yosef 2011, 175 – 192; Lieberman – Gordon 2018, 32 – 40*). At the same time, the transition from hunting, gathering, and broad-spectrum foraging to food production did not occur as a single event. It unfolded over many generations, at different tempos in different regions, shaped by local ecological constraints and by cultural choices, social organisation, and historically contingent pathways (*Beneš 2008, 34; Grosman – Mundro 2017, 699; Hayden 1981, 525 – 527, Bar-Yosef 2011, 191*).

Neolithisation is best understood as a bundle of intertwined changes rather than as a single milestone. In many places it involved increasing sedentarism, the domestication of plants and animals, and the reorganisation of labour, ownership, and cooperation. It also depended on storage and processing technologies, shifts in mobility and landscape management, and the emergence of new symbolic and ritual regimes that helped legitimate life in larger, more permanently co-resident communities. Even the technological markers often used as shorthand—pottery above all—do not behave as universal signatures with a single chronology. In parts of southwest Asia, long pre-pottery phases preceded fully developed ceramic traditions, while innovation clustered in architecture, toolkits, cereal processing, storage practices, and social organisation rather than in ceramics alone. Seen in this light, neolithisation was not only an economic change; it was a transitional mode of society–ecosystem relations, moving from extraction within a given landscape toward the gradual production of a landscape, as people reshaped habitats, altered nutrient flows, and in doing so also reshaped the risks they faced.

Göbekli Tepe and the wider southeastern Anatolian context offer a particularly revealing window into this transition. Its importance is not limited to questions of priority or monumentality, but lies in what it demonstrates about the early emergence of coordinated labour, symbolic communication, and likely regional networks capable of sustaining large-scale projects. Monumental and complex cosmological or ritual undertakings could be organised by societies (*Schmidt 2010, 244*) without metals and without a fully established agrarian regime. The site points toward explanations in which demography, seasonal mobility, ritual commitments, prestige economies, and resource availability are tightly interwoven, rather than explanations that run only from climate change to technological advance (*Renfrew 2009, 156 – 157, Dietrich et al. 2012, 675*).

Regional diversity remains central to the longer story. In parts of the Near East, relatively predictable seasonal cycles and rising productivity in particular ecosystems supported long-term investments in fields, irrigation, and storage, and helped make permanent or semi-permanent settlement more viable (*Mieroop 2010, 21 – 24*). In northern Africa, Holocene humid conditions enabled temporary habitability across areas that are now hyperarid: communities expanded into regions associated today with the Sahara and the Western Desert, leaving settlements, burial grounds, rock art, and evidence of pastoral strategies in landscapes structured then as mosaics of savannas, lakes, and wetlands (*Bárta 2016, 102 – 106, Kuper – Kröpelin 2006; Lieberman – Gordon 2018, 43 – 45*). Europe adopted agrarian strategies later and unevenly. Farming spread through combinations of migration, the diffusion of knowledge, and local adaptation to soils, climates, available domesticates, and existing social structures, producing distinct regional patterns rather than a single uniform package moving at a single pace (*Cavalli-Sforza, Menozzi and Piazza 1994, 257, Mateiciucová 2008, 30; Beneš 2008*).

Alongside these trajectories of expansion and reorganisation, climate history is also frequently approached through episodes in which climatic and hydrological shifts coincided with political instability or the weakening of complex polities. In some cases environmental change appears as a primary stressor; in others it interacts with processes already underway, including political fragmentation, economic strain, demographic pressure, inequality, or institutional breakdown. Because climatic shifts are variable across time and space, responses also diverge. Outcomes depend not only on the

strength, duration, and frequency of environmental stressors but on resilience and adaptive capacity: institutions, technologies, cultural norms, redistributive mechanisms, and the flexibility of economic strategies all shape whether pressure translates into crisis or into managed adjustment. External linkages matter in these histories because societies rarely developed in isolation. Exchange networks, migration corridors, and political competition created dependencies as well as opportunities. In highly connected systems, vulnerability can be relational: the weakening of one node—whether through harvest failure, conflict, or loss of access to a resource—can transmit stress through trade, alliances, and flows of goods and people, producing cascading effects beyond the original point of disruption.

A frequently discussed impulse around the transition from the third to the second millennium BC is the so-called 4.2-kiloyear BP event, often placed around 2200 BC. The evidence is better described as a temporally approximate but spatially uneven clustering of drier conditions and hydrological instability in some regions, recorded through multiple proxy indicators that include lake sediments, speleothems, ice cores, palaeobotanical data, and dust components. In some archives the signal looks less like a single short drought and more like a broader window of heightened aridity and variability punctuated by shorter episodes. The picture that emerges is therefore not of one uniform global anomaly expressed identically everywhere, but of a set of regional hydroclimatic shifts whose timing and character differ across landscapes and proxy records (*Headrick 2020*).

Within the broad late-third-millennium BC window, Mesopotamia shows changes in settlement patterns, irrigation intensity, and the stability of political formations (*Cooper 2006, 257*). The most informative accounts remain spatially differentiated: between northern and southern zones, between rain-fed agriculture and irrigated lowlands, and between short-lived shocks and longer trends such as salinisation, erosion, and the accumulating maintenance debt of canal networks. Where production depended on coordinated canal upkeep and large-scale labour mobilisation, environmental risk was bound tightly to institutional capacity. Systems of redistribution, legitimacy, administrative coordination, and security shaped whether irrigation infrastructure could be sustained precisely when conditions demanded more careful management, and military conflict or

political competition could erode that capacity even without a single dramatic environmental catastrophe.

In Egypt, the transition between the Old Kingdom and the First Intermediate Period is often discussed in relation to low Nile floods. At the same time, historical and archaeological data point to political fragmentation, regional power competition, and shifts in redistributive mechanisms as dynamics that could themselves generate crisis and amplify hardship. Beyond these two well-studied regions, late third millennium BC changes are not consistently tied to the same mechanisms or chronologies across south Asia and east Asia. In some settings, monsoon dynamics and river geomorphology appear central; elsewhere, the interplay between drier episodes and extreme floods seems more consequential. Across the broader Old World, the late third millennium BC is therefore often described most convincingly as a period in which multiple stressors converged in different configurations rather than as a single switch that mechanically determined civilisational outcomes (*Headrick 2020; Cooper 2006*).

Political formations in southern Mesopotamia illustrate how control of land and water could become the medium through which wider tensions were expressed. A long-running dispute between the Sumerian cities Umma and Lagash over boundaries and access to productive land and irrigation regimes is already documented in the mid-third millennium BC. Its value is not as an illustration of later aridification, but as a clear example of the way agrarian ecology and water-management infrastructure could function as a political arena, where environmental parameters and power interests were braided tightly together (*Mieroop 2010, 54 – 61*). Interdependence through trade and exchange adds another layer to the way breakdown and reorganisation can unfold. Networks carried raw materials and prestige goods, but also information, obligations, diplomatic ties, and alliance structures. When these networks were disrupted—through regional crises, conflict, or shifting access to resources—the buffering capacity of states could shrink. The ability to smooth local production failures, to finance administrative apparatuses, or to maintain political coalitions could decline, increasing the risk of de-integration even if no single shock was sufficient on its own (*Butzer 1997*).

In Mesopotamia, the movements and gradual integration of groups referred to as Amorites contributed to the reorganisation of power after the collapse of Ur's hegemony, with new dynasties emerging

in Babylon, Larsa, Isin, and Assur. In this context, proposed links between drought and the fall of the Third Dynasty of Ur are most informative when treated as interactions between environmental pressure and sociopolitical dynamics rather than as a simple one-step chain from rainfall deficit to collapse (*Mieroop 2010*). In Egypt, accounts of social unrest, hunger, and indebtedness appear alongside narratives of declining Nile floods during the First Intermediate Period, suggesting a meaningful intersection of environmental and social factors. Interpretation is also shaped by the fact that Egyptian literary and ideological motifs of chaos and restored order could serve as instruments of political legitimation, not merely as straightforward reports of climatic conditions. Even where scholars debate the weight to assign to climatic drivers, the combination of environmental and social dynamics remains central to explanation (*Headrick 2020; Trigger et al. 2005; Malek 2003; Lieberman – Gordon 2018; Moreno García 2021; Seidlmayer 2003*).

The decline of Minoan Crete, long placed in older narratives around 1500 BC, remains a classic case for understanding how natural hazards, conflict, and sociopolitical change can interact across time. The eruption of Thera was among the largest Holocene eruptions and plausibly carried regional consequences, including seismic impacts, tsunami risks in some coastal zones, ash fall, and disruption of maritime movement. Present understanding, however, is more attentive to chronology and to multi-step causality. Absolute dating of the eruption commonly falls between the late seventeenth and sixteenth centuries BC depending on method (*Pearson et al. 2018*), while major destruction horizons at Cretan palace centres and the consolidation of Mycenaean dominance are generally associated with later phases of the Bronze Age. The eruption can still be integrated into explanation as a source of longer-lived economic and logistical vulnerability that later actors could exploit, while internal tensions, shifts in distribution, and changing alliances also shaped outcomes.

The crisis and transformation often grouped under the label of collapse around 1200 BC likewise resolves, on closer inspection, into a series of regionally connected disruptions across the eastern Mediterranean and the Near East (*Shaw 2003, 343; Singer 2011, 14, 15, Kaniewski et al. 2010, 213, Mieroop 2010, 169*). Palace systems and political formations in multiple areas were destroyed, radically restructured, or displaced; Egypt survived, though at substantial cost

and with later fragmentation. Explanations combine military conflict and internal revolt with the vulnerabilities of palace redistribution economies, earthquakes along seismically active belts, piracy and disruption of maritime routes, and climatic or hydrological pressures that may have contributed in some regions to repeated crop failures and migrations (*Weiberg – Finné 2021, 215 – 242, Knapp and Manning 2016*). The spread of iron belongs to this story, but its wider adoption in many contexts appears as much a consequence of reorganised economies after the disruption of bronze exchange networks as a primary cause of systemic breakdown. The Sea Peoples, known from Egyptian inscriptions and iconography, are increasingly interpreted as heterogeneous coalitions and migratory conglomerates with varied origins and motivations rather than as a single ethnically homogeneous actor (*Killebrew – Lehmann 2013, 16 – 17*). Their movements can be placed within a landscape of combined pressures in home regions, opportunities for raiding and resettlement, and weakening state control along maritime and coastal corridors.

In late antiquity and during the dissolution of the Western Roman Empire, relationships between climate, ecology, and state stability become still more intricate. In the fourth and fifth centuries AD, the western Roman state faced structural tensions among military expenditure, fiscal capacity, political fragmentation, and shifting frontier geopolitics. Environmental factors in this setting functioned less as a single decisive trigger than as variable background conditions that could influence agricultural output, mobility patterns, and disease dynamics (*Hakenbeck 2022*). The distinction between West and East is also crucial: the end of western imperial authority in 476 AD was the outcome of a long process shaped by politics, warfare, and economic change, and it does not reduce neatly to climate. At the same time, Roman and post-Roman systems were sensitive to multi-year fluctuations in production and to disruptions of transport corridors, and the later sixth century brought pronounced climatic anomalies together with epidemiological shocks that affected Mediterranean demography and state capacities in a world already reshaped by earlier political transformations. Across these cases, environmental stressors can be understood as factors that alter the probability and texture of crisis, while the trajectories that follow depend on vulnerability, institutional adaptability, and the presence—or absence—of collective mechanisms capable of translating risk into coordinated response rather than into cascading political and economic failure.

1.2 Environmental migration

Environmental migration is best understood not as a single phenomenon but as a spectrum of human mobility, ranging from short-term evacuations after floods or storms to long-term shifts in livelihoods and settlement as precipitation regimes change, soils degrade, water tables fall, or salinisation undermines agriculture. Within that spectrum, contemporary research often works with a threefold distinction that helps keep very different dynamics analytically separate. Displacement refers to movement compelled by immediate threat, coercion, or sudden loss of shelter and safety; it is frequently temporary and can allow return within days, weeks, or months, even if return is delayed. Migration is a broader frame that can include preventive, seasonal, and opportunity-seeking movement with varying degrees of constraint and choice, sometimes undertaken precisely to reduce future risk rather than to escape an already unfolding emergency. Planned relocation describes organised resettlement mediated by institutions, usually framed as a response to recurring or escalating exposure, intended to move people out of high-risk zones while creating conditions for durable livelihood recovery in the receiving area (*Cattaneo et al. 2019*).

In lived reality these categories interpenetrate. Repeated evacuations can harden into prolonged displacement; prolonged displacement can become migration once return is socially, legally, or economically unviable; and environmental risk can also immobilise people, producing trapped populations who would like—or need—to move but lack cash, legal status, information, safe routes, or receiving networks. This risk-multiplier framing also sharpens what migration can mean when the analytical lens is extended to antiquity and underscores the need for an explicitly interdisciplinary approach. Paleoclimatology and historical ecology can identify when and where precipitation, temperature, extremes, and water availability shifted (*Hughes 2012, 21 – 22*); environmental archaeology and bioarchaeology can trace changes in subsistence, health, and individual movement; and ancient history and migration studies can show how institutions, inequality, trade networks, and violence mediated those pressures into displacement, migration, immobilisation, or planned relocation.

Several influential ancient civilisations, before their crises or transformations, reached a degree of connectivity that can be described

as a cautious form of globalisation: not modern global integration, but dense interregional exchange linking distant regions through trade, diplomacy, military alliances, and the mobility of artisans, merchants, mercenaries, and, at times, forcibly moved populations, as in Near Eastern Bronze Age states, Hellenistic monarchies, or Imperial Rome. Such connectivity could generate prosperity and resilience through diversified supplies, but it also created systemic vulnerability. A shock in one node—crop failure in a breadbasket, a disrupted sea route, the loss of port, a breakdown of taxation, the interruption of metal supplies—could propagate through the network and reshape household decisions about whether to stay, temporarily leave, diversify livelihoods, or relocate. In premodern settings, mobility rarely equated to permanent exit. It included seasonal movement, transhumance, shifts in settlement hierarchy within a microregion, temporary movement into towns during crisis followed by return to the countryside, and the formation of diaspora communities tied to trade and specialised crafts. Environmental pressure tends to become more visible in these contexts when the balance between risk and resources shifts—when yields become more volatile, extremes more frequent, or access to water, pasture, and arable land more constrained—but the step from stress to movement is mediated by institutions, property regimes, debt relations, violence, and the availability of social networks that can make relocation feasible.

Within that mediating space, experiences of catastrophe or unusual weather could also be preserved in collective memory and narrative, sometimes refracted through myth. Modern readers have occasionally tried to align mythic episodes with particular environmental shocks, reading the Titanomachy against the backdrop of the Thera eruption, treating imagery such as Homer's snow-covered Olympus as a cultural echo of cooler episodes in the first millennium BC, or associating motifs such as Fimbulwinter and Ragnarök with severe volcanic winters and climatic downturns discussed for the mid-sixth century AD. These alignments illustrate less a straightforward archive of precisely datable events than the layered and adaptive nature of mythic transmission. Such narratives are repeatedly retold, rearranged, and repurposed across changing historical contexts, so their strongest evidentiary value often lies in how communities framed uncertainty, hazard, and moral order, not in serving as direct records of specific eruptions or drought sequences pinned to a single year.

A similar caution is warranted even where the underlying evidence can be dated more tightly. In Mesopotamia toward the end of the third millennium BC, evidence consistent across several proxies in several areas points to deterioration in water balance and episodes of aridity that could reduce yields and intensify pressure on irrigation (*Headrick 2020, 70 – 75; Cooper 2006, 257*). Even so, the social trajectory does not reduce to drought forcing migration. A more realistic chain runs through yield shocks, shifts in the fiscal and redistributive capacity of palace and temple institutions, rising indebtedness and social polarisation, conflicts over canals and labour, and then mobility, whether as flight from obligations, movement toward better-watered zones, or reorganisation of settlement within a wider region. Environmental stress is real in this account, but movement becomes a mirror of how risk is distributed, who bears scarcity, and whether institutions offer credible pathways of relief.

Few ancient episodes display the interplay of climate, conflict, and mobility as vividly—and as analytically demanding—as the transition from the Late Bronze Age to the Early Iron Age in the eastern Mediterranean. Older syntheses sometimes framed this as a sudden collapse of civilisation, but the evidence fits better with a complex transformation of palace systems, economies, and political structures unfolding over decades to generations, with sharply different regional trajectories. Some centres disappeared, others contracted or moved, some areas saw the interruption of written administration, while elsewhere settlement continuity and adaptation persisted. Proxy records from parts of the eastern Mediterranean suggest episodes of drier conditions and climatic instability in this period, but the spatial pattern is not uniform, and individual proxies can respond strongly to local hydrology or vegetation dynamics rather than to a single regional climatic regime (*Weiberg – Finné 2021, 215 – 242*).

Climate therefore enters most robustly as one stressor among several that could tighten food security and amplify conflict in particular contexts, not as a single cause of violence and mobility. Equally important are the systemic properties of Late Bronze Age political economies: high specialisation, dependence on imported strategic materials, sensitivity to disrupted shipping, concentrated storage in palace redistributive centres, and competition over ports, fields, and labour. When repeated damage to infrastructure, falling yields, and fractured trade flows accumulate, mobility can become a rational survival strategy, sometimes as movement into less exposed micro-

gions, sometimes as the formation of armed migrant coalitions seeking resources and political settlement within newly opened spaces of power (*Shaw 2003, 343; Singer 2011, 14, 15, Kaniewski et al. 2010, 213*).

In this context, the so-called Sea Peoples and the emergence of a Philistine cultural enclave in the southern Levant are most coherent when approached as outcomes of mixed movements and rapid reconfiguration rather than through a single, simple invasion narrative. Archaeological evidence from some early Iron Age Philistine centres does show strong Aegean-related elements in ceramics, cuisine, and certain technologies, yet such signals do not automatically imply a single massive demographic replacement. A picture that allows for mixed groups, selective adoption of cultural forms, local continuities, and fast processes of integration and identity formation fits both the variability of the material record and the broader instability of the period (*Singer 2013, 19 – 27; Barako 2003, 163 – 164, Killebrew – Lehmann 2013, 16 – 17*). Framed this way, the environmental question shifts from whether a drought episode expelled one neatly bounded people to how a conjunction of risks—yield volatility, conflict, piracy, weakened redistribution, and broken routes—created conditions in which new coalitions formed and new settlement regimes emerged at the margins and within the remnants of post-palatial networks.

In Greece after around 1200 BC, the traditional model that attributed major demographic change to a sudden, decisive movement of Dorians into the Peloponnese has increasingly given way to a mosaic of regional developments. The collapse of Mycenaean palace centres, changes in settlement hierarchy, movement toward more defensible locations, variable degrees of demographic contraction, and the gradual formation of new communal ties appear in different combinations across regions. Mobility likely took multiple forms, including short-distance relocations within regions, movement toward islands and coastal zones, and, over longer horizons, the creation of networks across the Aegean and the western coast of Anatolia. The label Greek Dark Ages functions most precisely as a conventional shorthand for a phase with limited written evidence and reorganised material culture, rather than as a judgement of civilisational “night,” because archaeology also reveals continuity, innovation, and adaptive strategies that helped enable the later emergence of the polis (*Kotsonas 2016*).

The subsequent expansion commonly known as the "Great Greek colonisation" shows how mobility could become more systematic and strategically organised, while still remaining diverse in actors and aims. Its core belongs roughly to the eighth to sixth centuries BC, when Greek communities founded *apoikiai* in southern Italy and Sicily, along the shores of the Black Sea, in North Africa, and across other parts of the Mediterranean, while earlier movements in the Aegean–Anatolian zone after the Mycenaean collapse formed a distinct background. Colonisation was not simply military expansion. It comprised variable projects mediated by kinship ties, cult, and trade networks, shaped by intersecting motivations that could differ sharply from one case to another: internal conflict and political struggle within city-states, pressure on land in some microregions, the desire to secure access to grain, metals, timber, and strategic harbours, and opportunities to refound communities with new distributions of land and status (*Tsetskhladze 2006, Tsetskhladze 2008*).

Environmental factors mattered here chiefly through the quality and accessibility of land, the reliability of water regimes, and local risk profiles. Colonisation also acted back on environments. New settlements transformed landscapes through clearance, intensified agro-systems, terracing, and new pasture use, thereby altering their own long-run exposure to scarcity and extremes. Where the returns on olives and vines required multi-year investment and remained sensitive to climate variability, cycles of harvest, debt, and social tension could plausibly increase incentives to leave, though the mechanism runs through unequal access to land and capital as much as through rainfall itself. Similar precision helps when later expansions are attributed to environmental stress. The spread of La Tène material culture and the historically documented Celtic expansions in the late fifth and early fourth centuries BC are generally understood as the outcome of multiple interacting processes. These include shifting political configurations, military organization and economies, and the circulation of prestige goods and social networks, while environmental conditions are typically treated as a broader contextual framework that shaped opportunities and constraints rather than as a direct causal driver.

In the Roman world, environmental migration becomes even harder to isolate because the empire itself continuously produced mobility through military deployments, veteran settlement, mercantile diasporas, the forced movement of enslaved people, and administrative transfers. Climatic impulses therefore often acted indirectly

through food supply, price volatility, taxation, and the stability of frontier zones. The case of the Cimbri and Teutones illustrates this complexity because later narratives have often reduced it to a single environmental cause such as flooding in northern Europe. Even if environmental stress contributed to an initial impulse, the historically consequential trajectory depended on coalition-building, conflicts with neighbours, Roman diplomacy, and the logistics of war, with decisive Roman victories occurring at the end of the second century BC, culminating in 102 – 101 BC.

From the second to the sixth centuries AD, it is plausible to speak of a period marked by cooling and increased climatic variability that coincided with far-reaching changes across the Roman Empire and its neighbouring regions. Such a general outline, however, only becomes analytically meaningful when it is grounded in regional differences and in the functioning of institutions that shaped how environmental pressures were experienced and managed. Climatic fluctuations did not operate as a uniform external force acting on the empire as a whole; rather, they formed part of a changing background against which political, military, economic, and demographic processes unfolded (*McCormick et al. 2012, 169 – 220*).

The Marcomannic Wars of 166 – 180 AD illustrate this dynamic particularly well. They are sometimes presented in simplified narratives as the result of pressure from the north caused by climate-induced harvest failures that pushed populations toward Roman frontiers. A more comprehensive interpretation situates these conflicts within the context of frontier politics, the formation and reconfiguration of barbarian coalitions, imperial military strategy, and existing demographic and economic strains within the empire. Environmental variability may have contributed by periodically reducing agricultural output or disrupting local supply systems, thereby increasing stress in frontier zones, but it did not by itself generate war. Instead, climatic pressures interacted with political decisions, military mobilisation, and the distribution of resources, amplifying tensions that were already present and shaping the timing and intensity of conflict rather than determining its occurrence outright.

Processes commonly associated with the Migration Period from the fourth to the sixth centuries AD show how environmental stress, political and military dynamics, and social transformation could reshape societies, while resisting a single chain in which a drought

somewhere automatically produces migration and then the fall of an empire (*Hakenbeck 2022*). The political-military sequence can be stated more firmly: Hun expansion altered power balances across the steppe, increased pressure on Gothic groups, contributed to their crossing of the Danube, and exposed weaknesses in Roman integration and border control, culminating in the catastrophic Roman defeat at Adrianople in 378 AD. The extent to which these processes were climate-driven is harder to specify in general terms. Even when well-dated climatic anomalies exist, social outcomes depend on how grain and fodder reserves are organised, how negotiation and coercion are institutionalised, what levels of violence actors treat as legitimate, and how state capacity responds under strain.

Likewise, the divergent trajectories of the western and eastern halves of the empire in late antiquity can be understood only within this broader pattern of interacting pressures rather than through a simple contrast in climatic exposure. The relative resilience of the Eastern Roman Empire was shaped above all by its fiscal capacity, administrative continuity, geopolitical position, and urban and infrastructural organisation, together with the uneven spatial and temporal distribution of crises across the imperial world. Climatic pressures operated within this constellation as an additional layer of risk, capable of intensifying existing stresses or accelerating unfavourable trends, yet insufficient on their own to account for the complex patterns of migration, conflict, and state transformation that characterised the period.

1.3 Reconstructing Hydroclimate

Reconstructing past climate, and especially the spatial distribution of precipitation, relies largely on indirect archives that record climatic signals only through the mediation of physical, chemical, and biological processes operating within landscapes. It is precisely this mediation that makes hydroclimate more difficult to reconstruct than temperature. Rainfall and water availability result from the interaction of atmospheric circulation, seasonality, topography, and evaporation, while individual proxies are often sensitive to only one component of the water balance or to a specific season rather than to annual precipitation as an integrated whole. In many regions, tree rings primarily record growing-season water stress, a signal that can be amplified by

high temperatures through increased evapotranspiration. As a result, narrow rings may reflect dry conditions, hot conditions, or a combination of both, rather than reduced rainfall alone (*Bradley 1999, 8 – 9, Guibal – Guiot 2021, 117 – 120*).

