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Surveys and Speculations

Roman technological progress in comparative context: The Roman Empire, Medieval Europe and Imperial China

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ABSTRACT

The Roman Empire experienced both extensive and intensive economic growth. This article first surveys the role of technology in that process, engaging with recent literature on intensive growth under Malthusian constraints. It goes on to investigate the difference in technological progress between the Roman Empire and medieval Europe. It argues that political fragmentation explains why medieval Europe was more innovative than the Roman world, invoking a comparison with imperial China to complement the analysis. The technological success of China under the Tang and Song shows that political fragmentation is not a precondition for progress. However, Roman emperors never invested in the practical application of useful knowledge, the way Chinese rulers did.

1. Introduction

Hotly debated among Roman historians is the question of economic growth under the Empire, especially its extent, duration and causes. To clarify the terms of that debate, it is worth setting Roman growth in the context of long-term economic development (as argued also in Terpstra, 2018, 2019). This paper is a contribution to creating an encompassing narrative, with a specific focus on technological progress. The paper will first engage with recent work in economics on the role of technology in producing intensive growth under Malthusian constraints. It will proceed to frame the debate on Roman innovational advancement, contrasting it with medieval developments. Next, it will consider disincentives and incentives to Roman technological progress, complementing the analysis with a comparison to imperial China. It will appear that in medieval Europe, innovation was driven by competition within a fragmented states system, while in Tang-Song China it was driven by the emperors' support. The paper will conclude that Roman progress was slow by comparison, because the Roman world benefited from neither of those conditions.

Ancient economic performance cannot be measured directly, as the statistical evidence needed to do so is lacking. But archeological data increasingly provide useful, if imperfect, proxies.[1] The most widely cited dataset suggesting Roman growth, as well as late-antique contraction, is the one visualized in Fig. 1: the number of dated shipwrecks on the bottom of the Mediterranean.

The data are less reliable for the post-Roman period. Ancient ships transported liquids and also some solid goods in ceramic containers, but from the early medieval period onward a shift occurred toward the use of wooden barrels (Wilson, 2011; Bevan, 2014). As barrels tend to disappear from the seafloor, the data give the false impression that Mediterranean shipping ca. 1500 CE had only reattained Iron-Age levels.[2]

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[1] A selection of recent significant work: Renberg et al., 2001; De Callataÿ, 2005; Koepke and Baten, 2005; Kron, 2005; Jongman, 2007a, 2007b; Wilson, 2011; Erdkamp, 2016; Harper, 2017; Manning, 2018; McConnell et al., 2018; McConnell et al., 2019; Jongman, Jacobs and Klein-Goldewijk, 2019.

[2] The imbalance in representativeness is perhaps magnified by improved medieval ship design; see below.

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