Pollen spectra, by contrast, integrate changes in vegetation and soil moisture across broader catchments, but they are also strongly influenced by land-use practices such as clearance, grazing, and cultivation. This means that the hydrological signal they preserve is often inseparable from human impacts on the landscape. Speleothems can provide high-resolution chronological records, yet their isotopic and trace-element signatures usually reflect several influences simultaneously, including changes in moisture source, precipitation seasonality, temperature, soil evaporation, and the effects of prior precipitation. Lake and marine sediments add valuable multiproxy information, but they introduce further interpretive challenges (*Bradley 1999, 247 – 250; Veron 2009, 198 – 206*). Their spatial representativeness can be uneven, sedimentation rates may vary through time, reservoir effects can complicate radiocarbon dating, and the dominant signal often reflects hydrological processes such as runoff or lake-water balance rather than precipitation amounts in a strict sense.

Chronology represents a fundamental constraint across all of these archives. Even with improved radiocarbon calibration and high-precision U–Th dating (uranium–thorium dating used mainly for speleothems), realistic uncertainties on the scale of decades to centuries frequently complicate attempts to identify synchronicity, especially when records from different environments are compared as if they shared the same temporal resolution (*Kalvová, Mikšovský and Raidl 2009, 281*). This is why multiproxy approaches and regional clusters of records have become increasingly important, and why interpretations are strengthened by a clear distinction between local, regional, and pan-continental perspectives (*Horák 2021, 11 – 15*). In practice, the same time interval can encompass contrasting hydroclimatic tendencies across Europe and the Mediterranean, making spatial context—where a record comes from, which season it reflects, and which component of the water balance it records—a central part of interpretation rather than a minor technical detail (*Kalvová, Mikšovský and Raidl 2009, 281*).

Many questions remain open when reconstructing climate over longer timescales, not because evidence is missing, but because the available records are diverse and strongly dependent on local context. Climatic and environmental archives rarely point to a single, clearly bounded transition. Instead, they indicate gradual and spatially uneven changes in seasonal insolation and atmospheric circulation, shaped by interactions within the ocean, cryosphere, and biosphere. From a hydroclimatic perspective, these processes tend to produce regionally differentiated patterns rather than uniform shifts across large areas. In archaeological discussions, such changes are often placed within a broad chronological window, most commonly between about 4000 and 3000 BC (*Dreslerová 2005, 543 – 545*). Climatic archives, however, more frequently suggest a drawn-out and sometimes multi-phased reconfiguration, with local developments appearing earlier in some regions and later responses emerging elsewhere, rather than a single moment of change shared across Europe or the Mediterranean (*Dreslerová 2005, 543 – 545*). This difference in perspective highlights the importance of scale: what appears as a transition in archaeological periodisation may correspond, in climatic terms, to a long sequence of overlapping regional processes rather than to a sharply defined turning point.

When scholars seek to explain precipitation variability in Europe and the Mediterranean over periods of several decades to several centuries, attention often turns to the North Atlantic. The importance of this region, however, lies not in the existence of a single transferable climate pattern, but in the way large-scale atmospheric circulation influences the distribution of rainfall (*Finné et al. 2019, Trigo, Osborn and Corte-Real 2002*). References are made to so-called Bond cycles or Bond events, identified through increased ice-rafted debris in North Atlantic sediments and often associated with cooling and changes in circulation. Their main value is that they point to recurring phases of circulation reorganisation rather than to a regular, clock-like cycle that could be projected directly onto Mediterranean hydroclimate. For precipitation, the decisive processes involve how atmospheric pressure gradients shift, how the position and strength of the westerly winds change, how often cyclones develop and follow particular tracks, and how persistent blocking situations reorganise airflow. The North Atlantic Oscillation plays a central role in this context, not as a fixed cycle, but as a dominant mode of atmospheric variability that alters the pressure contrast between the subtropical

Atlantic and the Icelandic region. Through this mechanism, it strongly influences storm tracks and winter rainfall across Europe (*Trigo, Osborn and Corte-Real 2002*).

A simplified way of describing this influence is to imagine storms tending either toward northern Europe or bending southward into the Mediterranean. While this image can be useful for basic orientation, it does not describe a stable rule. The often-invoked contrast between wetter conditions in parts of northern Europe and drier conditions in parts of the Mediterranean, or the reverse situation, is not fixed in space or time. The eastern Mediterranean and continental interiors frequently respond in different ways, depending on synoptic circulation patterns, topography, and interactions with other modes of atmospheric variability. This complexity has direct consequences for proxy interpretation. The same large-scale circulation anomaly can result in wetter conditions in one subregion and drier conditions in another (*McCormick et al. 2012, 169 – 220*). Moreover, commonly used terms such as aridity, drought, or humid phase can refer to different underlying constraints, depending on whether the limiting factor is winter snowfall, seasonal rainfall, runoff, evaporation, or soil moisture. As a result, precipitation variability is best understood as a spatially differentiated response to circulation dynamics rather than as a uniform signal imposed across Europe and the Mediterranean.

These interpretive principles become especially consequential in discussions of well-known hydroclimatic episodes. The drought and instability often discussed toward the end of the third millennium BC and commonly referenced under the umbrella of the 4.2-kiloyear BP aridification event has appeared in older syntheses as an almost global turning point linked to the decline or collapse of complex societies across large parts of the world (*Headrick 2020, 70 – 75*). A more empirically grounded description treats it as a cluster of regional hydroclimatic anomalies with varying timing, duration, and in some cases even direction of change. In parts of southwest Asia and in segments of the Mediterranean, multiple records align with drier conditions or heightened variability, while elsewhere the signal can be weak, ambiguous, or locally wetter.

Framed in those terms, historical linkage is most convincing as a story about a risk environment becoming more difficult: agricultural yields become less reliable, provisioning more volatile, pressure rises on redistribution, taxation, and water infrastructure, and political for-

mations become more vulnerable to additional stressors. In Mesopotamia, where accounts sometimes connect weakening urban states with reduced winter precipitation in the Mediterranean sphere that feeds the headwaters of the Euphrates and Tigris, the strongest formulation remains conditional (*Headrick 2020, 70 – 75, Cooper 2006, 257*). Hydroclimatic change affecting upper-basin recharge could raise stress in downstream systems, but the downstream outcome depended on whether livelihoods relied primarily on rain-fed agriculture or irrigation, on the robustness of storage and interregional transfers, and on concurrent conflicts and shifts in power.

Similarly, hypotheses connecting Late Bronze Age aridity in the eastern Mediterranean to shifts in winter storm track can be compatible with parts of the proxy record, yet confirmation is not uniform across all subregions (*Weiberg – Finné 2021, 215 – 242*), and plausible mechanisms include changes in blocking frequency, sea-surface temperatures, and the interaction of multiple modes of variability rather than a single tidy rerouting of cyclones.

Another frequently discussed episode is cooling and hydroclimatic change in the first millennium BC, sometimes labelled the 2.8-kiloyear BP event and, in some interpretations, associated with reduced solar activity affecting atmospheric dynamics and hydrology in parts of western Europe. Terms such as a Homeric minimum or Homeric oscillation circulate in this context. The most usable way to handle these designations is to treat them as working labels rather than as universally standardised intervals with one agreed mechanism (*Harding et al. 2022*). Temporal coincidences with indicators of solar variability can be suggestive, but hydroclimatic causation still runs through circulation regimes that distribute precipitation in spatially differentiated ways. In many discussions, some archives point toward wetter or more cyclonic conditions in parts of western and northwestern Europe, while other regions, including parts of eastern Europe and some Mediterranean zones, show signals of drier or more unstable conditions. This kind of spatial mosaic fits the known sensitivity of European precipitation to circulation patterns and helps explain why a hemispheric event can register in regionally contrasting ways.

It also frames how links to historical processes can be formulated. Greek expansion, and in some contexts Phoenician mobility, unfolded above all through social, political, and economic drivers: structu-

ral tensions within poleis, trade opportunities, and power strategies. Environmental conditions are most plausibly treated as one contextual pressure among several, shaping agricultural risk and access to resources in specific localities rather than supplying a general explanation for colonisation as such (*Tsetskhladze 2006, Tsetskhladze 2008*). Within the Greek world, the centrality of water and fertile land is visible not only in outward expansion but also in domestic conflicts. The struggle over the Lelantine Plain between Chalcis and Eretria on Euboea, traditionally referred to as the Lelantine War, remains a powerful illustration of how control over productive land could become a focal political issue (*Thuc.1.15.3*). The evidence base, however, supports a broad dating horizon rather than a narrow one, and the conflict is commonly placed around the late eighth to seventh centuries BC. What later tradition presents as a single war may have consisted of episodes whose scope was expanded retrospectively.

Spatial variability remains equally important for broader European trends across the Iron Age. The term Iron Age cold epoch is sometimes used for a neoglacial phase with cooler conditions in parts of the North Atlantic sector, often placed roughly between the ninth and fourth centuries BC (*Harding et al. 2022*). The useful content of that frame lies in recognising a set of episodes whose expressions differ by region rather than in imagining a homogeneous block with one peak and one hydroclimatic response everywhere. This is also why the overlap between heightened climatic variability and the cultural, economic, and political flourishing of fifth-century BC Athens does not, on its own, imply climatic causation. Athens is explained primarily through institutional change, geopolitics, and imperial resources; climate could influence agricultural risk and logistics, but without direct evidence the soundest statement is that the trajectories overlap in time rather than that one produced the other. The same general point applies across Europe: warming and cooling trends, and shifts in precipitation, can be different or even opposite across northern, central, and southern regions (*Dreslerová 2010, 19*).

Similar caution is needed when using labels such as the Roman Warm Period or the Roman Climatic Optimum. These terms are best understood as broad heuristic frames that refer to relatively favourable conditions in certain parts of Europe and the imperial periphery during the late Republic and early Empire, rather than as descriptions of uniform or stable climate across the Roman world (*McCormick et*

al. 2012, 169 – 220). Even in phases often regarded as comparatively favourable, hydroclimatic conditions remained uneven. The Mediterranean continued to be sensitive to multi-year droughts, episodes of extreme flooding, west–east contrasts between basins, and local effects of volcanic activity that could alter temperature and atmospheric circulation and thereby influence water regimes (Lieberman – Gordon 2018, 58). At the same time, the Roman economy was able to take advantage of exceptionally high productive capacity in some regions, most notably North Africa and parts of southern Spain. These areas were integrated into long-distance supply networks that sustained large urban populations, above all the city of Rome. The same networks that enabled prosperity also introduced systemic vulnerability. Regional harvest failures, disruptions to transport, or political and military crises could transmit stress across wide areas, exposing the dependence of urban centres on stable flows of grain and other resources.

Imperial demand for food and the logistical systems that supported urban consumption formed part of a wider interconnected world that also included large-scale entertainment economies. Among the most striking examples were the *venationes*, arena hunts and staged combats involving wild animals transported from across the empire. From the late Republic onward, such spectacles expanded significantly in scale, and later monumental amphitheatres, culminating in structures such as the Colosseum, created architectural settings in which mass entertainment could be regularised and intensified. In some regions, especially North Africa and parts of the eastern provinces, this demand contributed to sustained hunting pressure on wildlife and, in certain cases, to the depletion or local disappearance of large animal populations.

Even where long-term conditions appear relatively favourable, catastrophic events remained an integral part of the lived risk environment. The eruption of Vesuvius demonstrates how local disasters could abruptly reshape population patterns and economic activity irrespective of average climatic conditions. Earthquakes, floods, and episodic volcanic events were capable of interrupting trade, driving up prices, and triggering emergency movements of people. From the perspective of precipitation, instability often arose not only from gradual long-term change but from increased variability. Alternating years of deficient winter rainfall and years of extreme precipitation could prove more socially disruptive than a slow, moderate trend,

because volatility undermined planning, storage strategies, debt relations, and confidence in systems of provisioning.

For late antiquity and the transition to the early medieval period, scholarship increasingly points to a context of heightened climatic variability, including cooling episodes associated with major volcanic events, while patterns of precipitation remain markedly uneven across regions (*Finné et al. 2019, Büntgen et al. 2016*). In some phases, parts of the eastern Mediterranean show signals consistent with relatively favourable or more stable winter precipitation, whereas other areas of the empire and its surrounding regions experienced greater variability and, in certain cases, drier conditions. How these patterns are interpreted depends crucially on whether the available records primarily reflect winter or summer hydroclimate and on the ways individual proxies translate climatic conditions into measurable signals (*McCormick et al. 2011, 169 – 220*). Within this setting, changing climate conditions can be understood as one factor that increased pressure on economies, fiscal systems, and the provisioning of armies and cities. Their historical significance, however, lies not in direct causation but in how they interacted with institutions, inequality, redistributive mechanisms, and security arrangements. Political outcomes emerged from these mediating structures rather than from climatic stress alone.

Regional examples illustrate this interaction clearly. Sicily's role as a major grain-producing region, together with dendrochronological evidence indicating relatively regular precipitation regimes in parts of the Levant, points to areas where environmental conditions supported continued agricultural output (*Haldon et al. 2018, 3210 – 3218*). At the same time, evidence for prolonged drought in parts of Anatolia between roughly 400 and 540 AD suggests substantial regional stress that could affect local economies and settlement patterns. Responses to such pressures, however, cannot be reduced to climate alone. Large-scale water infrastructure in Constantinople reflects the city's structural requirements for water security rather than a simple reaction to drought. Aqueducts and large cisterns formed part of a strategy aimed at reliability and redundancy in a metropolis whose population size, administrative centrality, and military vulnerability, including the risk of siege, made secure water supply a political imperative. The Aqueduct of Valens, constructed under Emperor Valens in the fourth century AD, is best understood as one element within a broader system that was expanded and maintained

for demographic, political, military, and environmental reasons, with climatic variability reinforcing the value of storage and redundancy without acting as the primary driver of investment.

Finally, precipitation reconstruction contributes most to understanding the migration period of the fourth to sixth centuries AD when it is used to clarify mechanisms linking environmental variability with political and military processes. Steppe pastoral societies were indeed sensitive to changes in precipitation and pasture productivity, and climatic pressures could affect economic stability, patterns of mobility, and the potential for conflict. These environmental influences, however, operated within a broader field of political dynamics (*Hakenbeck 2022*). The large-scale movements associated with the transformation of the late Roman world arose primarily from developments within steppe confederations, including shifts in power, military domination, alliance-building, violence, and the strategic exploitation of vulnerabilities along Roman frontiers. The Roman state itself played an active role in shaping mobility through federate agreements, organised resettlements, diplomacy, and coercion, even as it faced internal constraints related to military finance, political legitimacy, and administrative coordination. For Gothic groups as well, the evidence points to long-term reconfigurations around the Black Sea and Danube regions, where demographic pressures, economic connections, and occasional harvest failures may have contributed to instability. At the same time, direct explanations that attribute movements in the second century AD primarily to overpopulation or repeated crop failures remain hypothetical and are not firmly supported by the available evidence.

1.4 Volcanic Forcing and Climatic Cooling

When reconstructing episodes of climatic cooling, volcanic eruptions illustrate how a single geophysical process can enter social history through two distinct, though often overlapping, pathways. One pathway operates at the local and regional scale and is materially direct. Explosive eruptions can damage or destroy settlements, ports, roads, agricultural land, orchards, and water infrastructure through pyroclastic flows and surges, ash fall, associated seismic activity, landslides, and, in coastal settings, tsunami-like inundations. In these contexts, impacts are spatially concentrated and immediately legible

in the archaeological record as physical disruption of built and cultivated environments.

The other pathway is indirect and mediated, and it can be experienced far from the source of the event. In this case, climatic forcing occurs when a volcanic eruption injects sufficient sulfur into the stratosphere, altering Earth's radiative balance by forming a sulfate aerosol veil (Gao, Robock and Ammann, 2008). This veil reflects part of the incoming solar radiation and increases the likelihood of short-lived anomalies in temperature and hydroclimate. A single eruption can therefore be a devastating archaeological catastrophe in its immediate surroundings while appearing, thousands of kilometres away, only as a statistically detectable atmospheric signal whose local expression depends on circulation patterns, seasonality, and ecological conditions.

A deep-time reference point that shows both the strength and the limits of volcanic explanation is the supereruption of Toba on Sumatra around 74,000 years ago. Geologically, the event is well documented by the enormous volume of erupted material and by the wide dispersal of ash across the Indian Ocean region. It is reasonable to expect that an eruption of this magnitude produced some form of climatic disturbance, potentially including cooling, changes in circulation, and ecological stress (Ambrose 1998). At the same time, the scale and duration of such effects almost certainly differed from region to region, and the leap from climatic perturbation to a single, global demographic catastrophe is far more difficult to substantiate. Genetic patterns often interpreted as evidence for a sudden population bottleneck can arise through multiple processes, and archaeological sequences in several regions point to continuity of occupation during and after the deposition of Toba tephra. Even very strong volcanic forcing does not automatically lead to a uniform demographic outcome, because human responses are shaped by regional climate and ecology, by mobility, and by the technologies and strategies through which communities secure food and resources.

In climatic terms, a volcanic winter is defined not by ash fall itself, but by the radiative effect of sulfur gases, especially SO_2 , which are oxidised in the stratosphere into sulfate aerosols. These aerosols reflect a portion of incoming shortwave radiation back into space, leading to cooling that typically lasts a few years (Gao, Robock and Ammann, 2008). When eruptions occur in close succession, this sig-

nal can be prolonged, and in some regions it may be amplified by feedbacks involving the ocean and sea ice. Cooling and changes in rainfall do not necessarily occur together. Temperature anomalies may coincide with shifts in precipitation seasonality, storm tracks, or monsoon dynamics, but the direction and intensity of hydroclimatic responses depend on latitude, season, and on whether volcanic aerosols are injected at tropical or high latitudes. As a result, even when volcanic forcing is clearly recorded in ice cores, regional histories of drought and flooding can differ sharply.

Changes in atmospheric circulation can redistribute moisture, while cooling simultaneously alters evaporation rates and snow dynamics, producing contrasting local outcomes. For this reason, reliable reconstructions rely on the convergence of evidence from multiple independent archives rather than on any single, visually striking signal. Ice cores can record sulfate deposition and, in some cases, microtephra that help to date eruptions and estimate the scale of aerosol loading. Tree rings can document summer temperature anomalies and growth stress, while speleothems, lake sediments, and historical sources provide insight into regionally specific hydrological responses. Each of these archives captures a different aspect of the climate system and carries its own sensitivities, limitations, and chronological uncertainties, which makes their combined use essential (*Finné et al. 2019*).

The same interpretive logic applies to the Holocene and to historically documented periods. Icelandic volcanism is frequently discussed not only because of its potential climatic effects, but also because tephra layers form valuable chronological markers that allow palaeoecological records across parts of northwestern Europe to be aligned. The late Bronze Age eruption of Hekla, often referred to as Hekla 3, is a well-known example, widely used to synchronise environmental sequences and anchor regional chronologies (*Baker et al. 1995*). High-latitude eruptions of this kind can produce pronounced regional cooling, yet their global impact is typically weaker than that of large tropical eruptions. In older periods, interpretation is further complicated by dating uncertainties and by the difficulty of separating volcanic signals from other sources of climatic variability. For historical analysis, it is therefore more accurate to speak of an increased likelihood of short-term climatic anomalies than of a uniform or universal cooling effect.

A different category is represented by eruptions such as Vesuvius, where the dominant impact was local destruction and only secondarily any broader climatic effect. Vesuvius illustrates what defines a high-hazard volcano: not periodicity, but the combination of explosive potential with exceptional exposure, including dense populations, critical infrastructure, and complex urban systems located within reach of lethal flows (*Doronzo et al. 2022*). In Campania, seismic unrest already formed part of the background risk landscape, and the earthquake of AD 62 had severely damaged Pompeii and its surroundings, showing how cumulative damage and prolonged reconstruction could increase vulnerability well before the eruption itself. The eruption of AD 79, which destroyed Pompeii, Herculaneum, and other settlements, is therefore best understood as a locally catastrophic event rather than as a driver of regional climatic change. Its social consequences arose primarily from the direct physical hazards of pyroclastic currents and surges and from the interaction of repeated shocks with existing demographic, economic, and institutional stress. Contemporary sources reflect how tremors, eruption, and subsequent hardship were experienced as a sequence of crises, sometimes associated with disease, scarcity, and political response (*Dio Cass.45. 17. 8, 66. 23. 5; Suet. Tit. 8. 3*).

Over the longer history of the Roman world, periods of cooler conditions toward the later imperial era are sometimes discussed in connection with large-scale environmental influences, including volcanic activity and changes in solar output (*Wanner et al. 2011*). For historical interpretation, however, the crucial point lies less in identifying a single external cause than in recognising the growing importance of variability in a system whose functioning depended on its capacity to absorb stress. Shifts in climate could affect agriculture, transport, and frontier environments, thereby increasing the likelihood of supply disruptions and influencing when and where logistical pressure emerged. These effects were not uniform across the empire and were closely intertwined with warfare, fiscal resources, and the organisation of provisioning systems. Differences between regions, often described in terms of contrasting experiences in the western and eastern parts of the empire, are most clearly understood as variations in exposure to risk rather than as direct reflections of climate alone. Even where conditions were relatively favourable in certain areas, stability depended on administrative structures, infrastructure, and security arrangements (*McCormick et al. 2012: 169*

– 220). Similar environmental pressures could therefore lead to very different social and political outcomes, shaped by how resources were managed, how authority was exercised, and how inequality was distributed.

The mid-sixth century stands out as an unusually well documented period of strong volcanic influence on climate, supported by evidence from several independent sources. Ice cores preserve large sulfate deposits that indicate the presence of extensive aerosol veils in the stratosphere, while tree-ring records from wide areas of the Northern Hemisphere show signs of abnormal summers and growth stress consistent with reduced incoming solar radiation (*Büntgen et al. 2016, 231 – 236, Harper 2017, 252 – 253, Baillie et al. 1994*). Together, these records point to a significant disturbance of the climate system rather than to a local or isolated event. Within this broader body of evidence, the account by Procopius of Caesarea describing a dimmed or weakened sun gains particular significance (*Procop. Pers. 4.14.5*). It is best understood not as a precise meteorological measurement, nor as direct proof of a specific volcanic eruption, but as a contemporary observation of unusual atmospheric conditions. Its interpretive value lies in the fact that it coincides in time and general character with independently reconstructed signals from ice cores and tree rings, strengthening the case for a widespread atmospheric disturbance. Current reconstructions commonly interpret the mid-sixth-century episode as involving at least two, and possibly three, major volcanic impulses, occurring around AD 536, around AD 540, and again later in the 540s (*Baillie et al. 1994*).

At the same time, linking individual sulfate layers in ice cores to particular volcanoes remains difficult. In many cases, diagnostic volcanic ash is absent, transported over very long distances, or preserved in quantities too small to allow secure geochemical identification. As a result, several potential source regions have been proposed, including Central America, the western Pacific, and Indonesia. The climatic effects of volcanic forcing do not take the form of a single, uniform cooling across the entire Northern Hemisphere (*Gao, Robock and Ammann, 2008*). Although aerosol veils can influence climate on a broad scale, changes in atmospheric circulation often produce pronounced regional differences. Some areas may experience stronger cooling, others primarily shifts in precipitation patterns, and still others an increase in variability rather than a sustained trend. What is often described as a Late Antique Little Ice Age is therefore best un-

derstood not as a single, clearly bounded climatic episode, but as a longer period during which the likelihood of cold anomalies increased in parts of the North Atlantic region and Eurasia (*Büntgen et al. 2016, 231 – 236*). This pattern appears to have been maintained by a sequence of volcanic eruptions and reinforced by ocean and sea-ice feedbacks, while local climatic trajectories varied considerably in timing and expression.

From a historical and ecological perspective, the key analytical task is to follow the pathways through which climatic forcing translates into the risk of scarcity (*Büntgen et al. 2016*). In agrarian societies, summer cooling and changes in seasonal patterns could reduce crop yields, shorten growing seasons, delay or prevent the ripening of vines, or increase susceptibility to plant disease. At the same time, hydroclimatic shifts could disrupt pasture productivity and river transport, affecting both food supply and mobility. These pressures, however, did not operate in isolation. Harvest failure did not automatically result in famine. Outcomes depended on storage capacity, redistribution mechanisms, price controls, military requisitions, and the ability of state authorities and local institutions to redirect resources. Where supply networks were resilient and alternative livelihoods available, climatic stress might be reflected mainly in higher prices or limited population movement (*Hakenbeck 2022*). Where political authority was weakened by conflict, heavy taxation, or insecurity, similar pressures could escalate into widespread nutritional crisis and social unrest (*Procop. 2.14, Dio Cass. 60.11*). In this sense, volcanic forcing acted less as a direct cause than as an amplifier of stress, exposing vulnerabilities and accelerating tensions that already existed within the system.

This framework also helps clarify the relationship between sixth-century climatic disturbances and the first historically documented plague pandemic in the Mediterranean world, commonly known as the Justinianic plague. The causative agent is securely identified as *Yersinia pestis*, and the initial major outbreak affected the Eastern Roman Empire in AD 541/542, followed by recurrent episodes over several decades. The precise routes by which the pathogen entered Mediterranean environments remain debated, and estimates of overall mortality vary widely and almost certainly differed from region to region. Climatic anomalies and episodes of food stress may have increased vulnerability and strained the capacity of communities and states to respond, but the dynamics of plague transmission depended

on ecological reservoirs, vectors, patterns of mobility, and social interaction. These processes cannot be reduced to temperature change alone. A more plausible historical picture is one of concurrence, in which warfare, population movements, disruptions to provisioning, local harvest failures, and climatic variability combined to create conditions in which a pathogen with viable transmission pathways could generate repeated crises.

In the Eastern Roman Empire, this concurrence also had a distinct political and military dimension. During the later sixth century, the state faced recurring epidemics alongside intense strategic pressures, including prolonged conflict with the Sasanian Persian Empire and destabilising incursions by Slavic and Avar groups (*Bouzek 2005, 514*). These challenges reduced strategic flexibility and narrowed the capacity to absorb additional shocks. Some scholars have also pointed to heightened seismic activity in the eastern Mediterranean during this period, sometimes described as an Early Byzantine tectonic paroxysm, inferred from a combination of historical accounts, archaeological destruction layers, and geological evidence. The evidentiary basis for identifying earthquake clustering remains uneven, since historical catalogues depend on the survival and distribution of sources and on how events and impacts are defined. What is more securely observable is the cumulative effect of repeated shocks on urban infrastructure. Damage to cisterns, aqueducts, harbours, and granaries increased exposure to later climatic shortfalls and military threats, compounding vulnerability over time.

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2 Natural hazards

2.1 Understanding Natural Hazards

Research on past natural disasters becomes more informative once it starts from a basic but crucial insight: a catastrophe is not something that exists on its own inside a volcano, a fault line, a river valley, or a coastline. It emerges when a physical hazard encounters a specific society, shaped by particular infrastructures, land-use decisions, institutions, and social inequalities. From this perspective, hazard and risk are not interchangeable terms. Hazard refers to the physical potential for events such as earthquakes, tsunamis, floods, eruptions, or fires, and to the range of intensities these processes can reach. Risk arises only when such hazards intersect with exposure and vulnerability: where people and assets are located, how settlements are built and governed, how resources are distributed, and what capacities exist for warning, response, and recovery (*De Pascale 2023, 2 –19*). This distinction is not merely conceptual. It determines what kinds of evidence can answer which questions, and it prevents descriptions of “what happened” from being confused with explanations of “why it had serious social consequences.” It also helps explain why research on ancient and historical disasters has, for several decades, relied increasingly on interdisciplinary approaches.

By combining historical texts, archaeological evidence, geoscientific data, palaeoecology, and modelling, scholars can reconstruct both the physical event and the social processes through which it mattered (*McCalpin 2009, Cutter et al. 2008, 598 – 606*). These processes may lead to food shortages, population movement, increased disease vulnerability, or conflict, but they can also result in recovery, institutional learning, and long-term changes in landscapes and settlement patterns. Methods that lie at the boundary between earth sciences and archaeology have played a key role in this shift because they move analysis away from dramatic narratives and toward measurable processes and recurring patterns. Approaches such as paleo-volcanology, paleoseismology, and geoarchaeology make it possible to study not only individual events, but also their frequency, typical size, and spatial extent (*Ambraseys 2006, 1008 – 1016, Goldberg, and Macphail 2006*). They also highlight that stress often accumulates

through repeated shocks, whether closely spaced in time or spread across generations, rather than through a single spectacular disaster.

In earthquake research, one of the most practically important objects of study is the active, or capable fault. This term refers to a fault that has deformed the ground surface or shallow geological layers in the recent geological past and is therefore capable of producing surface deformation relevant for regional risk. Such faults can be studied through surface mapping of displaced landforms and by excavating trenches across fault scarps or deformed sediments (*Jusseret and Sintubin 2017*). These trenches expose layers created by successive rupture events, which can then be described and dated. Radiocarbon dating, luminescence techniques—especially optically stimulated luminescence (OSL)—and statistical analysis allow these events to be placed within time ranges expressed as probabilities rather than exact dates (*Wintle and Murray 2006, 369 – 391*). These results are well suited to hazard assessment based on scenarios and ranges, rather than precise predictions. The same methods also make their limitations clear. Paleoseismology does not yield precise forecasts of the timing and magnitude of future earthquakes, because the geological record is incomplete and unevenly preserved.

The recent history of northeast Japan illustrates how scientific knowledge of hazards and institutional risk management can diverge. Geological research on the Sendai Plain showed that coastlines accustomed to historical tsunamis had also been affected by much rarer but far more extreme events, expanding the range of scenarios relevant for coastal planning and infrastructure design, even without precise predictions of timing or magnitude (*Minoura et al. 2001, 83 – 88; Sawai et al. 2012*). The 2011 earthquake and tsunami exposed the consequences of such extremes, including cascading failures at the Fukushima Daiichi nuclear power plant, where tightly coupled infrastructure amplified risk. The key lesson is not simply ignored warnings, but structural misalignment: scientific evidence can define what is possible, while preparedness is shaped by standards, institutional routines, economic priorities, and political choices that do not automatically follow that evidence.

The same disaster–exposure–vulnerability framework also links disaster research to ecological questions that are directly relevant to present concerns about biodiversity. Sudden shocks can reshape habitats, eliminate some species, and create opportunities for oth-

ers. These changes may happen quickly, but they can also unfold through long recovery processes lasting decades or even centuries. Palaeoecology has long used proxies such as pollen, charcoal, plant remains, isotopes, and sediment chemistry to trace these dynamics, and in recent years it has increasingly incorporated molecular methods. Analyses of ancient DNA, and especially sedimentary environmental DNA (sedaDNA) preserved in lakes, wetlands, or soils, can detect the presence of species even where visible remains are rare or pollen signals are unclear (*Parducci et al. 2017, 924 – 942*). These methods are most informative when they reveal consistent patterns of presence or change across stratigraphic sequences and when they align with evidence from other proxies. At the same time, their limitations are well defined. Problems of contamination, uneven preservation, time-averaging, and difficulties in measuring abundance mean that molecular data are most reliable when used as part of a broader multiproxy approach rather than as a complete inventory of past ecosystems.

Archaeology and the historical sciences add a crucial social dimension to this picture. Without them, even the most detailed environmental reconstruction risks portraying nature as acting on passive societies. Excavated remains and written sources show how communities understood extreme events, what they lost, what they rebuilt, and how authority, trust, and decision-making were tested. They also reveal how responses to crisis were organised, whether through evacuation, rescue, provisioning, or longer-term institutional measures. Importantly, they make clear that disasters rarely end when the immediate event is over. Death, loss of housing and property, contamination of water and food, and the disruption of services often set in motion longer processes such as economic decline, population loss, famine, or epidemic disease. These extended consequences can shape societies across generations and may become embedded in collective memory, preserved in stories, rituals, or lasting changes in settlement patterns and land use.

Material evidence from archaeological contexts, however, seldom points to a single, clear moment of rupture. What later appears as a sharp turning point is often, in stratigraphic terms, the result of multiple episodes of damage, repair, political change, and gradual deterioration. The destruction layers on Crete around the transition between the eighteenth and seventeenth centuries BC illustrate this well. These horizons have often been linked to earthquakes and

fires and used to mark the end of the First Palace period. More recent research, however, highlights regional differences, variations in building practices and storage systems, the complex formation of destruction deposits, and the role of human decisions and political-economic processes alongside any physical disturbance (*Macdonald 2017, 327 – 358*). From this perspective, the issue is less whether an earthquake “ended” a period and more how vulnerability and recovery capacity shaped different outcomes. This interpretation is reinforced by the fact that, several generations later, Minoan society experienced renewed cultural and economic growth, visible in mural painting, stucco relief, and small sculpture.

Assessing the impact of earthquakes on cities and populations relies on two main sources of evidence: patterns of damage observed in excavated contexts and information preserved in written records. Neither source, however, provides physical parameters comparable to those of modern instrumental seismology, and archaeological destruction layers are often ambiguous. What appears to be the result of a single event may in fact combine several episodes that occurred close together in time, or it may merge sudden collapse with slower processes of decay, reuse, and rebuilding (*Karkanas 2021, 34 – 49*). This is where microstratigraphic and micromorphological soil analyses, central methods of geoarchaeology, become especially valuable. They make it possible to distinguish processes that look similar when viewed at a larger scale. Such analyses can separate deposits formed directly by an event from material that was later reworked, distinguish ash and charcoal that accumulated in place from material that was transported, and identify post-event processes such as erosion, redeposition, wall collapse, deliberate clearing of debris, reuse of damaged spaces as refuse areas, levelling prior to reconstruction, or phases of prolonged abandonment (*Ambraseys 2009, 13 – 59*).

Remote sensing and geophysical methods extend this approach beyond individual excavation areas. Techniques such as high-resolution topographic mapping, radar interferometry, magnetometry, and ground-penetrating radar allow deformation, buried structures, and geomorphological traces of past events to be mapped across wider areas, often revealing spatial patterns that cannot be detected through trenches or test pits alone. Even with these tools, attributing damage to earthquakes remains difficult because similar traces can be produced by different causes. Warfare, fire, structural failure, later construction activity, and seismic shaking can all leave overlapping

signatures in the built environment. Earthquake damage is therefore identified most convincingly when several independent indicators align. These include a coherent spatial pattern of destruction, collapse directions consistent with plausible shaking, geological evidence such as liquefaction or landslides, and comparable signals across multiple sites (*Galadini, Hinzen and Stiros 2006*). Conceptual clarity is also essential. Archaeological damage and historical descriptions primarily reflect intensity, meaning the effects of shaking at a specific location, whereas magnitude refers to the size of the earthquake source and the total energy released, usually expressed as moment magnitude (Mw). Moving from evidence of intensity to estimates of magnitude requires additional information about fault geometry, rupture length, local geological conditions, and secondary processes that can strongly influence how shaking is experienced.

Tsunamis introduce further interpretive challenges. Their sedimentary traces are episodic, unevenly preserved, and highly sensitive to local topography and coastal configuration before the event. In coastal plains, lagoons, and estuaries, tsunami deposits may appear as sand or gravel layers that thin inland and may contain erosional bases, fragments of vegetation, marine microfossils, or geochemical indicators of seawater (*Bruins 2008, 191 – 212*). None of these features is uniquely diagnostic, as storm surges, river flooding combined with marine intrusion, or breaches of coastal barriers can produce similar deposits. For this reason, the most reliable tsunami reconstructions rely on multiple lines of evidence. These typically combine sedimentological analysis with microfossils, salinity indicators, spatial mapping of deposit continuity, and modelling of flow and transport.

Flood reconstruction faces challenges similar to those encountered in earthquake research, largely because rivers are dynamic systems even in the absence of extreme events and because human engineering can substantially alter baseline conditions. Floods can leave a variety of traces, including coarse-grained event layers, slackwater sediments deposited in sheltered zones or beneath rock overhangs, shifts in river channels, or repeated erosion of riverbanks. In deltas and estuaries, however, these signals are often difficult to separate from the effects of storms and from longer-term changes in relative sea level. In such environments, context is essential rather than supplementary. Flood reconstructions are therefore most reliable when they combine multiple lines of evidence that capture both the indi-

vidual hydrological event and the broader geomorphological setting in which it occurred.

Volcanic deposits offer a different type of evidence. In archaeological contexts, volcanic ash layers can serve as particularly useful markers of short-lived events, especially when the volcanic source is securely identified and when primary ash fall is clearly distinguished from later reworking. This distinction often depends on comparing visible ash layers with cryptotephra that can only be detected through microscopic and geochemical analysis. How confidently an ash deposit can be used to synchronise sequences across sites depends on this contextual work (*Lowe 2011, 107 – 153*). Volcanic ash also illustrates the ambivalent role of disasters over longer timescales. In the short term, ash fall can damage vegetation, contaminate water, reduce agricultural productivity, and overload roofs. Over longer periods, however, weathering can enrich soils with mineral nutrients and improve certain properties. These longer-term effects are not automatic. They depend on ash thickness, chemical composition, rainfall, erosion, and farming practices, which means that similar deposits can lead to very different outcomes in different regions.

Fire is one of the most common signals in archaeological and palaeoecological records, yet it is also among the most difficult to interpret. This difficulty arises because fire can result from both natural processes and human activity. In urban contexts, fires may follow earthquakes or warfare; elsewhere they may be linked to craft production, routine domestic activity, or intentional burning for land management. The analytical task is therefore not simply to detect burning, but to determine its scale, intensity, spatial extent, and social context. Evidence such as charcoal, ash, changes in soil colour and structure, shifts in magnetic properties, thermally altered biological remains, and burnt plant materials can all contribute to this reconstruction. At the same time, each indicator is influenced by preservation conditions and by the duration and temperature of heating.

Carbonate materials illustrate these difficulties particularly clearly. Lime-rich residues or calcined fragments can point to exposure to high temperatures, but the thresholds at which such transformations occur depend on composition, grain size, and heating time. As a result, calcined material may reflect catastrophic fires, but it may also originate from organised activities such as lime production or mortar

preparation (*Conedera et al. 2009*). Even evidence for very high temperatures, such as the decarbonation of marble, becomes meaningful only when interpreted within a broader contextual framework that includes architecture, activity areas, fuel sources, and site-formation processes, rather than being treated as a simple indicator of fire intensity.

Across all these types of hazards, the archaeological record of an event is often shaped substantially after the event itself. Communities clear debris, reuse building materials, create temporary shelters, dig pits into destruction layers, and level surfaces in preparation for rebuilding. Natural processes such as erosion and redeposition continue to modify what remains, sometimes rapidly and sometimes over centuries (*Karkanas 2021, 34 – 49*). Rapid collapse of roofs and walls can seal artefacts and human remains, but it can also displace or deform them. The presence of buried human or animal remains does not, by itself, demonstrate a catastrophic natural disaster, since similar patterns can result from violence, epidemic disease, famine, or emergency burial practices during periods of social stress.

2.2 Ancient Cities, Disasters and Recovery

Archaeology seldom preserves an ancient city in a clean before-and-after tableau following a disaster. What it more often reveals is a longer urban sequence in which destruction, improvisation, repair, and occasionally prevention accumulate as additional layers in streets, houses, waterfronts, and monuments. Within that sequence, earthquakes, fires, eruptions, and tsunami appear less as self-contained events than as physical hazards whose historical consequences depend on exposure and vulnerability: where people live, how buildings are designed and maintained, how water and food are stored and distributed, how harbours and roads function, and whether institutions can mobilize labour, materials, and credit when the ground breaks, a district burns, or a shoreline is reworked. Read in this way, the archaeological record does not function only as an inventory of ruin. It can also register recovery and deliberate changes in the management of risk, and it can show that a dramatic collapse horizon in stratigraphy sometimes corresponds, in social terms, to redistributed urban functions, a contraction of the inhabited footprint,

a move onto safer topography, or a political rebranding rather than a simple ending.

Across many ancient contexts, communities did return to workable routines within one or two generations (*Fachard and Harris 2021, 1-33*), but that capacity was never a stable attribute of civic character. It depended on resources, on social and commercial networks, and on governance—on whether elites, civic bodies, and external patrons could coordinate supply, credit, labour, and legitimacy quickly enough to keep people fed, housed, and invested in staying. Where those supports were weak or fractured, a similar physical shock could trigger longer reconfiguration, and the visible form of recovery could involve re-scaling and reorientation rather than restoration of what had existed.

Antioch on the Orontes, today's Antakya, illustrates both the strengths and the limits of this way of interpreting past disasters. In antiquity, the city was a major commercial and administrative centre, located on key routes connecting the eastern Mediterranean with inland Syria and regions farther east. At the same time, it lay within a seismically active zone where earthquakes recurred over long periods. Across several centuries, the city experienced repeated shocks and compound crises. These included severe damage in the fifth century AD, conventionally dated to 458; a catastrophic sequence in the later 520s, marked by the earthquakes of 526 and 528 followed by extensive fires; further damaging events later in the sixth century; and, critically, a major political rupture in 540, when the city was captured and sacked (*Borsch 2023, 201 – 241*). That military disaster was not simply an additional blow, but a qualitatively different kind of shock whose effects could interact with, and intensify, the consequences of earlier natural events.

Accounts by authors such as Evagrius Scholasticus (*Evagr. Hist. eccl. 2.12, 4.5, 5.17, 6.8*), alongside Procopius and John Malalas, do more than describe physical destruction. They reveal how disasters became moments of political action and interpretation. These sources show what was rebuilt, who claimed responsibility, and how reconstruction was presented as evidence of imperial authority and divine favour. Under Justinian I, rebuilding in Antioch involved not only the repair of public buildings and urban infrastructure, but also a symbolic reshaping of the city's identity, most visibly expressed in its renaming as Theoupolis. Such acts were part of a broader imperial strategy through which renewal was proclaimed, interventions in

urban space were legitimised, and material reconstruction was tied to religious and political meaning (*Borsch 2023, 201 – 241*).

Antioch's longer history makes clear, however, that endurance did not imply stability. Later earthquakes, notably those of 577 and 588 AD, demonstrate that repeated reconstruction did not remove exposure to hazard. Instead, the city persisted while changing in scale, function, and internal organisation, adapting to recurring shocks without escaping them. The earthquake sequence that struck the region in 2023 and severely damaged modern Antakya does not serve as proof of ancient reconstructions, nor does it validate specific historical interpretations. What it does underline is the longevity of the hazard context. The same broad tectonic setting has produced destructive earthquakes over millennia, while the human consequences at any given moment have depended on historically specific factors such as building practices, preparedness, inequality, and institutional coordination. This distinction between persistent hazard and contingent social outcomes is precisely what allows ancient evidence to inform present questions without being misused as direct prediction or confirmation.

Constantinople, originally Byzantium, provides a parallel case that shows how exposure and institutional capacity interacted. Located near the North Anatolian fault, the city was repeatedly affected by earthquakes. The event of 447 AD famously damaged the Theodosian walls, a serious threat to a city whose security and identity depended on its fortifications. Written sources also describe dramatic landscape changes, such as uplift, subsidence, and even the emergence of new islands (*Evagr. Hist. eccl.1.17*). These details mix observation with narrative exaggeration rather than precise measurement. Under Justinian (527 – 565 AD), the city is said to have experienced at least fifteen earthquakes, culminating in a major shock in 557 that damaged Hagia Sophia, the harbour, and the walls after a sequence of smaller foreshocks (*Barış et al. 2021, 386 – 396*).

Comparisons across major urban centres can sharpen the analysis, provided they remain grounded in the concrete ways cities functioned. Large urban centres often had superior access to money, labour, and supply routes, and that could make recovery feasible where smaller communities struggled. At the same time, the concentration of people and infrastructure raised exposure: a failure of water delivery, food logistics, or harbour function could cascade into

disease, unrest, or flight. In late antiquity, rebuilding also regularly involved ideological renovation. Catastrophe could become an occasion to reorder public space, recalibrate civic identity, and renegotiate relationships among local elites, ecclesiastical structures, and imperial authority, so that reconstruction was simultaneously material and political, and the city that emerged afterward could embody a new settlement logic even when the name and many inhabitants remained (*Borsch 2023, 201 – 241*).

An earlier analogue, shaped by a different political ecology but driven by a comparable logic, is Rhodes after the devastating earthquake of 226/227 BC. The revealing feature of the Rhodian case is not only that walls and temples were repaired, but that the city activated an international field of assistance in a world without modern humanitarian institutions. Aid arrived as money, materials, food, specialized craftsmen, and even military support, and it moved through a mixture of solidarity and strategy (*Bresson 2021, 189 – 227*). Rhodes's harbour sat within dense maritime and commercial networks, and many donor states had practical incentives to stabilize a node essential to exchange; assistance therefore carried diplomatic weight and protected economic interests as much as it expressed sympathy. Even so, external support did not mechanically produce recovery. The decisive factor was the ability of local institutions to convert incoming resources into coordinated reconstruction, to restore harbour and defensive infrastructure, and to re-establish credibility in trade. In that sense, recovery functioned as an active political-economic strategy rather than a passive return to what had existed before.

The same comparative perspective also makes the limits of recovery visible. Cities did not always regain their former size or role, and when decline occurred it was often the result of repeated impacts or of the cumulative interaction between natural hazards, political violence, and economic contraction. Over time, these pressures could weaken demographic stability and fiscal capacity rather than produce a single moment of collapse. Even so, the notion of simple disappearance rarely reflects what the material record actually shows. Kourion on Cyprus, which came to an end in late antiquity after a series of earthquakes, is better understood through the slower processes of urban transformation (*Erel and Adatepe 2007, 241 – 252*). Maintenance ceased in some districts and monumental buildings, functions shifted, settlement cores moved, and the scale implied by the term

city gradually changed. Rather than vanishing outright, the urban fabric was reconfigured and reduced.

A similar pattern can be observed in Cilicia, where Anazarbos appears repeatedly in the sources as damaged by earthquakes. Evagrius records that under Justin I (518 – 527) the city suffered a powerful earthquake for the fourth time (*Evagr. Hist. eccl.*4.8). Such testimony is valuable because it documents recurrence, but recurrence did not necessarily lead to abandonment. Instead, it often prompted selective rebuilding, changes in fortification strategy, or administrative relocation. These processes can leave an archaeological record that suggests abandonment in one area while continuity persists elsewhere, albeit at a different scale or density. For this reason, broad historical trajectories can be misleading if they flatten complex local developments, but vivid individual episodes can be equally deceptive when treated as straightforward snapshots of lived behaviour. Robust interpretation depends on holding both scales together and recognising how gradual transformation, rather than sudden disappearance, often shaped the long-term fate of ancient cities.

2.3 Evacuation and Return

Archaeological evidence captures disaster response only through its material residues rather than moments of decision. Evacuation is therefore best understood not as an immediate or uniform act of flight, but as a temporally extended and socially differentiated process. People could leave in phases, divided by status and access to information; some fled while others stayed; many returned quickly to retrieve livestock, tools, documents, and valuables; and a pattern that looks like “flight” in the distribution of objects can also reflect later clearance or salvage. The Cretan site of Anemospilia, often associated with a seventeenth-century BC earthquake, is regularly presented as showing people attempting to escape during a building’s collapse, yet its interpretation remains debated in relation to the site’s ritual context and the exact reading of bodies, objects, and architecture (*Recht 2014, 403 – 432*).

The case of Thera (Santorini) raises a related methodological problem. The Bronze Age eruption is commonly linked to a picture of pre-eruption evacuation, supported by the striking absence of bodies and by indications that some portable valuables were removed,

but absence itself remains open to more than one process (*Martin, 2018, 107 – 116*). It can reflect the limits of excavation, taphonomic histories, differential destruction and burial, or departures at different points between precursor shocks and the main eruptive phases. Finds described as bed frames stacked for transport, intact vessels and amphorae placed near doorways, and other signs of selective ordering can fit a picture of salvage and attempted recovery, while still leaving room for multiple timelines and decision patterns rather than a single script of organized flight. What the evidence supports most securely is a sequence in which people responded to an evolving hazard in uneven ways, sometimes ordering belongings and attempting to protect capital, and sometimes leaving without the possibility of return.

Vesuvius in 79 AD provides a different kind of laboratory because it combines exceptionally rich material evidence with detailed literary witness, yet it also resists simplification. Pompeii and Herculaneum experienced different sequences of ash fall, building collapse, and later pyroclastic surges, producing distinct patterns of death and escape. Many inhabitants tried to flee; some died on roads or in courtyards, others sheltered in buildings, and in Herculaneum the remains of victims waiting near the waterfront have long concentrated scholarly attention on the timing of hope and catastrophe. Discussion mentions evacuation by sea organized by the imperial fleet, and the Bay of Naples did see rescue activity linked to naval capacities and individual initiative, but the outcome depended on constraints that no authority could fully control: wind direction, sea state, and the rapid evolution of the eruption. Material evidence also captures decisions that do not fit a simple binary of panic versus paralysis. The Boscoreale treasure—silver and gold vessels and coins concealed in a villa cellar—shows a household strategy that weighed escape against safeguarding concentrated wealth, including the assumption that return might be possible if valuables were hidden effectively.

A contrasting vignette comes from Kissamos on Crete, where a house-owner apparently died in a basement while trying to reach hidden valuables during a fourth-century AD earthquake. Here, too, the material pattern supports a plausible scenario of return or last-minute retrieval without granting direct access to a person's intent, which remains archaeologically opaque (*Stiros 2010, 54 – 63*). Coins from Antonine and Constantinian contexts at the site nevertheless hint at a wider texture in which disasters were experienced, including periods when natural shocks intersected with economic strain,

military pressure, and changing imperial circumstances. Across these cases, survival and mortality were shaped by variables that no single narrative can flatten: the type and tempo of the hazard, local topography, building practices, prior damage, information flows, and the availability—formal or improvised—of rescue.

The time of day could matter, and ancient traditions about nocturnal catastrophes carry rhetorical force partly because darkness magnifies vulnerability and uncertainty. The tradition of Helike and Bura in the fourth century BC, said to have been swallowed by the sea, became one of the most durable disaster stories of the Greek world (*Katsonopoulou 2005, 15 – 32, Stiros 2022a, Stiros 2022b, Katsonopoulou and Koukouvelas 2022*). Some accounts imply overwhelming loss and an inability to recover bodies, and later generations turned the submerged ruins into a site of curiosity and tourism. Reports associated with the story—Eratosthenes allegedly glimpsing a bronze statue of Poseidon beneath the water, Pausanias noting walls still visible centuries later (*Paus.7.25.4-8*), Roman visitors including Ovid drifting above the site—function as evidence for the afterlife of catastrophe in cultural memory as much as they function as descriptions of underwater remains. What they unmistakably capture is the way a disaster could become a landmark in collective time, a place to which people returned not to rebuild but to look, to narrate, and to interpret the boundary between land and sea as a moral and political lesson.

When recovery did occur, it unfolded in stages that archaeology can sometimes trace through pragmatic signatures embedded in destruction layers. Rescue pits, zones where debris was concentrated for removal, re-leveled streets, recycled stone, and makeshift installations cut into earlier deposits can reveal the work of stabilizing a city before any ambitious rebuilding could begin. Immediate priorities were concrete: locate survivors, retrieve the dead when possible, secure drinkable water, shore up dangerous structures, and improvise shelter, followed by decisions about whether to reconstruct housing, repair harbours, or invest in symbolic buildings that reasserted civic identity. Evidence from Izmir on the western Anatolian coast, including rescue pits and designated areas for removing rubble, suggests that some communities organized clearance and rebuilding in planned ways rather than relying only on spontaneous action (*Şahoğlu et al. 2021, 1 – 8*).

2.4 Post-Event Reconstruction

Urban reconstruction in antiquity was not a predictable technical sequence in which a city was damaged, repaired, and restored to its previous form. It unfolded as a social process shaped by decisions, resources, and power relations. The physical shocks themselves were real and often severe. Earthquakes could disrupt the structural logic of buildings and, through uplift, subsidence, liquefaction, landslides, or coastal deformation, alter the landscapes on which urban life depended. Floods brought erosion, sediment redeposition, contamination, and the gradual undermining of roads, bridges, and water systems. Fires destroyed organic structures and transformed the chemical composition of occupation layers. Volcanic eruptions combined ash fall, toxic gases, pyroclastic flows, and longer-lasting secondary effects on agriculture and water supplies.

The social consequences of these hazards, however, depended on exposure, vulnerability, and the ability of institutions and networks to mobilise labour, materials, capital, and authority (*Pickett 2024*). The same destruction horizon could lead to rapid rebuilding in one place and to a slow reorientation in another. Urban functions might be redistributed, neighbourhoods thinned out, public spaces reorganised, or settlement shifted toward safer locations. Even identical material traces—clearing layers, levelled surfaces, reused building stone—can mark very different paths, from renewed prosperity to gradual contraction that only later appears in the archaeological record as abandonment (*Karkanas 2021, 34 – 49*).

Volcanic burial makes the contrast between physical devastation and social reorganisation particularly clear. After major eruptions such as that of Thera, rebuilding the same urban core was often less practical than relocating settlement and production elsewhere. Where reoccupation occurred, it tended to be uneven and episodic, shaped by access to shipping routes, land availability, political relations, and changing economic networks. A similar distinction is necessary for Campania after the eruption of Vesuvius in AD 79. Pompeii and Herculaneum were not restored as full cities in their original form, yet the surrounding landscape did not become empty. The initial phase likely involved flight, temporary shelter, emergency measures, and later returns to recover property and renegotiate ownership, while longer-term urban life shifted toward other centres (*Cass. Dio 66.24*).

Across the wider Bay of Naples, elite capital did not simply vanish. Where access routes, water sources, ports, and markets remained usable, wealthy owners could rebuild, remodel, or relocate villas and estates, allowing economic activity to resume in altered forms. This asymmetry is crucial for interpretation. Return after catastrophe could mean recovery and reinvestment for landowners, creditors, and administrators, but for artisans, wage labourers, tenants, and households dependent on daily income, the same event could mean prolonged hardship. Lost tools, interrupted work, and broken supply chains could be as decisive as the collapse of walls. Understanding urban recovery therefore requires attention not only to rebuilding, but to who was able to recover, on what terms, and at what social cost.

Volcanic disasters also created material opportunities alongside losses. From the Bronze Age onward, volcanic rocks and minerals entered construction and craft economies. Builders used tuff, ash, and mixtures of burnt lime with volcanic materials, practices visible in Greek contexts such as fifth-century BC Rhodes and later developed extensively by Roman engineers. Roman construction made wide use of pumice and tuffs from Campania and Latium, and especially of pozzolan, a fine volcanic ash from the region of Puteoli (Pozzuoli). Mixed with lime and water, it produced a hydraulic binder that could harden underwater, enabling durable harbours, piers, and ambitious architectural projects.

Where earthquakes were the main hazard, reconstruction usually began with basic and practical needs whose archaeological traces are often easy to overlook. Temporary shelters, cleared streets, stabilised walls, restored access to water, and the careful sorting and reuse of rubble were immediate priorities. In the archaeological record, these actions may appear only as cleaning layers, rescue pits, levelled surfaces, or the secondary use of stone and timber, long before any major reorganisation of the city layout becomes visible. Over time, however, such early measures could develop into more substantial decisions that reshaped the urban fabric. Some districts might receive thicker walls or modified foundations, courtyards could be redesigned, and certain civic buildings might be selectively restored because they carried symbolic or administrative importance (*Pickett 2024*). Labour and investment were often redirected toward particular areas, producing uneven patterns of recovery rather than uniform rebuilding.

In antiquity, these changes rarely followed formal seismic regulations. Instead, they emerged from craft traditions, local experience, and practical judgement about what had failed and what had endured. Features that later appear earthquake-resistant therefore usually reflect multiple motivations. Timber incorporated into masonry could add flexibility and help absorb movement during shaking, but it also depended on material availability and established building practices. More massive or deeper foundations could help distribute loads and reduce uneven settling, yet the surviving evidence points more clearly to pragmatic construction choices than to deliberate strategies comparable to modern seismic engineering. In seismically active regions such as the Aegean, repeated experience during the Bronze Age may nevertheless have encouraged building methods that performed relatively well during earthquakes (*Stiros 1995, 725 – 736, Palyvou 2017, 249 – 265*). Timber framing, wooden lintels (*Tsakanika 2017, 267 – 285*), carefully bonded masonry, and finely dressed stone blocks laid without mortar—sometimes connected with clamps or dowels—allowed limited movement between elements and reduced the risk of sudden collapse.

At the same time, cities faced multiple hazards, each prompting different responses. Flood and river risks led to investments in drainage channels, embankments, raised floors, and elevated ground in vulnerable zones, as well as efforts to redirect watercourses. These measures were rarely isolated responses to danger alone. They often accompanied broader urban projects, such as widening streets, rebuilding public squares, constructing new cisterns or aqueducts, and reorganising suburban areas. While such interventions served aims related to sanitation, water supply, circulation, or civic display, they could also reduce exposure to flooding as a secondary effect.

Beyond city walls, earthquakes could reshape coastlines and river catchments in ways that influenced urban life over decades rather than days, altering anchorages, sedimentation patterns, and the movement of water through the wider landscape. Harbours and shorelines were particularly exposed to long-term sequences of interacting processes. Earthquake-related uplift or subsidence could alter coastal geometry (*Stiros 2010, 54 – 63, Stiros 2022, 319 – 328*), but the silting up or loss of ports—often a critical factor in ancient prosperity—usually resulted from several factors acting together. Erosion in river catchments, gradual changes in relative sea level, coastal engineering, patterns of maintenance or neglect, and in some cases

sudden tectonic deformation all contributed, with earthquakes often accelerating trends that were already under way rather than creating entirely new conditions. Shifts in river courses could further disrupt transport and irrigation, and ancient observers sometimes described these hydrological changes as part of the disaster itself. Evagrius, for instance, reports that after the Bosphorus earthquake of AD 447 several rivers dried up while new springs appeared where dry land had existed before (*Evagr. Hist. eccl.* 1.17).

Catastrophe also intersected with security in ways that left lasting political effects. Damage to walls, garrisons, and administrative routines could create opportunities for violence, not as an automatic result of the hazard, but through opportunistic action in a destabilised setting. Thucydides' account of the Spartan commander Astyochus attacking Meropis on Kos after an earthquake illustrates how natural disruption could facilitate military operations by exploiting local disorder, while the outcome still depended on the specific circumstances of war, intelligence, and timing within the Aegean theatre (*Thuc.* 8.41.2 – 3). A damaged city was therefore vulnerable not only in physical terms, but also institutionally and strategically, and recovery often depended as much on restoring order and protecting resources as on repairing buildings.

The Aegean, Anatolia, and the Levant lie along active tectonic zones (*Shtienberg et al.* 2021, *Shaw et al.* 2008, 268 – 275), and cities such as those on Crete and Rhodes were repeatedly exposed to strong earthquakes. Many of the best-known cases of urban damage cluster precisely where seismic activity coincided with dense settlement and vulnerable coastal infrastructure. Ephesus, one of the wealthiest cities of Asia Minor, is often said to have experienced around seventeen earthquakes over its long history. The destruction traditionally linked to an earthquake in 261 or 262 AD is widely regarded as a major disruptive episode. Important public buildings, including the Serapeion, the Library of Celsus, and sections of the city walls, appear to have been damaged and rebuilt. Hypotheses about epicentres or associated tsunamis circulate in the scholarship, but they gain real weight only where geological evidence supports what is suggested by architectural remains and written sources (*Ambraseys* 2006, 1008 – 1016).

For late antiquity, the situation becomes more complex. Many regions appear to have experienced repeated shocks between the

fourth and sixth centuries AD, a clustering often described as an Early Byzantine tectonic paroxysm. This label is best understood as an interpretive shorthand rather than as a sharply defined phase. Part of the reason lies in the sources themselves: the fifth and sixth centuries preserve more detailed and genre-specific accounts of catastrophe in some regions, while earlier periods are less well documented. On the ground, what mattered most was the cumulative nature of stress. Repeated earthquakes, fires, epidemics, warfare, and fiscal pressure could converge and gradually undermine recovery capacity, even when no single event caused immediate collapse.

The earthquake off Crete on 21 July 365 AD is often treated as a key example of such compound risk (*Shaw et al. 2008, 268 – 275*). It is associated with strong ground deformation and a major tsunami, and modern estimates sometimes suggest a very large event, with magnitudes up to about 8.5. At the same time, translating ancient descriptions and geological traces into a single physical value remains uncertain (*Stiros 2010, 54 – 63*). Later narratives can also compress several destructive episodes into one dramatic scene, especially in literary traditions that framed disaster as a sign of divine intervention. Even with these uncertainties, the event highlights an important feature of urban recovery: a regional shock could produce very different outcomes. Some communities repaired harbours and water systems, while others reorganised settlement, reduced their scale, shifted functions, or relocated altogether.

Tsunamis further complicated urban recovery because they were highly visible in narrative sources but often difficult to identify clearly in the material record. For cities, the impact of a tsunami depended above all on local conditions. Microtopography, coastal configuration, the layout of harbours and inlets, and the location of water and sanitation infrastructure all shaped how damage unfolded. Low-lying quarters and harbour installations were especially vulnerable. In archaeological contexts, tsunami deposits are often mixed and discontinuous. They may include transported debris, sometimes incorporating charred material swept up from fires triggered by the event.

The tsunami associated with the earthquake off Crete in AD 365 is repeatedly cited as one of the most destructive in antiquity. Written sources describe its effects across a wide area of the eastern Mediterranean, from Greece and the southern Adriatic to Sicily, Libya, and the Nile delta. At the same time, its intensity varied greatly from place

to place, depending on shoreline shape and harbour geometry (*Stiros 2022, 15 – 17; Shaw et al. 2008, 268 – 275*). Ammianus Marcellinus presents the catastrophe at Alexandria as a sequence of events: the initial earthquake, the sudden retreat of the sea as a warning sign, and the arrival of a powerful wave (*Amm. 26.10.15*). Descriptions of ships being carried from harbours into city streets, and even onto rooftops, convey not only water depth but also the force of currents, the impact of debris, and the destruction of crucial infrastructure (*Kelly 2004, 141 – 167*). The tradition also associates the disaster with the sinking of the islet of Antirrhodos in Alexandria's Great Harbour and with severe damage to coastal quarters. Apollonia in present-day Libya is likewise described as having been partly submerged, with casualty figures reaching into the tens of thousands. As with other ancient disaster numbers, these figures express perceived scale rather than verifiable totals.

2.5 Dating Disaster Events

Dating natural disasters in the past rarely means identifying a single, exact year in which an event occurred. More often, it involves aligning different types of evidence that were never created to fit neatly together. A fault rupture, a flood deposit, or a layer of volcanic ash can be described in geological terms as a discrete event, but in archaeological contexts these processes usually appear as sequences rather than as single moments. Destruction and collapse are followed by cleaning, dumping, reuse of materials, erosion, and rebuilding, all of which leave their own layers.

Written sources add yet another kind of record, selective by nature and shaped by literary conventions, authorial intentions, and the time gap between the event and its description. An interdisciplinary approach becomes convincing not simply by combining methods, but by making the chain of reasoning explicit. This means asking what physical phenomenon best explains the evidence, what traces it would be expected to leave in a particular landscape and built environment, which of those traces are likely to be primary rather than reworked or redeposited, and what kind of dating the available archive can actually support (*Ambraseys 2006, 1008 – 1016*). In some cases this may be a specific calendar year, but more often it is a limited time window or a relative sequence of events. Within

this framework, it is essential to distinguish between the date of the physical event itself, the date when a text was written, and the date of an archaeological layer that might appear to represent a single catastrophe horizon.

Written sources remain indispensable, especially where disasters entered social memory, administration, or political representation, but they also introduce systematic distortions that must be taken into account (*Guidoboni and Ebel 2009*). Antiquity preserved accounts written by historians, philosophers, poets, and rhetoricians, and in late antiquity increasingly by Christian authors whose interpretations could be explicitly moral or theological. Inscriptions can document rebuilding through claims of repair, benefaction, and civic pride, yet they are not neutral measures of damage; they form part of public self-presentation and competition between communities or elites. Narrative texts are often brief and uneven, expanding where the affected place was prominent, where losses could be framed as extraordinary, or where the event could be interpreted as a portent or punishment. Casualty figures and descriptions of total destruction frequently serve rhetorical purposes and are difficult to anchor demographically.

Traditions surrounding a powerful earthquake in Syria during the reign of the Armenian king Tigranes II in the early first century BC illustrate this tension clearly. Some accounts attribute the episode to extraordinarily high casualty figures, sometimes cited at around 170,000, and to the destruction of numerous towns. Such reports may preserve the memory of a major seismic event or a sequence of shocks, yet neither the precise numbers nor their attribution to a single ruler can be accepted as established fact without independent archaeological and geological corroboration.

At the same time, written narratives are uniquely valuable for what they reveal about lived experience. Accounts of the earthquake at Antioch in AD 526, for example, dwell on fear, displacement, bereavement, and the moral frameworks through which suffering was interpreted. Fire, social disorder, mass flight, looting, violence against refugees, and desperate attempts to recover valuables recur alongside reports of extraordinary casualty figures, often given as 250,000 – 300,000 and sometimes linked to the presence of pilgrims (*Borsch 2023, 201 – 241*). These numbers function less as verifiable statistics than as rhetorical expressions of scale within the conventions of catastrophe writing. Their historical significance lies not in numerical

accuracy, but in the picture they construct of urban services collapsing and social trust eroding under compounded stress, as a physical shock expanded into a crisis of coordination, shelter, and provisioning.

Even where literary testimony is unusually detailed, the same methodological discipline applies. The eruption of Vesuvius is exceptional because of Pliny the Younger's letters, yet these should not be read as modern eyewitness reports (*Plin. Ep. 6.16, 6.20*). Pliny observed from across the bay and wrote retrospectively, shaping his account as composed literary evidence. Its value lies in the dynamics it conveys—darkness, panic, and the sequence of observable phenomena—while the physical record remains essential for testing, refining, or correcting those impressions.

Archaeology provides a physical record of past events, but that record rarely comes with a clear indication of cause, and its chronological value depends on separating the primary event from what happened afterward. A destruction layer may result from an earthquake, fire, warfare, structural collapse, abandonment, or from several of these processes acting in quick succession. What appears at first glance to be a single dramatic moment can in reality be a composite of repeated damage, cleanup, reuse, and repair. This is where microstratigraphic and micromorphological analysis becomes crucial (*Karkanas 2021, 34 – 49*). By examining deposits at very fine scale, it is possible to distinguish rapid episodes of deposition from slow accumulation, collapse from backfill, and primary layers from sediments created later through clearance, dumping, erosion, or renewed occupation.

The same practical realism applies to the choice of samples for dating. Short-lived organic remains such as seeds, fruits, or small fragments of charcoal that can be plausibly linked to a specific episode usually provide more meaningful chronological constraints than large timbers or reused beams. Wood may have been cut decades before it was incorporated into a collapse, and charcoal does not automatically date a disaster, since it can derive from everyday burning, later intrusions, or secondary transport during floods or tsunamis. In this sense, interdisciplinary dating is not just a laboratory procedure. It requires demonstrating that the sampled material is both stratigraphically secure and causally connected to the event being dated.

Non-invasive and digital methods have greatly improved the ability to place samples in context, but they also need to be described accurately. Ground-penetrating radar and other geophysical techniques, together with satellite and aerial remote sensing, do not transmit measurements in real time; rather, they produce images of subsurface structures and surface patterns. These methods can reveal buried buildings, collapse zones, streets, deformation features, and later disturbances (*Parcak 2009, Conyers 2013*). At sites such as Pompeii, they help move excavation away from reliance on a single trench and toward spatially representative sampling, reducing the risk that chronological arguments rest on an untypical sequence. Three-dimensional laser scanning, photogrammetry, and virtual reconstruction add further control by documenting architecture and damage with high geometric precision. They allow ideas about collapse direction, debris removal, and rebuilding to be tested against measurable form rather than impression alone. Most of these methods, however, do not date events directly. Their main contribution is contextual: they improve confidence in what is being sampled and why.

Radiocarbon dating remains one of the main tools for building chronological frameworks in prehistory and parts of antiquity (*Taylor and Bar-Yosef 2014*), but disaster contexts make interpretation especially delicate. A radiocarbon result represents a probability range rather than an exact date, and calibration can widen that range considerably, especially where the calibration curve flattens. In marine or freshwater environments, reservoir effects can shift apparent ages by decades or centuries. The key question is whether the dated material was actually affected by the event. Food stores sealed in a room offer a stronger link than structural timber that may have been reused or curated for a long time. Statistical modelling, including Bayesian approaches that combine multiple dates with stratigraphic information, can narrow plausible windows, but it does not eliminate uncertainty. Instead, it makes assumptions explicit and shows how strongly conclusions depend on them (*Bronk Ramsey 2009*).

For sedimentary event deposits such as floods, tsunami layers, landslides, and some earthquake-related deposits, luminescence methods like optically stimulated luminescence (OSL) can be especially useful when suitable organic material is absent. These techniques date the last time mineral grains were exposed to light, which can closely approximate the moment of deposition (*Aitken 1998*,

6 – 36). Here again, results depend on careful attention to site formation. Incomplete exposure to light, post-depositional mixing, and changes in radiation dose can limit precision, particularly in chaotic tsunami environments. The practical aim is therefore not to privilege one dating method over others, but to match each type of evidence to the kinds of chronological resolution it can genuinely provide, and then to look for agreement across different approaches, where shared uncertainty is least likely to distort results in the same way.

Volcanic events illustrate the logic of disaster reconstruction with particular clarity, because eruptions can leave both sharply defined stratigraphic markers and broader environmental signals. Tephrochronology is especially valuable in this respect. Tephra—volcanic material ejected into the atmosphere and deposited as fallout, ranging from fine ash to lapilli and pumice—can act as a time marker across large areas, provided that the volcanic source is securely identified and that primary fallout is clearly distinguished from material that was later reworked (*Lowe 2011, 107 – 153*). Geochemical fingerprinting of volcanic glass and minerals, using microanalytical techniques that measure elemental composition, makes it possible to correlate tephra layers across different sites and archives with a reliability that local stratigraphy alone often cannot achieve.

This makes tephra a powerful tool for synchronising records, but not an automatic indicator of regional impact (*De Boer and Sanders 2005, 19-21*). A common misunderstanding arises when volcanic ash is treated as the main driver of longer-term climatic effects. In reality, the sustained climatic forcing associated with large eruptions is caused primarily by sulfur gases, especially SO_2 , that enter the stratosphere and are transformed into sulfate aerosols. These aerosols reflect incoming solar radiation and alter Earth's energy balance. Ash particles can have strong local and short-term effects, but they usually settle out of the atmosphere more quickly and contribute less to prolonged, large-scale cooling than sulfate aerosols. This distinction matters for both interpretation and method. Sulfate layers preserved in Greenland and Antarctic ice cores therefore play a central role in reconstructing the timing and frequency of major eruptions (*Raynaud – Parrenin 2009, 453 – 457, Parrenin 2021, 123 – 135*). Even so, linking a sulfate peak to a specific volcano is often uncertain. In some cases the association is clear, but in many periods—especially when several eruptions occurred within a short time span—attribution becomes probabilistic. Secure identification usually requires the con-

vergence of multiple indicators, such as microscopic volcanic ash particles, geochemical signatures, independent dating, and regional evidence from other archives.

Tree rings provide another high-resolution archive and can be exceptionally informative where well-established chronologies exist. In favourable cases, they allow dating at annual resolution and sometimes even offer clues about seasonal stress. However, tree-ring signals do not automatically reveal their cause. Ring width reflects several interacting influences, and in many settings parameters such as latewood density, stable isotope ratios, or combined growth models are more informative than width alone. Strong interpretations therefore rely on the alignment of multiple lines of evidence: tree rings may indicate years of environmental stress; some of those years may plausibly coincide with volcanic aerosol forcing or other climatic anomalies; and attribution becomes more convincing when tree-ring patterns match signals in ice cores, sedimentary records, and, where available, historical descriptions of unusual atmospheric conditions or agricultural failure. Precision in dating is valuable, but it has to be grounded in archives capable of supporting it (*Cook and Kairiukstis 1990*).

Material analysis further broadens the evidentiary base by helping to reconstruct the physical conditions under which destruction and preservation took place. Charred plant and animal remains can provide insight into diet, environment, and economic activity, and when they come from well-defined contexts they are often suitable for radiocarbon dating (*Asouti and Kabukcu 2021*). Inorganic materials such as minerals, glass, and building fabrics can be examined microscopically and chemically to identify sources, technologies, and degrees of thermal alteration. Here, methodological caution is essential. Microanalysis does not yield a single, precise temperature for a fire or eruption. Instead, thermal histories are inferred from combinations of indicators, including mineral transformations, changes in clay structure, shifts in magnetic properties, and alterations in glass texture. These signals depend on factors such as heating duration, oxygen availability, and later post-depositional change. Techniques such as electron microscopy with elemental analysis, X-ray fluorescence, and mass spectrometry are therefore most useful for identification, correlation, and technological interpretation, while absolute dating usually depends on other types of archives.

Volcanic glass as a raw material provides a particularly instructive meeting point of geology, archaeology, and chronology. Pumice, a porous volcanic glass, was widely used in the Mediterranean as an abrasive in crafts and grooming, and because it can float, long-distance movement by currents and wind is physically plausible. That property complicates interpretation: a pumice find does not always indicate trade, because drift can mimic exchange. Obsidian, by contrast, is a silica-rich volcanic glass produced by rapid cooling of lava in various settings, not solely by lava meeting water, and it became a key material for sharp-edged tools and, later, for decorative objects. Geochemical analysis of trace elements can identify obsidian sources with high confidence, allowing mobility and exchange networks to be reconstructed, but provenance is not chronology (*Shackley 2005*). Geochemistry establishes origin, not age. The chronometric technique associated with obsidian is obsidian hydration dating, which measures the growth of a hydration rim as water diffuses into a freshly fractured surface. The physical-chemical process can be quantified, yet converting rim thickness into calendar time depends on temperature history, humidity, and the properties of the specific obsidian source. It works best when calibrated locally against independent dates and used as a complement rather than as a universal absolute clock (*Stevenson et al. 2002, 93 – 109*).

Disasters are sometimes described as agents of preservation, and this idea is based on real processes, but those processes are selective and depend on specific conditions. Fire usually destroys, yet under certain circumstances it can preserve (*Asouti and Kabukcu 2021*). Charring can slow or stop biological decay, and accidental firing can stabilise clay objects, as happened with cuneiform tablets at Ebla around 2300 BC or at Nineveh in 612 BC. Whether fire preserves or destroys depends on oxygen availability, temperature, and duration. The same heat that preserves some materials can completely eliminate others and disturb stratigraphic relationships. Volcanic eruptions can produce similar effects. Rapid burial by volcanic material can isolate buildings and objects from later disturbance, but preservation should not be treated as uniform or automatic (*Vaknin et al. 2023*). Pyroclastic deposits vary widely, and preservation does not depend on high pressure. Charring is primarily a thermal process under low-oxygen conditions, not a product of compression. The buried architecture of Thera, where multi-storey buildings survive to more than one level in places, and the exceptional Roman contexts around the Bay of Naples show

how rapidly deposited volcanic material can preserve a built environment with unusual clarity. Tephra layers, understood broadly as volcanic fallout ranging from fine ash to larger fragments, can also protect sites from later erosion or looting. In some cases, they even preserve traces of attempted theft, such as the oil lamp left behind by would-be robbers in the Roman Villa Regina at Boscoreale.

At Akrotiri on Thera—often described as the prehistoric equivalent of Pompeii—the late Bronze Age eruption around 1600 BC preserved walls with frescoes and, in some cases, traces of organic material. Even in such striking cases, preservation should not be confused with chronological certainty. The absolute date of the eruption remains debated across different chronological frameworks. Botanical evidence, such as an olive branch preserved in volcanic deposits, provides valuable information, but translating growth patterns into calendar years is methodologically demanding and does not yield a single, uncontested date (*Manning et al. 2014, 1164–1179*). In Pompeii, the convergence of seasonal indicators—crop remains, storage practices, inscriptions, and coin circulation—has narrowed the likely season of the eruption in AD 79, but the conclusion is strongest when presented as a bounded inference rather than as a precisely fixed day.

Herculaneum illustrates how preservation can differ even within the same disaster. Buried by hot pyroclastic material, the site preserved large amounts of wood and other organic matter, including a unique assemblage of carbonised papyrus scrolls. Recent research using advanced imaging methods, including micro-CT scanning and computational analysis often grouped under the term artificial intelligence, has begun to recover text without physically unrolling the scrolls, in some cases identifying individual words. These advances greatly expand what the material can reveal about ancient intellectual life, even though they are only indirectly relevant to dating the eruption itself. Comparable preservation occurred far beyond the Mediterranean. At Joya de Cerén in present-day El Salvador, an eruption of the Loma Caldera volcano around AD 600 buried a farming settlement beneath ash. Houses, fields of maize and beans, gardens with crops such as chili peppers and guava, and everyday tools were preserved in place (*Sheets 2002*).

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3 Biodiversity Decline

3.1 Understanding Biodiversity

Biodiversity, understood as the living variety of Earth, is not limited to the sheer number of species but refers to a complex, layered structure of living systems. It encompasses genetic variation within and among populations, the diversity and relative abundance of species, the functional traits through which organisms acquire resources and interact with their environment, and the phylogenetic relationships that embed present ecosystems within long evolutionary histories. This perspective naturally includes animals and plants, but also fungi and microbial communities that play central roles in ecological processes. In some contexts, the concept extends further to include entities such as viruses, whose biological status and ecological relevance are defined primarily through genomic characteristics and patterns of interaction rather than through classical morphological criteria.

The scientific importance of biodiversity lies in its organization as much as in its extent. Ecosystems consist of communities shaped by specific abiotic conditions, within which organisms are linked through networks of interaction. Competition, predation, mutualism, symbiosis, parasitism, and facilitation structure the circulation of energy and matter and shape the capacity of systems to persist through disturbance (*Cardinale et al. 2012*). These interaction networks give ecosystems their characteristic dynamics, determining productivity, stability, and pathways of recovery. Changes affecting individual components can therefore propagate through the system, altering community composition and ecological functioning even when overall species numbers appear relatively stable.

In the present world, biodiversity patterns reflect the combined influence of habitat transformation, climate variability and long-term climatic trends, pollution, and the movement of organisms across biogeographic boundaries. Ecosystem resilience and the continuation of processes that support human societies, including food production, water regulation, disease mediation, and climate-related feedbacks, are closely tied to the structure of biological communities and to the genetic diversity that enables populations to adapt to changing conditions. Biodiversity change thus manifests in multiple ways: through

the disappearance of species at a global scale, through local losses that reduce geographic ranges, through population declines that reshape demographic structure, and through shifts in community composition that favour broadly tolerant taxa over more specialized ones (*Dirzo et al. 2014*). These transformations unfold unevenly across regions and taxonomic groups and over different temporal scales, producing landscapes and seascapes that differ markedly from those of the recent past (*Cardinale et al. 2012*).

Long-term perspectives situate these processes within the broader history of life. The fossil record documents intervals during which extinction rates rose sharply relative to the formation of new species, producing pronounced reductions in biodiversity across large parts of the biosphere. Such episodes were associated with profound environmental disruptions, including rapid climatic shifts, large-scale volcanism, changes in sea level, and extraterrestrial impacts. Although these events caused extensive losses, they also restructured ecological systems and were followed by periods of diversification among surviving lineages (*Hannah 2021*). Contemporary biodiversity change occurs against this background, shaped by a distinct combination of environmental pressures and biological responses (*Wagler 2011, 78 – 83, Barnosky et al. 2011*).

Across shorter timescales, biodiversity change is often expressed through reorganization rather than simple decline. Communities may retain similar levels of species richness while undergoing substantial turnover in species identity, functional roles, and evolutionary composition. Such changes alter how ecosystems respond to future disturbances and influence their capacity to sustain established ecological relationships (*Dornelas et al. 2014*). For this reason, biodiversity is described using multiple complementary dimensions that capture variation within sites, differences among sites, and patterns at regional scales. Together, these dimensions reveal how biological diversity is distributed and how it changes through time. Empirical research relies on a wide range of observational and analytical approaches. Field surveys, trapping methods, acoustic monitoring, remote sensing, and molecular techniques all contribute to the detection and characterization of organisms, each providing access to different components of biodiversity (*Chao et al. 2014, Gotelli and Colwell 2001, Magurran 2021*).

The interpretation of biodiversity patterns depends on how these observations are integrated across spatial and temporal scales. When extended into the past, biodiversity reconstruction draws on archives that preserve biological information unevenly. Fossils, sediments, archaeological remains, and historical documents each record different aspects of past ecosystems, shaped by processes of preservation, deposition, and human selection. Historical ecology and conservation paleobiology combine these sources to trace long-term trajectories of ecological change. Fossil assemblages, pollen and spores, charcoal deposits, diatoms, and other micro-organisms provide records of vegetation, climate, and environmental disturbance. Archaeological evidence, including animal bones and plant remains, documents interactions between human societies and biological communities. Stable isotope analyses add further resolution, revealing aspects of diet, mobility, seasonality, and environmental conditions (*Albarella et al. 2017, 3 – 25*). Recently, sedimentary environmental DNA has expanded the range of detectable organisms, capturing traces of biodiversity that are otherwise invisible in the macrofossil record (*Thomsen and Willerslev 2015*).

Within this expanding toolkit, established paleontological disciplines remain central. Micropaleontology illuminates fine-grained environmental conditions, paleobotany reconstructs plant communities, palynology tracks vegetation change across millennia, and paleoecology integrates organisms and environments into coherent historical systems. Zooarchaeology and paleozoology recover animal histories from fragmentary remains, while ZooMS (Zooarchaeology by Mass Spectrometry) enables taxonomic identification from small bone fragments through collagen analysis. Isotopic methods based on carbon, oxygen, and strontium ratios further enrich these reconstructions by linking biological remains to specific ecological and geographic contexts (*Richter et al. 2022*).

The incorporation of genetic data has transformed the study of past biodiversity. Paleogenetics enables direct investigation of extinct and ancient populations through the recovery and sequencing of ancient DNA (aDNA). These data provide insights into population structure, adaptation, and evolutionary relationships that are inaccessible through morphology alone (*Hofman 2015, 540 – 549, Brzobohatá 2020, 95 – 103*). Major advances in this field include the sequencing of Neanderthal genomes and the identification of genetic exchange between archaic and modern human populations, work

recognized by the Nobel Prize in Medicine awarded to Svante Pääbo in 2022 (Green, Krause et al. 2010, Meyer et al. 2012). Reports of exceptionally ancient genetic material, including samples dated to two million years from Greenland sediments, further illustrate the expanding temporal reach of molecular approaches under favourable preservation conditions (Kjær et al. 2022). Environmental DNA complements these methods by capturing genetic material dispersed in water, soil, and sediments. While such data are particularly effective for detecting the presence of organisms, their interpretation relies on integration with other lines of evidence to reconstruct ecological patterns and change through time. Together, genetic, isotopic, archaeological, and paleontological data form a convergent framework for understanding biodiversity dynamics across deep and recent history.

Recent technological developments have also prompted renewed interest in the biological legacy of extinct species. Research into genome editing, selective breeding, cloning, and assisted reproduction explores the possibility of restoring lost traits or reconstructing aspects of extinct phenotypes. CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats), recognized by the Nobel Prize in Chemistry in 2020, has made precise genetic modification feasible and has broadened the scope of experimental intervention. In practical terms, these efforts focus on proxy organisms and partial trait restoration rather than the re-establishment of extinct species as ecologically integrated populations (Doudna and Charpentier 2014, Shapiro 2015, Poinar et al. 2006).

Alongside these experimental directions, the conservation of genetic resources has become a central strategy in biodiversity research and management. Cryopreservation and biobanking store genetic material in the form of tissues, cells, gametes, or DNA, preserving evolutionary information for potential future use (Droege et al. 2016). Initiatives such as Frozen Ark and International Society for Biological and Environmental Repositories (ISBER) exemplify international efforts to safeguard genetic diversity through standardized, long-term repositories. Genetic information of endangered animal species is preserved through cryopreservation. These collections preserve biological potential but remain embedded within a broader ecological context, as living biodiversity ultimately depends on functioning ecosystems that support interaction, reproduction, and evolutionary change.

Written sources and historical observations add another layer to the reconstruction of biodiversity change. Literary accounts, administrative records, and natural histories document how past societies perceived and interacted with biological resources, noting scarcity, abundance, and environmental transformation. The case of silphium, described in ancient sources as disappearing around Cyrene during the reign of Nero (*Plin. Nat. 19.15*), illustrates how textual evidence can signal biological change while remaining inseparable from its cultural and historical context. Such records gain explanatory power when they are integrated with archaeological, botanical, and environmental data. Despite the growth of datasets and analytical capacity, knowledge of past biodiversity remains partial, shaped by uneven preservation and the challenges of aligning evidence across different archives and timescales (*Hannah 2021, 76 – 98*).

3.2 Domestication and Human–Animal Co-evolution

The long history of humans and biodiversity can be described as an ongoing co-production of the biosphere by human societies, in which symbiosis, commensal living, and cooperative entanglements with other species have unfolded alongside conflict, extraction, and landscape degradation. The pressures that dominate modern environmental histories—loss, degradation, and fragmentation of habitats—appear within wider ecological dynamics that also include geological change, climate variability, and shifting hydroclimates. Within the Holocene, the present interglacial that began roughly 11,700 years ago, many regions show an intensification of human interventions as populations grow, settlements become more stable, agriculture and pastoralism expand, infrastructures thicken, and economies move toward more energy- and material-demanding forms. This intensification draws on practices with deep Paleolithic roots, including controlled fire and sophisticated tool use, while the major shift lies in scale, tempo, spatial persistence, and the institutionalization of land use and resource management (*Cilek et al. 2005*).

Neolithization does not appear as a single switch with a universal date. It emerges as a long, mosaic-like, regionally uneven process in which communities moved along a continuum: from mobile hunting and gathering to seasonal sedentariness, from low-intensity management of plants and animals to more stable food production, and

from flexible access to resources to new regimes of storage, property, labor organization, and inequality. Ecological consequences follow the shape of this social complexity. The creation of anthropogenic open habitats, new fire regimes, and human-maintained successional stages could increase heterogeneity locally, producing patchworks of niches and edge environments. As intensification advances, many landscapes shift toward more uniform land-cover patterns, and specialists dependent on the continuity of older habitat mosaics lose space as generalist and disturbance-tolerant species expand. Domestication sits at the center of this reorganization because it redirects flows of energy and material through managed trophic pathways, subjects selected populations to sustained human-mediated selection, protection, transport, and deliberate hybridization, and brings wild populations into new fields of competition, predation, and epidemiological exchange with people and their domesticates (*Larson and Fuller 2014*).

Domestication itself unfolds across a spectrum rather than as a punctual event. Commensal pathways, prey pathways, and more targeted management can all lead to long-term shifts in demography, spatial control, reproduction, and genetic structure (*Zeder 2012, 227 – 259*). Zooarchaeological signatures such as size change, kill-off profiles, and the spatial distribution of bones map parts of this process, and they sit alongside biomolecular evidence, isotopic signals, paleoparasitological indicators, and paleoenvironmental archives that place animals within changing landscapes, disease ecologies, and patterns of mobility. In Southwest Asia, early management and domestication trajectories for sheep, goats, pigs, and cattle take clearer form across the 9th to 8th millennia BC in different subregions of the Fertile Crescent and its wider hinterlands. These developments appear as interacting networks rather than a single point of origin, with repeated episodes of separation and renewed gene flow with wild ancestors. Beyond that core, other centers and secondary domestication processes unfolded across parts of Eurasia and Africa, and the later spread of domestic forms often involved introgression with local wild populations.

The dog remains the clearest example of deep-time cohabitation and one of the hardest to pin to a single place and date. It is the earliest domesticated animal, and it is often discussed within a wide window that includes estimates such as 21,000 to 12,200 years ago. The uncertainty lies in the way different lines of evidence converge only

partially: genetic divergence estimates, the identification of early “dog-like” morphotypes in skeletal material, and the reconstruction of commensal relationships do not always align cleanly (*Bergström et al. 2020*). By roughly 14,200 years ago, Europe provides compelling evidence for sustained human–dog cohabitation in contexts that imply social investment and care, and paleogenomic syntheses leave open the possibility that domestication processes began already in the late Pleistocene in northern Eurasia, perhaps under ecological stress around the Last Glacial Maximum (*Thalmann, O. et al. 2013*). As the record of well-dated, genetically characterized individuals grows, these scenarios can be framed with increasing resolution.

A different angle on human control of animal reproduction appears in the kunga, the first archaeologically attested animal hybrid, bred in the 3rd millennium BC. The kunga was a deliberately produced first-generation hybrid between a female domestic donkey and a male Syrian wild ass, created before the domesticated horse became widespread in Mesopotamia (*Bennett 2022*). Its production points to practical knowledge of reproductive barriers, the value of hybridity, and the political economy of prestige animals in diplomacy, ritual, and warfare. The wildcat provides another trajectory in which close association emerges through settlement ecology rather than through immediate human command. Wildcat domestication around 7500 BC in Southwest Asia fits a commensal pathway linked to early farming settlements and storage systems that attracted rodents and created a stable niche (*Driscoll et al. 2007, 519 – 523*). Early evidence of close association is strongest in the eastern Mediterranean, while genetic reconstructions indicate multi-wave dispersals across the ancient world and a gradual cultural stabilization of cats’ status from utilitarian pest control toward more symbolic and affective bonds.

3.3 Hunting, Predation, and Selective Pressure

The human–animal relationship is at once intimate and so wide-ranging as to resist exhaustive description. Even today, fundamental uncertainties persist regarding how many species exist and which traits prove decisive for their ecological roles (*Chao et al. 2014, Gottelli and Colwell 2001, Magurran 2021, Jost 2006*); for the past, these uncertainties are further compounded by differential preser-

vation and uneven sampling. Despite these limitations, long-term pressures leading to population contraction and species decline can be examined—cautiously—through the archaeological record of intensive hunting, precisely because certain animals occupy a position at the intersection of comparatively abundant material remains and relatively rich written or iconographic traditions. That examination, however, must be explicit about methodological filters: zooarchaeological assemblages are products of selective hunting, butchery, transport decisions, cooking practices, depositional histories, taphonomic loss, and research strategies; quantification units such as the number of identified fragments or the minimum number of individuals track the archaeological career of matter more directly than they track the true abundance of living populations, and interpretation must therefore consider biomolecular markers, mesh size in sieving, the preservation of fragile bones, and, for aquatic taxa, the chemistry and sedimentary conditions that govern survival of skeletal material.

With these constraints in view, the perennial debate about human roles in late Pleistocene and Holocene megafaunal losses becomes less a hunt for a single culprit and more an exercise in explaining regionally specific compound vulnerabilities. Humans are often associated with megafaunal extinctions at the end of the last Ice Age and into the Holocene, and it does appear that human influence was particularly consequential in parts of North and South America and in Australia, where the timing of extinctions often approaches the timing of human arrival and where hunting, burning practices, and rapid ecological reorganization could plausibly have acted together. In Europe, Asia, and Africa, extinctions of large-bodied species were often more prolonged and asynchronous, more visibly entangled with climate variability, habitat transformation, and the fragmentation of suitable ranges, though this does not exclude human impacts—especially where hunting pressure, competition for space and resources, and disturbance regimes overlapped with ecological stress (*Ponting 2018, 36 – 43*). Inter-species competition and unstable population dynamics add another layer: large mammals frequently occupy demographic edge conditions, and even moderate additional mortality can destabilize populations already weakened by shrinking habitats, altered seasonality, disease dynamics, or disrupted migration corridors.

The disappearance of mammoths is often connected to the combined effects of hunting and climatic change that transformed grassy

steppe-tundra into forests and wetlands across large areas (Wang 2021, 86 – 92). The mammoth record also includes prolonged persistence in refugial spaces, including isolated island populations that survived into the late Holocene and then vanished under the compounded pressures of small-population genetic erosion and environmental shocks. Paleolithic sites across Eurasia preserve osteological evidence of intensive use of large herbivores for meat, fat, hides, bone, and ivory. Dense accumulations of remains of herd animals, including reindeer, horses, and mammoths, appear in refuse pits and occupation contexts at Solutré, Dolné Věstonice, Pavlov, Kostenky, and Borševo. Such concentrations document repeated exploitation and sustained reliance on large-bodied prey, shaped by local landscapes that could funnel herds, by seasonal scheduling, and by the accumulation of episodes through time within favorable depositional settings. In many contexts, assemblages also incorporate natural mortality and complex site formation histories, and the archaeological record therefore preserves a composite picture of procurement, landscape use, and ecological opportunity.

The later prehistoric and historical record makes equally clear that hunting did not disappear with farming, but shifted its social meanings and ecological consequences. Wild game could remain a subsistence supplement, a risk buffer, a ritual medium, and, crucially, a language of hierarchy: small game was often taken by ordinary households, while the pursuit of large predators such as lions tended to belong to ruling elites because it demanded organized groups, specialized equipment, and access to controlled landscapes, and because the animal itself symbolized power. The lion—long treated as an emblem of strength and nobility—once ranged widely across Africa and through parts of Southwest and South Asia, with a more limited and historically contingent presence in parts of Europe (Bystrický 2019, 241 – 259); alongside this, the extinct cave lion (*Panthera spelaea*) represents a Pleistocene lineage adapted to colder environments that disappeared as late-glacial ecologies reorganized.

Modern lions show genetic and geographic structure that is often expressed as two main subspecies, northern (*Panthera leo leo*) and southern (*Panthera leo melanochaita*), though taxonomic frameworks continue to be refined; in any case, the key point for environmental history is that long-term human hunting, habitat change, and the decline and fragmentation of regional populations have helped shape both their distribution and their vulnerability. Over time, the

hunting and capture of large carnivores expanded beyond elite prestige into an economy of spectacle, and the Roman *venationes*—arena hunts and staged combats involving wild animals—offer a particularly vivid case of how institutions can translate ecological pressure into sustained extraction. These performances carried deep social and political meaning and remained popular across antiquity (*Plut. Pomp. 52, Claud. Stil. 3.283, Cassiod. Var. 3.51*); Cicero, Seneca, and Plutarch reflected on their cruelty and moral ambivalence (*Cic. Fam. 7.1*), yet such critiques sat uneasily beside the broad public appetite that made the spectacles politically valuable.

The Roman entertainment system drew on a wide range of species, from lions to hippopotamuses, deploying animals against each other, against humans, and even as instruments of punishment, and while senatorial and imperial authorities sometimes attempted regulation, the overall effect was to normalize large-scale demand for exotic fauna (*Suet. Tit. 7.3, Cass. Dio. 68.15, Ael. Sp. Had. 7. 12, 19. 3, SHA Ant. Pius. 10.9, SHA. Comm. 13. 3*). Amphitheaters were architectural solutions to that demand, requiring technical ingenuity in design and scenography, but they were also urban nodes where patronage, civic identity, and imperial ideology met; in the imperial era, *venatio* could peak in extravagance in ways that aligned with the logic of *panem et circenses*—bread and games—as a strategy for maintaining popular satisfaction and demonstrating state capacity (*Kalof 2011, 8 – 9*). Read ecologically, such capacity depended on supply chains: capture expeditions, provincial tributary flows, commercial intermediaries, transport networks with high mortality, and in some contexts forms of keeping and limited breeding that did not eliminate pressure on wild populations.

Over several centuries, the combined weight of hunting, trade, and large-scale capture and management of wild animals—especially in North Africa and the eastern provinces—contributed to dramatic declines and, in many cases, local extirpations of large predators (*Hughes 2014, 88 – 108, Them. Or. 10.140*); yet here too the most defensible explanation is multi-causal, because the *arène* economy operated alongside agricultural expansion, deforestation, and changing hydroclimates that reshaped habitats and corridors. Cicero, as governor of Cilicia in 51 – 50 BC, noted the declining availability of leopards and other animals for games in Rome, observations that can be read as signals of localized depletion and rising procurement costs rather than as literal wildlife censuses (*Cic. Fam. 2. 10, 8. 2,*

4, 8, 10 – 11, *Cic. Att. 5. 21*). Later sources report a marked reduction in the number of wild animals displayed during the millennium games of Emperor Philip the Arab in 248 AD compared with earlier centuries, which is compatible with long-term scarcity, but numerical comparisons require caution because lists of animals and figures in such accounts are shaped by genre, rhetoric, and the politics of praise.

The same interpretive care applies to the Carthage mosaic dated shortly before 250 AD with animals accompanied by numerals (*Dunbabin 1978, 70 – 73*), which may indicate counts but could also encode sums or program units; it is a powerful document of how animal spectacle was administered, but not a transparent ledger of population size in nature. Diocletian's price edict of 301 AD, setting maximum prices for categories of animals, likewise reflects scarcity and the high costs of capture and transport (*CIL III, 2208 – 2209*), yet it is also fundamentally a document of economic crisis and attempted market control, so its evidentiary weight lies more in showing that certain animals and related services had become expensive and regulated than in proving a direct trajectory of ecological collapse. The gradual decline of *venationes*, therefore, is best understood as a convergence of ecological constraints with institutional change: rising procurement costs, shifting elite patronage, transformations in urban public life, moral critique and legal restrictions in some contexts, fiscal and military pressures, and disruptions of long-distance trade. Even the often-invoked endpoint—the fall of the Western Roman Empire and the interruption of trade routes—should be treated as an acceleration within a longer transformation rather than as a single causal switch, not least because animal spectacles and related forms persisted in some settings into the early sixth century and the last attested games in the Colosseum belong to that later horizon.

3.4 Exploitation and Endangerment

To treat endangered species as a story that begins with industrial modernity is to underestimate how early human institutions learned to convert living beings into prestige, power, and portable value—and how quickly such conversions can erode populations long before a species disappears from the planet. The vocabulary of loss therefore needs to separate two endpoints. Extinction denotes the global end of a species.

Extirpation denotes the disappearance of a population from a region, whether that population formed a continuous range or a metapopulation sustained through connected subgroups. Because most evidence from antiquity is regional by nature—texts, trade records, and archaeological deposits illuminate particular territories, routes, and economic corridors—it most often registers extirpation: animals becoming scarce and then absent within a mapped human world. This distinction matters because regional decline and final disappearance are frequently separated by long time-lags. Even when the definitive endpoint falls in the recent past, the underlying dynamics—habitat transformation, prey depletion, persecution, and progressive fragmentation—may unfold earlier and proceed incrementally until ecological connectivity fails. The Caspian tiger (*Panthera tigris virgata*), which persisted into the twentieth century, is analytically useful precisely because its collapse is historically visible: sustained reworking of riverine and wetland landscapes, declining ungulate prey, intensified persecution, and increasing fragmentation converged to undermine the continuity on which a wide-ranging predator depends.

Questions of scale and correspondence become sharper still when ancient sources describe animals primarily as feared adversaries, luxury materials, diplomatic gifts, or objects of spectacle. Discussions of wildlife loss in antiquity repeatedly return to lions and elephants, which in older scholarship are frequently framed through regionally defined labels (Hemmer 1963, Hemmer 1967). These large-bodied mammals matter not only because they are culturally prominent, but because they can structure ecosystems in ways that propagate across food webs and landscapes. Elephants, as classic “ecosystem engineers,” can reshape vegetation structure and habitat heterogeneity through browsing, breaking woody plants, dispersing seeds, opening pathways, and modifying access to water and forage. Large felids act through different pathways: predation and risk effects alter herbivore abundance and behavior, with cascading consequences for plant communities and smaller animals. When animals of this kind vanish regionally, the result is not merely a subtraction from a faunal list; it can reconfigure interaction networks that stabilize ecosystems, while amplifying drought sensitivity and the compounding effects of fragmentation once movement corridors are cut. Ecologists sometimes describe such disproportionately influential taxa as “keystone species,” but the mechanisms by which elephants and large felids

shape environments differ—even when both can condition entire landscapes (*Power et al. 1996*).

The evidence for ancient elephants is rich but heterogeneous. Ivory carved into luxury goods tells one story: extraction, transport, skilled workmanship, and elite demand. Bones in local deposits tell another: presence, range, and in some contexts hunting or scavenging. Literary accounts tell another again, often framed through tropes of exotic reach and imperial power. Across these different sources, one theme remains consistent. Elephants in the ancient world were valued as strategic and representational resources: ivory for high-status art and craft, live animals for war, diplomacy, processions, and eventually spectacle. Ivory's prestige is visible not only in finished objects but also in workshop debris and semi-finished blanks that imply specialized production and regularized supply. Trade nodes such as Egypt, Syria, and the Aegean region functioned as junctions where maritime routes and overland corridors intersected, and where political authority could stabilize—or disrupt—the movement of bulky, high-value materials (*Tournavitou 2005, Barnett 1935, 178 – 180, Alp 2017, Carter 1985*). Under such conditions, extraction readily took institutional form: elite demand could be translated into organized expeditions, controlled access to hunting grounds, administrative mobilization of labor, and managed transport. A system structured in this way can remain operational even as ecosystems weaken, because it can intensify effort, widen catchments, and redirect procurement as local sources decline.

The Syrian elephant (*Elephas maximus asurus*) is best understood as a now vanished regional population of Asian elephants in the Levant and adjacent northern Mesopotamia. River corridors and wetland habitats in that zone formed ecological islands within expanding agricultural and settlement mosaics. In royal and elite contexts, elephants and ivory were tied to display, hunting, and the political economy of prestige goods (*Winter 2010, 207 – 210*), and pressure on such a population would have been concentrated precisely where habitat continuity was already patchy. The record also allows more than one mode of persistence: long-term local survival in refugial habitats, intermittent recolonization from neighboring areas, and occasional human-mediated movement of animals can all fit different parts of the evidence, and the history likely varied across subregions and centuries.

The North African elephant (*Loxodonta africana pharaohensis*) is harder to anchor to a single biological unit, even though its historical footprint in war and spectacle is clear. Ancient reports of Carthaginian and Ptolemaic elephants, claims about smaller body size, and differences in military performance can reflect source geography, ecological type, the age structure of captured animals, training regimes, and logistical conditions (*Polyb.*5.84, *Plin.Nat.*5.1.15 – 32). Capture zones could also shift over time as proximity and access changed. What emerges most clearly is the trajectory of access: elephants became increasingly costly to obtain and maintain as habitats were transformed by agricultural expansion, land-cover change, and longer-term aridification trends that altered hydroclimate, water reliability, and the spatial distribution of forage. In such landscapes, declining connectivity matters as much as outright killing, because corridors that once allowed movement between seasonal resources and refuges become severed.

Elephants' military history ties these ecological dynamics directly to state logistics. Elephants appear in Near Eastern imperial settings, but the most intensive political economy of war elephants is especially associated with the Hellenistic monarchies of the third and second centuries BC, when courts and armies required continued access to living animals that were difficult to breed outside their natural ranges and costly to maintain in captivity. Seleucus I's acquisition of a large elephant force from Chandragupta (conventionally reported as 500 animals) belongs to the diplomatic landscape that followed Alexander and captures the scale at which elephants could be treated as state-level resources rather than episodic curiosities (*Strab.* 15.2.1; *Polyb.* 11.39). Around the same period, elephant imagery in royal representation and coinage became a condensed signal of reach and legitimacy—grounded in access to distant resources and in claims to command at the margins of the known world.

Behind that symbolism lay the biology that makes elephant populations slow to replace. Long gestation, late maturity, extended birth intervals, and complex social organization constrain recovery under sustained loss. Captive reproduction is possible but structurally demanding: it requires space, social stability, specialized knowledge, and long-term investment (*Sukumar* 2003). Where institutions depended on a reliable supply of elephants for war or display, capture from the wild therefore remained central, pushing pressure back onto source landscapes. In the Nile-adjacent and Red Sea sphere,

Ptolemaic administrations invested heavily in acquiring elephants for military purposes, drawing on networks extending into northeastern Africa and the Red Sea hinterlands. Those efforts depended on ports, desert routes, specialized labor, and sustained state organization, demonstrating how capture could become an integrated administrative task rather than an occasional hunt.

Rome encountered elephants from the third century BC onward, developed tactics for neutralizing them, and in some contexts deployed them (*Polyb.* 30.25.11, 31.3.11; *App.* 11.46). The more consequential Roman transformation, however, lay in infrastructure and political economy: imperial networks capable of turning exotic fauna into a regularized medium of political theater and elite competition. That capacity—applied across many taxa—supported an extraction economy in which capture, transport, and display became normalized performances of imperial power (*Plut. Pomp.* 12, 14, 52, *Cic. Fam.* 7.1.3). In such systems, regional declines are rarely reducible to a single cause. Military capture, ivory extraction, habitat conversion driven by colonization and intensified land use, and background climatic variability could all act together on resilience by shrinking refuges, severing corridors, and lowering the buffering capacity of populations already constrained by slow life histories. Persistence was uneven—longer in some pockets than others, and unevenly visible in the record—but in many regions the overall trajectory was toward contraction, scarcity, and regional disappearance (*Them. Or.* 10.212).

3.5 Species Dispersal and Adaptive Dynamics

Species dispersal is, in the long view, a normal feature of evolution and biogeography. Since the late Pleistocene—and with particular force since the Neolithic—human societies have changed dispersal by altering how fast organisms move, which organisms move, where they move to, and what those movements do to ecosystems. A clear way to describe the process is to distinguish introduction, the human-mediated transfer of a taxon beyond its earlier range, from naturalization, the establishment of a self-sustaining population, and from invasion, the subset of naturalized cases in which spread accelerates beyond an initial lag and produces measurable ecological, economic, or health impacts. These terms matter because “native” and “non-native” are not timeless biological labels. Many organisms

moved so early and so repeatedly along human corridors—through farming, trade, and settlement—that they can feel self-evidently local today, even where genetic, archaeobotanical, or archaeozoological evidence points to older, human-linked pathways.

Because of this long history, non-native presence is not a single condition with a single meaning. What changes from case to case is the mechanism and the outcome: whether a transfer reorganizes community structure, shifts energy flow, alters disturbance regimes, or changes pathogen dynamics, or whether it becomes incorporated into managed socio-ecological systems with limited disruption. Benefits most often attach to intentionally introduced crops and domesticates within regulated agroecosystems, where human labor and institutions stabilize outcomes. The term *invasive*, by contrast, is generally used for non-native taxa whose self-propagating spread generates negative externalities and management costs, even if some gains can occur locally or under particular circumstances.

In that sense, neolithization was already a vast experiment in redistributing species. Alongside domesticates came weeds adapted to disturbed soils, parasites well suited to penned animals, and synanthropic species that thrived in more permanent settlements, storage facilities, and new building materials (*Boivin et al. 2016*). The origins of domestic animals also resist simple geographic oppositions. Wild aurochs ranged across Europe and much of western and central Asia, yet the principal domestication of taurine cattle occurred in southwest Asia, while an additional independent domestication in South Asia produced zebu. Later dispersals, repeated crossings, and gene flow with local populations reshaped cattle genetics across Eurasia in ways that cannot be reduced to a single European ancestor narrative (*Decker et al. 2014*). For pigs, too, the pattern is not a one-way import: alongside domestication in southwest Asia, Europe saw its own domestication processes and long-term introgression between wild and domestic *Sus scrofa*, so the presence of a wild progenitor in Europe is biologically true without functioning as a straightforward genealogy of historical husbandry lineages (*Larson et al. 2007*). Sheep and goats, by contrast, were domesticated in the Fertile Crescent, and their spread into Europe remains one of the clearest cases of human-mediated expansion closely tied to colonization, pastoral regimes, and the remaking of landscapes (*Naderi et al. 2008*).

In antiquity these deep processes intensified and took on a distinctive Mediterranean profile. Dense networks of ports, provisioning systems, and military corridors made repeated long-distance “jump” introductions easier, while maritime transport, bulk grain storage, and urban growth created conditions of high propagule pressure, with many chances for organisms to arrive and establish. In this setting, grain pests emerge as ecological beneficiaries of an engineered niche rather than as incidental irritants. Archaeologically attested stored-product insects from Bronze Age contexts, including finds from Théra–Santorini, show how large-scale storage and movement of dry foods could sustain populations that would otherwise lack such continuous substrates (*Panagiotakopulu and Buckland 1991*), while also reflecting the particular preservation pathways that make insect remains visible in the first place, such as burning, mineralization, and local sediment conditions. Along the same provisioning lines, the house mouse (*Mus musculus*) and the black rat (*Rattus rattus*) expanded as commensals by exploiting ships, granaries, sewers, and dense building fabric, though their trajectories differ (*Campbell 2014, 173*). Mice align closely with early agrarian storage regimes and likely spread with Neolithic settlement intensification, whereas black rats are especially associated with port worlds and long-distance trade networks.

Cats belong to the same story of settlement ecology. Their role in rodent control is often linked to the imperial period, yet cats first emerged as commensals and then domesticates in earlier Near Eastern and North African agrarian settings, spread through the Mediterranean in successive waves, and become more archaeologically visible and widespread in Roman urban contexts rather than appearing as a single imperial innovation (*Jennison 2005, 7*). As predators in human-built landscapes, domestic cats (*Felis catus*) sit at a junction of utility and ecological effect: they can reduce losses in storage-and-sanitation systems, while also strengthening predation pressure in anthropogenic environments. The consequences are especially pronounced in insular and coastal ecologies, even though the dominant calculations in ancient cities tended to focus on grain protection and disease risk rather than on impacts to native bird communities.

Military activity added another layer of mobility by creating temporary settlements, supply depots, and new corridors of people, fodder, and animals. The rabbit offers a vivid example of how a species can shift from resource to problem when demographic thresholds

are crossed. The wild rabbit (*Oryctolagus cuniculus*), historically concentrated in Iberia, became a food source for imperial forces (Campbell 2014, 162), and ancient observation already registers the possibility of population eruptions that devastate crops and undermine soils (Strab. 3.2.6). The report that inhabitants of the Balearic Islands appealed to Augustus for help in reducing rabbit numbers shows an early awareness that human-mediated movement and altered predator–prey settings could generate costly instability and attract state intervention (Plin.Nat. 8.81.55).

Aquatic cases fit the same logic, though the mechanisms can be harder to see archaeologically. The common carp (*Cyprinus carpio*) is naturally associated with large Eurasian river systems including the Danube, so accounts of its spread tied to military camps can blur different processes that look similar on the surface: local maintenance, managed ponds, and deliberate movement within an already connected biogeographic zone are not the same as introduction into a genuinely new region (Simberloff – Rejmanek 2011, 102). Widespread, systematic carp expansion is far more securely linked to later aquaculture, and claims about continent-scale Roman dispersal would rest on robust osteological identifications and clear archaeological contexts. Pliny’s report that a certain kind of fish was introduced to waters off Italy, where it later became common, fits well with elite practices of stocking and improving local waters, an intention to manage living resources rather than a taxonomic record in modern terms (Plin.Nat. 3 – 39).

Across these examples, the recurring pattern is not only that humans moved animals, but that human activity reshaped the conditions that make movement consequential. Trade, colonization, military logistics, and elite leisure created anthropogenic habitats, repeated introductions, and sometimes reduced the biotic resistance of local communities, allowing a naturalized species to tip into invasive dynamics. The present differs less in kind than in scale and velocity. Global commerce and mobility compress distances, multiply introduction events, and intensify the challenge of protecting regional habitats and biodiversity, including an epidemiological dimension in which some non-native taxa can act as reservoirs or amplifiers of disease.

These pressures have helped drive modern initiatives focused on securing sufficient, high-quality habitat, alongside recognition that many populations outside protected areas are especially vulnerable.

The historical record also contains earlier forms of restricted space, but their purposes were different. Royal hunting parks and reserves in the Near East and Egypt existed largely as instruments of prestige and control, and while they could function as refugia in practice, their logic was not biodiversity conservation in the modern sense. The Hellenistic and Roman fascination with exotic fauna likewise belongs primarily to menageries, displays of knowledge, and political theatre. During Alexander's conquests, exotic animals were reportedly housed in association with Aristotle's Lyceum in Athens (therotrofeion). Ptolemy II was famed for keeping large numbers of exotic animals (*Diod.3.36.3*). Alexandria's landscape of learning and gardens blended inquiry with imperial logistics and spectacle, including narratives connected to the first giraffes seen at Rome (*Plin. Nat.8.18; Dio Cass. 43.23.1*). Even the vast vivarium attributed to the orator Quintus Hortensius—an "aquarium" for reptiles spanning 13 hectares—most directly reflects luxury economies, controlled supply, and status (*Varro, Rust. 3.13. 1 – 3*).

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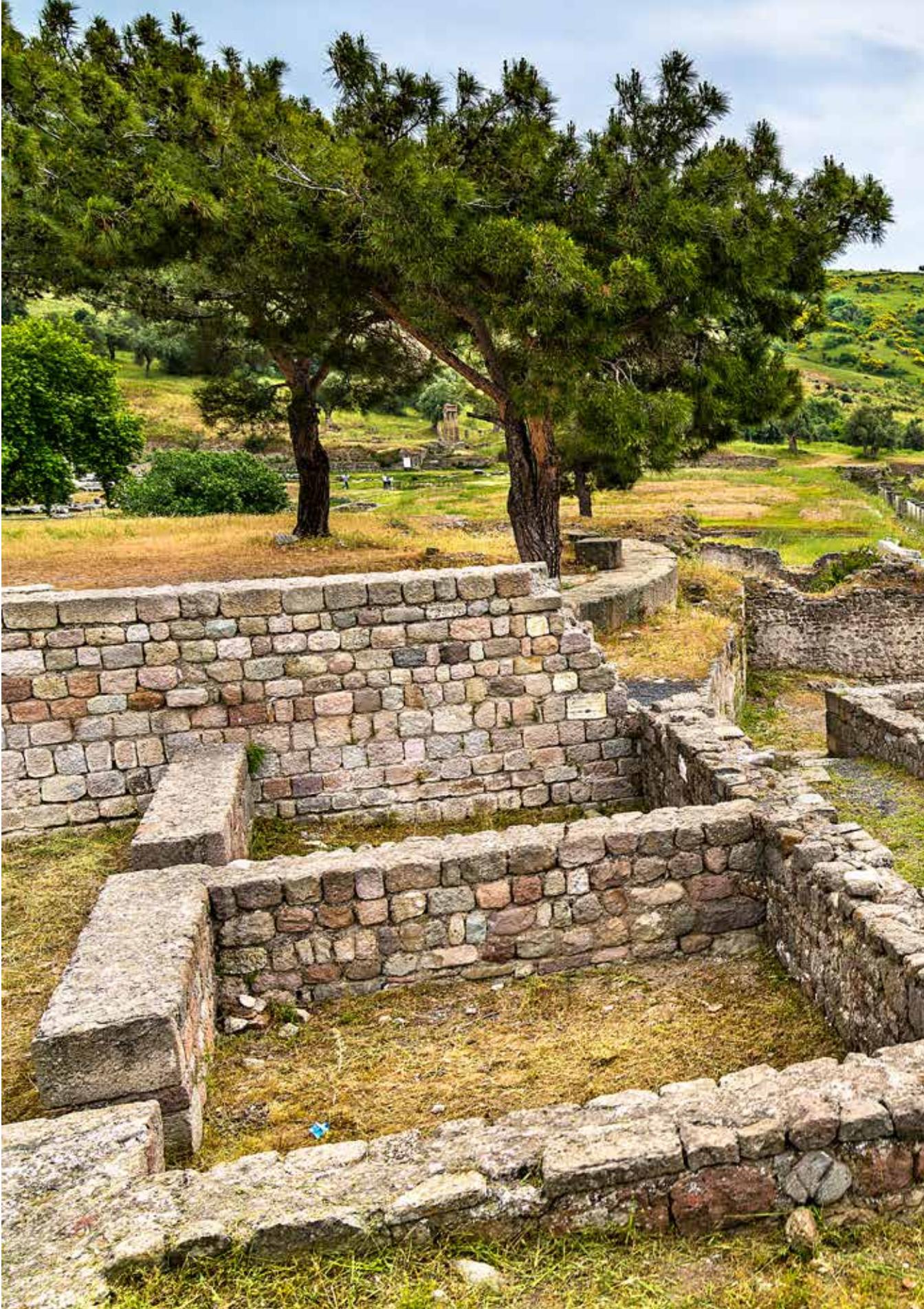
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4 Epidemics

4.1 Studying Epidemics

In epidemiology, an epidemic is defined by a measurable change: the number of cases of a disease or health event rises above what is normally expected in a clearly defined population, place, and time. That expected level is local and contextual. It belongs to a particular city, season, institution, risk group, or ecological niche. This is exactly what makes the concept useful, and also what makes it easy to misuse when we apply it to the distant past. In the same operational language, an outbreak usually refers to a more localized increase, often bounded to a specific community or institution, while a pandemic is a pattern of repeated introductions and sustained human-to-human transmission across multiple world regions, typically with major population-level consequences (*Porta 2014*). These distinctions matter because the past does not give us modern clinical definitions, surveillance systems, or laboratory confirmations. It gives us traces that are incomplete, unevenly preserved, and shaped by human behavior and environmental processes. For that reason, ancient disease crises cannot be reconstructed by taking a single type of evidence and attaching a modern label to it. The more defensible approach is deliberately multidisciplinary: it draws on independent lines of evidence and makes uncertainty visible instead of hiding it behind confident naming (*Little 2007*).

This is why current research increasingly links archaeology with molecular biology, and social interpretation with microbiological detection. Archaeological contexts—especially necropoleis and other burial settings—often provide the most direct material window onto mortality crises. On their own, however, they rarely tell us whether we are looking at disease, violence, famine, or another form of crisis. Their interpretive power becomes much stronger when they are examined together with osteological analysis, historical demography, stable-isotope evidence for diet and mobility, environmental and paleoclimate proxies that constrain stress and seasonality, and—when preservation allows—biomolecular evidence for pathogens and host responses. Interdisciplinarity helps most when it is organized around coordinated hypotheses, not when methods are simply

added side by side. A deposit of bodies carries far more interpretive weight when it can be independently dated to a short interval, when the age and sex structure deviates from the expected mortality profile, and when pathogen DNA is detected in tissues plausibly linked to infection (*Duchêne et al. 2020, Cappellini et al. 2018*), than when it remains only a striking find without chronological or biological anchoring.

Within this framework, epidemiology supplies the conceptual grammar even though its modern tools are distant from the ancient settings we are trying to understand. Its intellectual roots are often traced to Hippocratic traditions that reflected on environment, seasons, and living conditions. Methodologically modern epidemiology, however, developed through quantification, comparison, and inference: measuring incidence and prevalence, estimating case fatality and excess mortality, and modelling how risk is shaped by exposures, behaviors, and social organization. Its central aim is not the formulation of treatment. It is the description and explanation of disease distribution, the identification of determinants and transmission mechanisms, the evaluation of interventions, and—above all—prevention and control at the population level (*Porta 2014*). That population perspective is also what makes epidemiology so useful for historical inquiry. It pushes us to ask not only “what disease was it?” but also who was most vulnerable, how mortality and fertility changed, how migration and labour reorganized after crises, and how risk followed patterns of housing, nutrition, work, water access, and institutional reach. Many historical crises were composite. Pathogens interacted with undernutrition, famine, conflict, displacement, and climatic anomalies that reshaped contact patterns and immune resilience. A syndemic perspective is valuable here because it separates immediate causes of death from structural causes of vulnerability, without collapsing everything into a single-cause story.

If epidemiology frames questions at the population scale, paleopathology and bioarchaeology treat the body as an archive—while insisting, in their most disciplined forms, on what that archive cannot provide. Paleopathology studies disease in individuals through recognizable changes in human remains, but it also rests on a crucial asymmetry: the skeleton is mainly a record of survived, chronic, or repeatedly endured processes, not a reliable record of immediate cause of death. Many acute infections can kill without leaving diagnostic lesions in bone. Conversely, when skeletal pathology is pre-

sent, it often implies that the person lived with illness long enough for bone to remodel. This does not make skeletal evidence useless; it sets constraints. It steers interpretation toward differential diagnosis, toward probabilistic claims, and toward triangulation with context and biomolecular data rather than confident identifications from bone alone (*Larsen 2015, Ortner 2003*).

Archaeological evidence often enters epidemic debates through burial practice, especially where routine funerary behaviour seems compressed, improvised, or overwhelmed. Mass burial is frequently treated as an early material hint of epidemic conditions, but it is inherently ambiguous. Similar burial patterns can result from warfare, raids, natural catastrophes, famine, breakdown of care, long-term marginalization, or specific ritual practices. Dating therefore becomes decisive. Relative dating through typology is rarely enough; where possible, absolute dating is needed, and it is increasingly refined through probabilistic chronological modelling that integrates radiocarbon results with stratigraphy and contextual information while explicitly managing outliers and secondary deposits. Even with good dating, nonstandard burial does not automatically mean contagion. Empty or half-prepared graves, hurried interments without customary grave goods, careless body placement, or measures aimed at slowing decomposition can all indicate crisis, but they can also reflect status distinctions, the burial of outsiders, violence, or local ritual variability. The interpretive task is to establish what nonstandard means within that specific cultural and chronological repertoire, and against a baseline drawn from the same necropolis or region.

It is also risky to try to separate epidemic graves from war graves by stratigraphy alone. Stratigraphy can show sequences of deposition, but it does not diagnose cause. Warfare burials can accumulate in episodes, and epidemic mortality can produce catastrophic deposits over days if burial capacity collapses. For this reason, stronger inference relies on converging indicators: archaeoethanatomical analysis of body position and decomposition context, patterns of perimortem trauma, associated projectiles or other traces of violence, evidence for manipulation of corpses, and independent dating. Only when these strands align does an epidemic interpretation become the most plausible explanation.

Biological anthropology and bioarchaeology add another layer by reconstructing the biological profile of the dead and connecting it

to lived conditions. Age at death, biological sex, body proportions, markers of physiological stress, pathology, and injury are interpreted alongside evidence for diet, mobility, labour, and inequality. Precision in terminology is important here. Forensic anthropology is primarily defined by its legal and identification context and routinely works with skeletal material. The assessment of soft-tissue pathology and the determination of cause of death in legal settings typically belong to forensic pathology. In archaeological contexts, soft tissues can sometimes be examined—mummified bodies, remains preserved in bogs or ice—but interpretation requires strict separation of antemortem pathology from postmortem changes caused by the preservation environment. It also raises ethical and conservation concerns that favour minimally destructive approaches. Imaging has therefore become central: conventional radiography and CT are standard, high-resolution CT and micro-CT are increasingly used for fine internal structures of bone and teeth, and digital documentation through 3D scanning and photogrammetry supports reproducible analysis while reducing repeated handling.

The grave itself is not a neutral container. It is a changing micro-environment—effectively a small ecosystem—whose temperature, moisture, oxygen availability, pH, sediment type, microbial activity, hydrology, and interactions with textiles, wood, and metals shape decomposition, bone movement, and, crucially, diagenesis and biomolecule survival. This is why taphonomy is not an optional appendix but a methodological core. It reminds us that what survives is not a random sample of the past. It is a filtered residue shaped by burial practice, environment, and later disturbance. Taphonomy also helps correct a common conceptual mistake: epidemics spread through chains of infection and contact, not because there are many bodies. A mass deposit of corpses is an archaeological outcome of high mortality, social disruption, or a collapse of burial capacity, not a prerequisite for transmission. It is therefore unsurprising that clear epidemic mass graves are rare even in periods when written sources suggest frequent epidemics. Often we must reason from small samples, which raises the bar for statistical caution and for triangulation across evidence types.

Even basic definitions can mislead across disciplines. In anthropology, a mass grave may be defined as a grave containing three or more individuals, but archaeologically such deposits can form in many ways and do not necessarily indicate disease; they may relate

to natural disaster or military events. Multiple burials or bodies discarded in settlement pits, especially in Bronze Age contexts, have often been interpreted as ritual, but it is methodologically stronger to treat ritual as one hypothesis among several and test competing scenarios using spatial patterning, trauma evidence, mobility indicators, chronology, and settlement context.

Reconstructing a mortality profile—whether a crisis killed broadly across age and sex or affected particular groups—depends on age and sex estimation, and both come with uncertainty. Sex estimation from skeletal morphology can be difficult even in some adults and is effectively unreliable in subadults, because skeletal sexual dimorphism develops fully only after puberty (*Buikstra and Ubelaker 1994, Larsen 2015, Ortner 2003*). Genetic approaches offer an additional means of sex estimation, but only where nuclear DNA is preserved, as mitochondrial DNA does not carry information on biological sex. Good practice therefore requires transparent reporting of uncertainty and validation against reference collections relevant to the population under study. Age estimation in subadults can be relatively precise through dental development and skeletal growth, though nutrition and disease can shift developmental schedules. Adult age estimation relies on degenerative changes at joint surfaces and related indicators, with the pelvis typically providing the most informative features. Uncertainty increases with age and with individual life history, so results are interval estimates, not exact ages. Even so, estimating age at death within roughly five to ten years is often achievable and analytically meaningful (*Boyd and Boyd 2017*), because small changes in age assignment can reshape the inferred mortality curve and therefore the hypothesized transmission dynamics and vulnerability structure.

The limits of skeletal evidence are clearest for acute infections. Diseases such as cholera, smallpox, measles, or plague can kill quickly and therefore usually leave no diagnostic skeletal traces. This does not put them beyond study, but it shifts the evidential emphasis toward context, abrupt demographic change, biomolecular detection, and nonspecific markers of long-term physiological stress that indicate vulnerability more than cause (*Larsen 2015, Ortner 2003*). Some exceptions exist: systemic infection can sometimes produce periosteal reactions or septic complications, and repeated or prolonged episodes may leave remodelling traces. Even then, careful

differential diagnosis is essential, and such findings should never be treated as automatic signatures of a famous epidemic.

Classic stress markers also need careful framing. Porotic hyperostosis—porous lesions on the cranial vault—was long treated as a straightforward indicator of iron-deficiency anemia. Current interpretation is more cautious and plural. Cranial porosities and related orbital lesions can reflect marrow expansion under multiple anemia pathways, chronic inflammation that alters iron metabolism, parasitic infections and repeated blood loss, micronutrient deficiencies, inherited hemoglobin disorders, environmental and toxic exposures, and age-linked marrow distribution. At the population level, these lesions are better read as indicators of biological burden and stress that may increase susceptibility to severe infection, rather than as direct fingerprints of a single disease. Associating them with a specific diagnosis such as malaria is only one possible interpretation and requires independent support (*Brickley 2018, 896 – 902*).

Where research can move from inference toward identification, microbiological evidence can transform what is possible, but only under strict methodological discipline. Paleomicrobiology and paleogenetics work with very small amounts of fragmented, chemically damaged ancient nucleic acids and face persistent contamination risk from modern DNA and laboratory background. Methods are chosen based on tissue type and research goal, ranging from screening to full-genome reconstruction and phylogenetic placement. In recent years, high-throughput sequencing has become central (*Duchêne et al. 2020, Cappellini et al. 2018*). Metagenomic “shotgun” sequencing reads mixed DNA in an extract and searches for pathogen signals bioinformatically, while targeted enrichment through hybridization capture selectively increases specific pathogen or host sequences. Whatever the approach, authenticity criteria are essential: damage patterns consistent with ancient DNA (aDNA), fragment-length distributions, laboratory replication, negative controls, and phylogenetic plausibility. A “positive” signal has to be distinguished from postmortem contamination or harmless colonization, and a “negative” result can be a false negative caused by degradation, unsuitable tissue, inhibitors, or insufficient sequencing depth. Contemporary overviews stress both the power and the pitfalls of these approaches (*Krause and Trappe 2022*).

Preservation is the silent coauthor of every ancient biomolecular claim. Broad settings such as deserts, ice, or bogs can increase the chance of survival, but microenvironmental conditions are usually decisive: long-term temperature stability, moisture, pH, oxygen availability, soil chemistry, microbial activity, and interactions with burial materials. This is why sampling strategies increasingly prioritize tissues with higher endogenous DNA yields, such as tooth pulp, dental calculus, and dense regions of the temporal bone, and why taphonomic assessment is more often built into research design from the start (*Pinhasi et al. 2015, Warinner et al. 2015*). The detection of *Borrelia* DNA in the genome of Ötzi is frequently cited as one of the earliest direct molecular observations of that pathogen in a human, but even iconic cases remain open to refinement as reference databases expand and methods improve; earliest case is always provisional, not a fixed boundary (*Keller et al. 2012*). It also illustrates an essential conceptual point: identifying a pathogen in one individual is not the same as demonstrating an epidemic in a population, and the distinction becomes critical when interpretive enthusiasm exceeds the scale of the evidence.

Finally, methods have to match what ancient material can realistically support. PCR can amplify tiny fragments of ancient DNA, but its sensitivity is double-edged. It is especially vulnerable to contamination and nonspecific amplification, and ancient fragmentation limits the length of targets that can be amplified reliably. Without rigorous verification, a positive PCR result has limited interpretive force for pathogen attribution. LAMP, as an isothermal amplification method, offers speed and simplicity, but in ancient-material contexts it can face even sharper challenges of specificity and contamination. It is better treated as auxiliary or exploratory, not as a replacement for sequencing when robust identification and evolutionary inference are the goals (*Duchêne et al. 2020, Cappellini et al. 2018*). Relevant samples also do not come only from necropoleis. Pathogen traces and ecological context can sometimes be investigated through dental calculus, settlement sediments associated with waste and occupation, objects potentially contaminated by bodily fluids, and animal remains, widening the view toward zoonotic reservoirs, hygiene regimes, and the shifting interface between humans, animals, and the environments they share.

What emerges from this multidisciplinary landscape is not a single master key for diagnosing the past, but a disciplined way of narrow-

ing uncertainty. At best, ancient epidemics can be reconstructed as convergent explanations in which archaeological context, demography, taphonomy, and biomolecular signals align within a coherent chronology. The aim is not to force a single-cause narrative—pathogen, climate anomaly, or social collapse—but to trace mechanisms: how contact networks and institutions shaped exposure, how nutrition and stress shaped vulnerability, how burial practice and environment shaped what can still be observed, and how the blind spots of each method constrain what can responsibly be claimed.

4.2 Patterns of Spread

Paleogenetic research has become one of the sharpest tools for reconstructing ancient disease landscapes because it can extract two linked histories from the same archaeological contexts. On one side, it can clarify the demographic structure and kin relationships of past human groups. On the other, it can detect genetic traces of microorganisms that circulated through those populations. This double perspective has made older assumptions about past disease more testable—sometimes they hold up, sometimes they do not—but it also forces more careful language about what the evidence actually shows. Finding pathogen DNA in ancient material is never as simple as identifying the culprit. A detected signal sits at the end of a probabilistic chain. It can represent a true infection, but it can also reflect harmless colonization, background environmental DNA, or contamination introduced after death or during laboratory work. For that reason, strong reconstructions depend on authenticity criteria typical of ancient DNA (aDNA), strict negative controls, replication, and bioinformatic filtering that separates low-level noise from reads that are biologically meaningful (*Cooper and Poinar 2000*). At the same time, absence of detection cannot be treated as proof of absence, because biomolecules survive unevenly and selectively.

A key point in contemporary epidemic research is that the presence of a pathogen is not identical with an epidemic as an epidemiological phenomenon. An epidemic implies that occurrence rose above an expected level within a defined population and time window. In prehistoric contexts, expected level cannot be measured directly, so it is inferred from converging lines of evidence, including demographic patterns, changes in burial practice, stress indicators, and biomolecu-

lar findings. These archives do not function like modern surveillance data, but together they can support reconstructions of changing transmission regimes across different settlement and mobility systems.

In broad terms, infectious diseases were part of human life long before farming societies emerged, but the epidemiological behavior of infections differs between small, dispersed foraging groups and large, densely connected settlements. Pathogens that require sustained chains of transmission among humans are more likely to persist and amplify where contact networks are dense and where susceptible hosts are replenished continuously. By contrast, pathogens with non-human reservoirs, chronic or latent phases, vector-borne transmission, or environmental components can circulate under demographic conditions in which strictly human pathogens would be less stable. This is one reason why the Neolithic transition is often discussed as a major reconfiguration of infectious risk, not because infection began then, but because new forms of settlement, storage, sanitation, and human–animal contact increased opportunities for sustained transmission and for repeated cross-species exposure (*Sikora et al. 2025*).

Deep histories of specific pathogens are therefore approached as evolutionary and ecological problems rather than as single origin events. Malaria illustrates this well. Human malaria parasites have evolutionary relationships to primate parasites, consistent with long-term coevolution and recurrent host transitions, while the timing of particular shifts and expansions is approached through models that integrate parasite evolution, host history, and, where available, genetic and archaeological evidence. Similar considerations apply to discussions of pathogen exchange among different populations of the genus *Homo*. The literature considers such possibilities, but the most robust framing is in terms of complex, multi-lineage histories rather than direct, one-step transfers.

Leprosy and tuberculosis show how modern categories conceal biological diversity (*Schuenemann et al. 2013, Brites and Gagneux 2015*). Leprosy is a chronic bacterial disease caused by mycobacteria, with marked regional differentiation and a history that also includes zoonotic reservoirs in some settings. Tuberculosis is best understood through the *Mycobacterium tuberculosis* complex: closely related lineages adapted to humans and some animals, with transmission shaped by the crucial distinction between infection and active disease and by latent phases that can persist for long periods.

In historical and archaeological contexts, tuberculosis is associated with wasting, prolonged cough, and hemoptysis in advanced pulmonary forms, but its population dynamics depend on host immunity, living conditions, nutrition, and social structure. Proposed chronologies for the deeper emergence and diversification of the complex vary depending on whether inference is drawn mainly from modern genomes or anchored more strongly in ancient genomes, which provide time-stamped reference points (*Hershkovitz et al. 2015*).

Hepatitis B virus provides a parallel example of how ancient genomes can alter the picture of pathogen history. HBV is a DNA virus that replicates through reverse transcription, and ancient genomes indicate that past diversity was broader than modern strains alone suggest. Lineage turnover appears to have accompanied demographic change, and models that consider origins and deep timescales remain sensitive to assumptions and calibration choices (*Rifkin et al. 2017, 949 – 964*). The general implication is that pathogen histories often involve expansion, contraction, and replacement across time, rather than simple linear descent (*Kocher et al. 2021, Locarnini et al. 2021*).

The Neolithic transition reshaped epidemic potential through multiple, interacting pathways. Higher settlement density and stronger connectivity increased the opportunities for sustained transmission. New sanitation and storage regimes could intensify fecal contamination routes. Close and frequent contact with domesticated animals and their parasites expanded the interface for cross-species microbial traffic. These processes did not require a single dramatic “spillover moment.” Many zoonotic transitions are better understood as repeated exposure events, sometimes followed by pathogen adaptation and, only in some cases, the evolution of efficient human-to-human transmission. Domesticated species can also become high-frequency contact nodes that make repeated spillovers more likely, while occasional transmission from humans back to animals is also part of this ecology (*Sikora et al. 2025*). For that reason, compilations of diseases shared between humans and domesticates are most informative as indicators of dense cross-species interaction, even though the totals depend on how disease is defined and on uneven surveillance among animals (*Ponting 2018, 221 – 213, 216*).

Specific pathogen origin narratives can be sketched with varying degrees of confidence, and contemporary scholarship treats them as multi-step histories rather than single-source stories. Influenza a vi-

ruses have major reservoirs in wild aquatic birds, and pigs can act as amplifying hosts in close contact with humans, while their RNA genomes make direct archaeological detection rarer than for some DNA pathogens. Measles is most plausibly related to a virus associated with cattle, and its sustained circulation as a strictly human infection would have required large, persistently connected human populations (*Düx et al. 2020*). Smallpox cannot be reduced to a simple origin from cattle, because orthopoxviruses span broad host ranges and historical variola lineages include extinct branches, pointing to a more complex evolutionary trajectory. Terminology also matters for distinguishing superficially similar categories: louse-borne epidemic typhus is strongly linked to crowding and poverty, whereas typhoid fever is a fecal–oral bacterial infection with a human reservoir.

Nutrition and vulnerability interact with these transmission dynamics. Diets in many early farming societies could become more uniform, and micronutrient deficits can modulate immune responses, increasing susceptibility to severe outcomes. Undernutrition, crop failures, livestock die-offs, conflict, and displacement can therefore convert local outbreaks into broader epidemics by clustering vulnerability and increasing risky contacts. Fecal–oral transmission routes, mediated by contaminated food and water, were central in the past as they remain for dysentery, typhoid fever, and cholera. Paleoparasitology offers durable community-scale evidence here through coprolites and latrine or sewer sediments that preserve parasite eggs and cysts. Such deposits may be mixed and redeposited and rarely correspond to a single individual, but they document sustained exposure to sanitation regimes that repeatedly loaded the transmission vehicle—food and water pathways—with infectious material.

Wider landscape and economic change also reshaped human–animal–environment interfaces. Expansion into biodiverse zones, habitat fragmentation, hunting and animal trade, and the spread of pasturelands altered contact patterns among humans, domesticates, and wildlife. Domesticated animals can function as bridges between wild ecologies and households. At the same time, apparent patterns of pathogen sharing must be interpreted with awareness that domesticates are disproportionately monitored compared with most wild mammals, which affects what is visible in the record (*Johnson et al. 2020*).

A contemporary ecological framing of zoonoses depends on clear definitions. A zoonosis is a disease naturally transmissible between

vertebrate animals and humans, but transmission depends on different roles. Reservoirs are host populations or ecological systems in which a pathogen is maintained over time and from which transmission can occur. Vectors are biological transmitters such as ticks, fleas, and mosquitoes, whose competence and feeding behavior structure risk. Contaminated water is generally treated as a vehicle of transmission rather than a reservoir in the strict sense. Zooarchaeology can document the presence of potential host species in settlement and refuse assemblages, while establishing reservoir status for particular pathogens requires additional biological and ecological evidence. Archaeobotany, geoarchaeology, and paleoclimatology extend the frame by reconstructing climate variability, seasonality, and landscape change that influence host and vector abundance and pathogen survival, while local microenvironments—housing humidity, grain storage practices, rodent access to granaries—often shape exposure more directly than regional averages. Where direct evidence for vectors is limited, sedimentary DNA and other emerging approaches can contribute to reconstructing plausible transmission ecologies within specific contexts.

Many large historical epidemics involved pathogens that had zoonotic phases and later became predominantly human diseases after acquiring efficient human-to-human transmission, a process commonly described as the shift from zoonosis to anthroponosis (*Sikora et al. 2025*). In those settings, the built environment and social organization become crucial for reconstructing spread: housing density, settlement size, provisioning systems, and social stratification structure contact networks, while mobility and congregation—trade routes, troop movements, metropolitan life, military camps—create corridors of introduction and arenas of amplification. Mathematical epidemiology can explore whether proposed scenarios are consistent with plausible parameter ranges for transmissibility, contact heterogeneity, generation intervals, and susceptible replenishment, and it is most informative when treated as a way to map feasible dynamics rather than as a retrospective measurement tool in contexts where the underlying data are sparse and uneven.

In well-known historical cases, pathogen identification and impact reconstruction rest on different kinds of evidence and are therefore treated separately. For the Athenian epidemic described by Thucydides, the causative agent has not been definitively established, and interpretations focus on symptom narratives, social context, and the

epidemiological plausibility of different candidates (*Papagrigrorakis 2006, 206 – 213, Shapiro, Rambaut and Gilbert 2006, Cunha 2008, 4 – 9; Littman 2009, 456 – 465*). In contrast, the Justinianic pandemic is now linked by biomolecular evidence to *Yersinia pestis*, even though the scale and regional variability of demographic and economic effects remain matters of active research. Pathogen genomes also contribute to questions of connectivity and movement, but pathogen spread can track migration, trade, armies, animals, goods, or brief contacts without permanent resettlement, so genomic signals are interpreted most productively alongside isotopic and human genetic evidence and archaeological context (*Habicht 2020, 12; Meier 2009, 106 – 133, Mordechai 2019, 6 – 8*).

Plague provides the clearest example of how paleogenomics has reshaped historical reconstructions. Ancient genomes point to a long and complex Eurasian history, with deep diversity connected to Central Asian regions such as the Tian Shan and with some early identified strains discussed in relation to western China. These patterns are most informative as indicators of reservoir landscapes and basal diversity rather than as a simple route from a modern nation-state to ancient outbreaks. Reports of similarity between Justinianic victims in Germany and modern strains from China describe phylogenetic relatedness within a broad Asian diversity, not identity or a direct route map (*Rasmussen et al. 2015, Wagner et al. 2014, Habicht 2020, 13*).

Yersinia pestis is named after Alexandre Yersin, the Swiss-French physician who identified it during the 1894 Hong Kong epidemic. Clinically, plague includes bubonic forms typically following infectious flea bites with swollen lymph nodes, septicemic forms involving systemic dissemination and sepsis, and pneumonic forms capable of respiratory droplet transmission between humans. Severe septic cases can involve coagulopathy and peripheral ischemia with tissue necrosis, but such features are not universal and not uniquely diagnostic, which is why historical descriptions are read in relation to clinical variability (*Bergdolt 2002, 16 – 18*). Ecologically, plague is maintained in cycles among rodent reservoirs and their fleas, and spillover depends on local host communities, flea species, seasonality, human behavior, and environmental conditions that shape contact rates. Discussions of the roles of human ectoparasites such as *Pulex irritans*, as well as scenarios emphasizing *Xenopsylla cheopis* and rat-mediated cycles under particular climatic conditions, belong within a broader ecological picture in which transmission pathways

can vary by region and context and pneumonic spread can bypass vectors entirely.

What has become especially firm is the etiological anchoring of the Justinianic pandemic to plague in the bacteriological sense. Molecular findings from multiple late antique cemeteries, including sites in present-day Germany, have yielded *Yersinia pestis* DNA from dozens of individuals, sometimes summarized as on the order of forty-plus (*Habicht 2020, 13, Mordechai 2019, 6 – 8*). This is necessarily a small and preservation-shaped sample relative to historical populations, but it is sufficient to connect the historical pandemic to *Yersinia pestis*. At the same time, establishing the pathogen responsible for a pandemic is not the same task as quantifying mortality, measuring economic disruption, or mapping regional variability, which is why debates about magnitude and uneven impact remain active alongside secure etiological identification (*Mordechai 2019, 1 – 3*).

4.3 Epidemics, Society, and Resilience

Even in societies where infectious disease was a recurrent stressor—sometimes with severe and farreaching consequences—archaeological reconstructions of epidemics must begin from a basic constraint: material and spatial traces of crisis are rarely diagnostic. Similar archaeological configurations can arise from different historical processes, and what survives into the record is further shaped by selective preservation, uneven excavation, variability in settlement and mortuary practice, and later disturbance. Within this framework, settlement abandonment, whether of entire sites or individual quarters, is best treated as an outcome with multiple plausible causes. It may accompany epidemic mortality, but it is equally compatible with population relocation, environmental change, economic reorientation, political realignment, or responses to conflict and insecurity. For many archaeological traditions, abandonment is therefore approached as part of settlement dynamics rather than as an exceptional rupture that automatically signals catastrophe.

The analytical problem lies less in identifying abandonment than in reconstructing its form, tempo, and context. Distinguishing abrupt discontinuity from gradual transformation, temporary emptying from longterm reassignment of functions, and localized events from wider regional patterns requires chronological resolution beyond artefact

typology alone. Comparative work across parallel sites, coupled with independent evidence for demographic change, altered mobility, provisioning stress, and shifts in burial regimes, permits epidemic hypotheses to be evaluated alongside other explanatory models. Epidemics thus enter interpretation not as default explanations but as historically specific processes that must be supported by converging lines of evidence.

Where abandonment is an ambiguous signal, practices that reduced contact can align more closely with epidemiological dynamics, while still demanding careful contextualization. Reduced interaction between households or communities may lower transmission under certain conditions, yet its effectiveness depends on how a disease spreads and how social contacts are organised (*Steinová 2020, 55 – 56*). Transmission pathways differ depending on whether close interaction concentrates within households, marketplaces, military camps, or transport corridors; they also depend on whether high-intensity contacts cluster around a limited number of socially central nodes or diffuse across everyday interactions. In historical societies, measures that limited contact were rarely conceived as comprehensive population-wide interventions. They were more often selective and pragmatic, prioritising the protection of elites, key facilities, storage, or essential labour groups. At the same time, epidemic conditions rarely brought social life to a standstill. Communities still needed to secure food supplies, maintain protection and administration, care for the sick, and manage the dead.

Archaeological and textual indications that core activities continued under disease pressure—such as sustained military commitments during the Athenian epidemic or the persistence of mobility and exchange networks at imperial scale during late antique outbreaks—can be read as expressions of systemic continuity under stress rather than as evidence that disease had negligible effects. Continuity frequently depended on the uneven redistribution of risk: exposure could be intensified among marginal groups, coerced labour, caretakers, and those responsible for burial and provisioning (*Harper 2021*). In this sense, resilience is not synonymous with collective wellbeing. It describes the capacity of a system to preserve or reconfigure essential functions despite shock, often by reallocating costs in socially patterned ways. Resilience becomes visible when it is anchored in observable capacities: the ability to mobilise and redistribute resources, reorganise labour, sustain logistics, maintain legitimacy and trust,

stabilise fiscal extraction, and preserve military protection. Societies possessing such capacities could adapt and endure even in the absence of effective medical treatment. Conversely, where administrative reach was thin, where coercion substituted for consent, or where inequality already constrained access to subsistence and care, epidemics could accelerate fractures that were present before the outbreak (*Harper 2021*).

For this reason, current scholarship tends to treat epidemics as contributors to systemic transformation rather than as single, self-sufficient causes of collapse. Political transitions and structural breakdowns usually arise from multiple interacting pressures, and epidemics often operate as catalysts that amplify existing vulnerabilities, intensify fiscal strain, and alter political balances. The Roman Empire provides a clear illustration. The epidemic conventionally known as the Antonine plague weakened imperial structures (*Amm. Marcell. 23. 6. 24, Cass. Dio. 72.14.3 – 4; Herodian 1.12.1 – 3*), even if it was not the sole or decisive turning point in Roman history (*Cunha and Cunha 2008, 13, Habicht 2020, 7 – 9; Littman 1973, 243 – 252*). Its historical significance lies in how it exposed vulnerabilities inherent in a highly connected imperial system. Regardless of uncertainty surrounding the precise pathogen, consequences depended on the scale and duration of mortality, the recurrence of epidemic waves, and the extent to which longterm morbidity reduced labour capacity—factors that affected recruitment, taxation, and routine economic activity, and thus the empire’s resilience over time.

Economic consequences of epidemics are therefore reconstructed through indirect indicators rather than assumed as automatic outcomes. Reduced mining activity across multiple commodities is compatible with demographic shock, and researchers approach this problem through environmental archives and economic proxies that integrate signals of metallurgical output, construction intensity, and trade volume (*Duncan-Jones 2018*). Such archives, however, register large spatial scales and can also capture warfare, administrative reform, technological shifts, or changes in supply networks. Regional interpretations thus depend on localized archaeological and historical evidence. In the case of gold mining in Dacia, recovery patterns were shaped not only by disease but also by frontier security, administrative priorities, labour availability, and investment strategies. Epidemic disruption may have contributed to interruption or altered economic calculations, but it formed part of a broader constellation

of constraints. Similar considerations apply to silver and lead production in Britain, where demographic loss could reduce labour supply and demand, with secondary effects mediated by mobility, coercion, and reorganisation of work. Continental-scale signals, such as fluctuations in lead pollution recorded in Greenland ice cores, are consistent with changing metalworking intensity, but they require careful contextualisation against emission sources and complementary datasets to avoid singlecause interpretations (*McConnell et al 2018*).

Timber exploitation offers a comparable case. Dendrochronological datasets from parts of the Rhine region and northwestern France show phases of reduced felling that can be interpreted as diminished construction activity or altered demand for fuel and materials; they can also reflect shifts in building cycles, procurement strategies, and the structure of surviving samples. Stronger arguments emerge when such signals align with archaeological evidence for changes in building activity, repair and demolition sequences, material supply (brick, mortar), numismatic circulation, and epigraphic indicators of economic tempo. Epidemic impacts on economies are therefore most convincingly reconstructed through integrated analyses of institutions, infrastructure, and material flows rather than through isolated proxies.

Alongside these indirect approaches, the last decades have added a further evidential register that matters for any uptodate discussion of epidemics: bioarchaeology and biomolecular detection. Ancient DNA and related biomolecular methods can, under favourable preservation conditions, identify specific pathogens directly from human remains, and in some contexts have clarified the aetiology of historically attested outbreaks. The interpretive value is substantial but bounded (*Duchêne et al. 2020, Cappellini et al. 2018*). Absence of detection is not evidence of absence, sampling is rarely representative of entire populations, and many infections leave no skeletal lesions. Biomolecular results therefore do not replace archaeological context; they refine it. When pathogen identification, cemetery demography, burial practice, and settlement evidence align in time and space, confidence increases. When they diverge, the divergence itself becomes informative, pointing to the limits of preservation, to heterogeneity in exposure, or to the misattribution of crisis indicators.

In many historical contexts, epidemics are documented primarily in written sources even where material traces are limited or ambiguous, reflecting the different sensitivities of texts and archaeology (*Harper 2017, Little 2007*). Texts can preserve accounts of events without leaving clear archaeological signatures, while archaeology often records longterm consequences without specifying cause. Written evidence spans diverse genres, from ritual texts and administrative correspondence to historiography, each shaped by its own purposes. References to disease therefore require attention to genre and function. Ritual texts, administrative reports, and historical narratives do not aim to document illness clinically; they frame disease in relation to legitimacy, moral order, religious practice, and governance.

This pattern is evident in Mesopotamian sources, where explicit references to epidemics are relatively uncommon despite the abundance of medical texts. Illness frequently appears as a background condition unless it threatened palace labour, military campaigns, or elite security (*Prosecký 2015, 139 – 154*). The palace archive of Mari from the reign of Zimrilim (1775 – 1761 BC) is especially informative because it links disease to concrete administrative and logistical responses: the protection of key individuals, restriction of spaces, regulation of movement, and attention to potentially dangerous contacts (*Klíma 1976, 276, Neufeld 1986*). Such measures, reported even in the context of ongoing military operations, demonstrate how disease could shape planning and provisioning. Strategies aimed at limiting spread carried social costs. Flight could fragment households and extend infection along new routes, while isolation was unevenly applied and could be socially stigmatising. Accounts that describe signalling or restricting the houses of the sick—sometimes framed in ritual idioms—can also be read as practical mechanisms that structured interaction and risk perception in daily life.

In the Greco-Roman world, epidemic narratives are dominated by historians such as Thucydides (*Thuc. 2.47 – 2.54*) and Procopius (*Procop. De Bell. Pers. 2. 22*), Christian authors including Eusebius of Caesarea (*Euseb. Hist. Eccles. 8. 21 – 22*), and medical writers such as Galen, whose observations provide a different but complementary perspective. These accounts integrate descriptions of illness with reflections on moral order, political legitimacy, and collective suffering. The Athenian epidemic at the beginning of the Peloponnesian War remains a key example. Thucydides' narrative, informed by his own experience of illness, combines symptom description with

observations on behaviour and social response. He noted differential mortality, apparent immunity among survivors, and severe longterm impairment, underscoring that communities faced not only death but enduring disability. Such descriptions illuminate epidemic dynamics without fixing aetiology, since similar outcomes can arise from different pathogens or from complications such as dehydration and secondary infection (*Habicht 2020, 5 – 7*).

Archaeologically, the Athenian event left limited unambiguous traces, a pattern consistent with textual emphasis on disrupted funerary practice and improvised disposal under pressure (*Thuc. 2.52.4, Papagrigorakis 2006, 207 – 208*). Rapid or simplified burials in pits and shafts are often interpreted as emergency responses, but comparable patterns can also result from logistical overload, social tension, or shifts in funerary norms. More robust inference depends on whether such deposits cluster tightly in time, whether they coincide with broader changes in cemetery organisation and ritual, and whether independent demographic signals indicate exceptional mortality. Within this frame, cremation appears most convincingly not as a diagnostic indicator of epidemic disease, but as a pragmatic funerary response to exceptional mortality and logistical pressure, whose archaeological visibility depends on longer-term shifts in mortuary preference rather than on the outbreak itself. Developments in healing cults and sanctuaries—such as the Athenian Asklepieion or the sanctuary of Amphiaraos at Oropos—likewise speak to heightened preoccupation with health and care, while remaining embedded in patronage, ritual innovation, and political competition (*Mitchell-Boyask 2008, Kallet 2013, 355 – 382*). Their trajectories can be consistent with epidemic experience without serving as direct markers of a particular outbreak.

Medical treatises attributed to Hippocrates, fragments of Galen, and epigraphic and literary evidence also clarify how illness, seasonality, and environment were conceptualised. These texts often connect disease with famine or climatic stress, but the path from environmental variability to epidemic mortality is mediated by institutions, conflict, migration, sanitation, and pathogen ecology (*Harper 2021*). Volcanic events occupy a similar interpretive space: infrastructural disruption, respiratory injury, water contamination, and displacement can all raise disease risk without implying a single uniform mechanism (*Dio Cass. 45. 17. 8, 66. 23. 5; Suet. Div. Titus. 8. 3*). In military camps, besieged cities, and other highdensity

settings, epidemic dynamics are more directly tied to crowding, hygiene breakdown, compromised water supplies, and forced mobility, which can turn local outbreaks into wider transmission events (*Diod. 13. 12, 14. 70. 5, 13. 86. 1-3, 70. 4-5, Onos. 8-9, Veg. Epit. 3. 2, Amm. Marcell. 19. 4, 30. 6*). Many epidemics likely went unrecorded because they were geographically limited, politically inconvenient, or absorbed into endemic patterns; their cumulative effects, however, may still be detectable in longterm changes in labour, settlement organisation, and institutional capacity. Some pathogens may have disappeared or changed in clinical profile, while others persist with altered transmission dynamics under new ecological and social conditions (*Harper 2021*).

A synthesis that takes society and resilience seriously therefore rests on scale-aware comparison rather than on single signatures. Epidemics are best reconstructed where multiple registers—settlement and mortuary evidence, environmental and economic proxies, and, where possible, biomolecular identification—converge on the same temporal window and social context. The most consequential historical question is often not whether disease occurred, but how societies distributed exposure, maintained essential functions, and renegotiated authority and obligation under stress. In that sense, epidemics function as diagnostic episodes: they reveal institutional reach, social inequality, and the practical limits of coordination, leaving traces that are sometimes subtle, often indirect, and analytically legible only when interpreted in relation to the capacities that sustained—or failed to sustain—collective life.

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Conclusions

Environmental stress in antiquity becomes historically legible not as an external force that pushes societies along a single track, but as a field of interacting pressures that are always mediated by institutions, infrastructures, cultural practices, and ecological settings. Read through resilience, the book's case material demonstrates that shocks and slow pressures rarely act alone and that outcomes turn on how risks are perceived, distributed, and managed across nested levels of social and ecological organisation. Environmental stress is therefore legible as interacting hazards and constraints within historical systems, not as a single cause that mechanically produces collapse (*Adger 2000, 347 – 364, Folke 2006*).

Across the climate, hazards, biodiversity, and epidemics discussions, six recurring resilience mechanisms emerge as historically grounded patterns. The first is diversification, understood broadly as maintaining more than one way to meet basic needs when any single stream of food, income, or political support falters. Diversification includes mixed subsistence strategies, flexible land use, and the balancing of local production with exchange, but it also includes the social capacity to shift labour between activities and to recalibrate obligations when conditions demand it (*Walker et al. 2004*). In the manuscript's climate and biodiversity material, diversification is visible not only in what people grow and keep, but also in how they exploit landscapes, manage animals, and widen or narrow ecological niches. In the hazards and epidemics material, diversification becomes equally visible as a political and infrastructural phenomenon, as communities maintain more than one provisioning route, more than one water source, or more than one institutional pathway for mobilising relief.

A second mechanism is redundancy and storage, the deliberate creation of slack in food, water, and material systems. Agrarian societies are exposed to seasonal variability and multi-year anomalies, and the boundary between hardship and catastrophe often turns on whether reserves exist and whether access to them is governed in ways that preserve social cohesion. Granaries, cisterns, and irrigation works are material expressions of this logic, but they are inseparable from institutions of measurement, taxation, redistribution, and trust. Storage is also social: it includes obligations and reciprocities that

can be activated in crisis, and the expectation that authorities will act as coordinators rather than mere extractors. The manuscript's emphasis on long-distance provisioning networks reinforces the same point: redundancy can be built not only by stockpiling locally but by sustaining multiple links to hinterlands and maritime circuits, so that shortfalls in one zone do not automatically translate into urban famine.

A third mechanism is mobility, not as a single dramatic movement but as a spectrum of practices ranging from seasonal transhumance to temporary refuge, evacuation and return, and longer-term relocation. The hazards discussion demonstrates that evacuation is materially legible as a socially differentiated process: some people leave early with portable wealth, others remain to protect property, and many return quickly to salvage. Mobility can buffer risk when it enables people to move away from acute danger, to relocate labour in response to harvest failure, or to rebuild livelihoods elsewhere. It can also amplify stress by destabilising provisioning systems, provoking conflict over land and resources, and transmitting pathogens along routes of travel, trade, and warfare (*Hakenbeck and Büntgen 2022*).

A fourth mechanism is infrastructural maintenance and repair, understood as a continuous social practice rather than an occasional reaction to disaster. Recovery depends less on rebuilding everything than on restoring key functions such as water supply, sanitation, transport, and access to food (*Meerow, Newell and Stults 2016*). The manuscript shows how harbours, roads, bridges, walls, and urban water systems are not merely symbols of order but the practical means by which cities remain viable after shocks. It also demonstrates that building practices and material choices embed memory and learning: the decisions to reinforce walls, to reconfigure streets, to rebuild selectively, or to shift the focus of investment are forms of historical adaptation. Maintenance is not merely technical. It is political, because it allocates labour and surplus, and ecological, because it shapes sedimentation, flooding, and landscape stability over time.

A fifth mechanism is institutional coordination and legitimacy. Resilience in complex societies depends on the capacity to mobilise resources across space, organise labour, enforce or renegotiate obligations, and sustain credible narratives of authority in moments of disruption (*Meerow, Newell and Stults 2016, Gunderson and Holling 2002*). The late antique examples show that reconstruction can

be both functional and symbolic: rebuilding public space and reasserting order are political acts aimed at stabilising confidence, sometimes through renaming and ritual as well as through engineering and finance (*Borsch 2023, 201 – 241*). Institutions can also fail in resilient ways, preserving their own continuity while shifting costs downward. The point, made repeatedly across chapters, is that institutions are not external to environmental stress. They are part of the mechanism by which stress becomes crisis or remains manageable.

A sixth mechanism is connectivity, the networks of exchange, communication, kinship, and political alliance that bind local ecologies to wider systems. Connectivity can buffer deficits through imported grain, diversified inputs, and access to distant labour and knowledge. It can enable recovery through external assistance and through the circulation of skilled workers and building materials, as the manuscript illustrates in cases of Greek urban destruction and rebuilding, including the well-attested recovery of Rhodes (*Bresson 2021, 189 – 227*). At the same time, connectivity can amplify crises. It transmits price shocks and supply disruptions across regions, it concentrates dependence on key routes and nodes, and it can turn mobility and trade into vectors of disease (*Harper 2021*). Connectivity is therefore not a simple measure of strength. It is a structure that can both distribute and concentrate risk, depending on how it is governed and on whether it is matched by redundancy and maintenance.

These mechanisms come into focus most sharply when read through the lens of compound and cascading stress (*Gunderson and Holling 2002*). The manuscript repeatedly shows that crises in antiquity are better understood as sequences than as isolated events. Climatic anomalies alter yields and pasture, which shifts prices, credit relations, and the politics of redistribution (*Finné et al. 2019, Zscheischler et al. 2020*). Hazards damage harbours, roads, and water systems, constraining the very networks that might have buffered scarcity. Ecological change reshapes exposure to pests, vectors, and zoonotic interfaces (*Keesing et al. 2010*). Epidemics, in turn, can reduce labour availability, disrupt care networks, and erode confidence in institutions at precisely the moment when repair and coordination are most needed. The end of the third millennium in the Near East, discussed through the prism of the 4.2-kiloyear BP event, is instructive precisely because it resists reduction: aridity signals and hydroclimatic shifts intersect with changing state capacity, irrigation regimes, and political conflict. In Mesopotamia, the trajectories of Akkadian

imperial integration and later reorganisation under Ur III underscore how climatic pressure was refracted through canal management, labour control, and inter-polity competition, producing outcomes that were political as much as environmental. Comparable caution applies to Egypt, where debates about the transition from Old Kingdom centralisation to the First Intermediate Period must be framed as an entanglement of Nile variability, administrative practice, regional power, and the social consequences of uneven provisioning.

The Late Bronze Age material extends this argument because disruptions are visible across multiple regions and archives. The hazards chapter's treatment of the Thera eruption stresses that the most secure historical claim is not a single dramatic story of instantaneous destruction, but a sequence of uneven responses: precursor shocks, selective salvage, evacuation, and the transformation of places within wider exchange networks. The attention to tsunami deposits makes the point materially: a sudden marine inundation can be locally devastating while leaving adjacent areas relatively intact, and the longer-term effects depend on whether ports, agricultural hinterlands, and maritime links can be restored. When these hazard pathways are placed alongside hydroclimatic variability and evidence for strain in eastern Mediterranean political economies (*Finné et al.2019*), the problem is not to choose between climate, earthquake, or warfare as the prime mover. It is to understand how fragility emerges when several stressors converge, when long-distance systems that normally distribute risk instead transmit it, and when mobility and conflict become entangled with provisioning. The discussion of population movement and disruption at the close of the Late Bronze Age, often gathered under the label of Sea Peoples, can be read as both a response to stress and a driver of further cascades through raiding, resettlement, and the interruption of exchange.

Late antiquity provides perhaps the clearest illustration of compound and cascading stress because independent climate archives converge on a period of strong volcanic influence and climatic disturbance, while texts and archaeology record repeated earthquakes, warfare, fiscal pressure, and epidemic outbreaks. The manuscript treats volcanic cooling not as a deterministic trigger but as a factor that raises the likelihood of harvest stress and fiscal strain, thereby sharpening the consequences of political and military decisions (*Gao, Robock and Ammann 2008*). In this setting, earthquakes in cities such as Constantinople and Antioch could become more than lo-

cal disasters: damage to housing, water supply, and public buildings altered the conditions under which displaced people sought shelter and under which disease could spread. The Justinianic plague, discussed through both written testimony and biomolecular research identifying *Yersinia pestis* (*Little 2007, Mordechai et al. 2019*), exemplifies a cascade in which connectivity and density support imperial power while also enabling rapid transmission of mortality and fear.

Compound stress is equally visible at the scale of the city and its immediate hinterland. A major earthquake and associated tsunami can damage harbours and low-lying quarters, disrupt water and sanitation systems, and trigger fires, leaving a population exposed not only to aftershocks but to shortages and disease. The hazards chapter underlines that such events are difficult to trace and that their effects vary with microtopography, coastal geometry, and the built environment (*Ambraseys 2009, Stiros 2022*), meaning that risk is locally produced even when the seismic source is regional. This is a resilience lesson in the strict historical sense: the same hazard can generate different trajectories depending on prior maintenance, on the distribution of vulnerability in neighbourhoods and households, and on whether institutions can coordinate repair and relief without producing further conflict. Where ports are damaged, the consequences can propagate quickly into food systems and political legitimacy, because maritime connectivity is both a buffer and a dependency.

The manuscript's evidence therefore supports a view of adaptation that is rarely a simple return to an earlier equilibrium (*Walker et al. 2004*). Historical outcomes more often involve reorganisation, rescaling, and selective persistence. In some cases, resilience takes the form of institutional continuity and rebuilding, where key functions are restored and memory is incorporated into new practices. In other cases, resilience takes the form of relocation and reconfigured connectivity, where populations move, political centres shift, and new networks replace old ones. Even where narrative sources prefer a vocabulary of decline, the material record often reveals continuity in altered form: districts contract while others expand, functions are redistributed, and resilience is expressed as persistence of some capacities alongside loss of others. This is especially important for the book's treatment of collapse narratives. The evidence assembled here aligns more strongly with trajectories of fragmentation, recombination, and transformation than with abrupt systemic extinction.

This approach clarifies the trade-offs between adaptation and transformation. Systems can be resilient in a way that preserves hierarchy and extraction, stabilising order at the cost of deepening vulnerability among those with the least capacity to absorb loss (*Walker et al. 2004*). Conversely, periods that appear chaotic in political narratives may also be periods of creative reconfiguration, where communities experiment with new forms of settlement, subsistence, and alliance. The manuscript's evidence supports a spectrum of outcomes, including persistence with adaptation, persistence through coercive stability, and transformation through forced reorganisation. What appears as recovery at one scale can simultaneously be displacement at another, and what appears as stability can be maintained through the accumulation of hidden ecological and social debt.

Power and inequality are therefore central findings, not slogans. Access to information, mobility, and portable wealth shapes survival and recovery. Reconstruction, even when framed as communal renewal, depends on unequal capacities to mobilise labour, materials, and finance, and on the coercive or negotiated structures through which those resources are obtained. The climate discussion of imperial provisioning highlights how long-distance supply networks can sustain large urban populations while imposing systemic vulnerability on those who produce, transport, and tax the surplus. The biodiversity chapter sharpens the point by showing how elite consumption and spectacle could place sustained pressure on animal populations, as in the *venationes*. The story of silphium, remembered as a prized plant whose disappearance was linked to overexploitation and narrow ecological range, offers a smaller but telling illustration of how value, scarcity, and ecological fragility can interact. And how economic persistence can therefore be ecologically harmful even when it appears socially stable.

The linkage between biodiversity change and epidemics deepens the resilience argument further, because it reveals shared drivers in human–environment entanglement and a shared sensitivity to connectivity (*Cardinale et al. 2012*). The biodiversity chapter underscores how domestication, hunting, habitat modification, and the translocation of plants and animals reshape species communities and ecological feedbacks (*Johnson et al. 2020, Zinsstag et al. 2011*). The epidemics chapter complements this by treating pathogen histories as evolutionary and ecological processes rather than as single origin events. Settled life, dense habitation, and grain storage create op-

portunities for commensal species and vectors, while long-distance exchange and forced mobility connect distant disease ecologies. The Athenian plague, assessed through historical description and biomolecular claims pointing toward typhoid (*Papagrigrorakis et al. 2006*), and the Justinianic plague, supported by genetic identification of *Yersinia pestis*, become more than episodes of mortality: together they reveal how different configurations of vulnerability—urban crowding, mobility, and sanitation in the former case, and zoonotic reservoirs, vectors, and long-distance connectivity in the latter—were structured by connectivity and urban form (*Mordechai et al. 2019*). The chapter’s discussion of long-lived diseases such as tuberculosis and of environmentally mediated risks such as malaria reinforces the same point: resilience to disease is tied to ecology, infrastructure, and inequality as much as to medicine or belief.

Methodologically, the manuscript’s central achievement lies in its insistence on triangulation and consilience across different kinds of sources, each with distinct temporal and causal affordances. Texts provide narrative, perception, and institutional context, but they encode genre conventions, moral interpretation, and uneven coverage. Archaeology records material traces of damage, recovery, and everyday practice, but it is shaped by taphonomy and selective visibility. Palaeoclimate and palaeoenvironmental proxies provide independent constraints on variability and extremes, yet they often operate at resolutions that do not map neatly onto the eventful tempo of political history (*McCormick et al. 2012, Haldon et al. 2018*). Bioarchaeology and biomolecular research, where available, extend the evidentiary base into health, demography, and pathogen identification, and thereby allow more precise questions about exposure and vulnerability. The manuscript demonstrates that resilience research in antiquity advances most decisively when these archives are brought into disciplined conversation, so that any single line of evidence is checked, limited, and contextualised by others.

The limits of this approach are as instructive as its strengths. Chronological uncertainty remains a persistent challenge (*Bronk Ramsey 2009*), especially when correlating hazard events, climatic anomalies, and social change across wide regions. Representativeness is uneven, both socially and geographically, and absence of evidence can reflect gaps in preservation as much as historical reality. In the disease domain, retrospective diagnostic certainty is particularly dangerous, because similar symptoms can arise from different causes

and because the absence of biomolecular evidence is not evidence of absence. In the hazards domain, there is a temptation to treat striking destruction layers as unambiguous signatures of single events, when the material record may compress repeated damage, repair, and reuse. These limitations do not undermine the resilience framing; rather, they define the standards by which future historical resilience research must proceed, prioritising transparency about uncertainty, careful chronological reasoning, and explicit causal pathways over narratively satisfying simplifications.

The implications that can be carried from these ancient cases into present debates are therefore bounded and methodological rather than prescriptive. The manuscript supports the portability of certain questions and mechanisms: how compound risks produce cascades; how connectivity can buffer and transmit; how redundancy, maintenance, and diversification shape the capacity to absorb volatility; and how inequality and power determine who bears the cost of persistence and change (*Gunderson and Holling 2002, Walker et al. 2004*). What is not transferable are direct lessons framed as policy templates, because the ancient world differs fundamentally in energy regimes, technological capacity, medical knowledge, state reach, and the scale and speed of global connectivity. The book nevertheless contributes to contemporary resilience research by offering a long baseline for observing how societies behave under repeated stress and by highlighting mechanisms and trade-offs that remain structurally recognisable even when circumstances differ. Its cautious value for the present lies in sharpening questions about vulnerability, governance, and cascading risk, not in offering comforting analogies or deterministic warnings.

A forward-looking research agenda follows naturally from this book's approach. Future work should develop integrated, openly accessible datasets that link high-resolution climate proxies with archaeological indicators of settlement, land use, and production, enabling genuinely multi-hazard syntheses rather than parallel narratives. Comparative studies of urban recovery should combine archaeoseismology, building archaeology, and institutional history to distinguish repair, reconfiguration, and abandonment as different resilience pathways. Disease history in antiquity should increasingly connect biomolecular identification with environmental reconstruction and network analysis, so that the ecological conditions of emergence and the social conditions of spread can be analysed together. Biodiver-

sity research should continue to trace how human niche construction alters species communities, while integrating these findings with disease ecology and with the material history of storage, sanitation, and urban form. Methodological work should prioritise better chronological modelling and clearer statements of uncertainty, especially where multiple stressors converge within short windows. Above all, future research should treat resilience as a question about interaction, scale, and distribution, asking not only whether systems persist, but for whom, by what means, and at what ecological and social cost.

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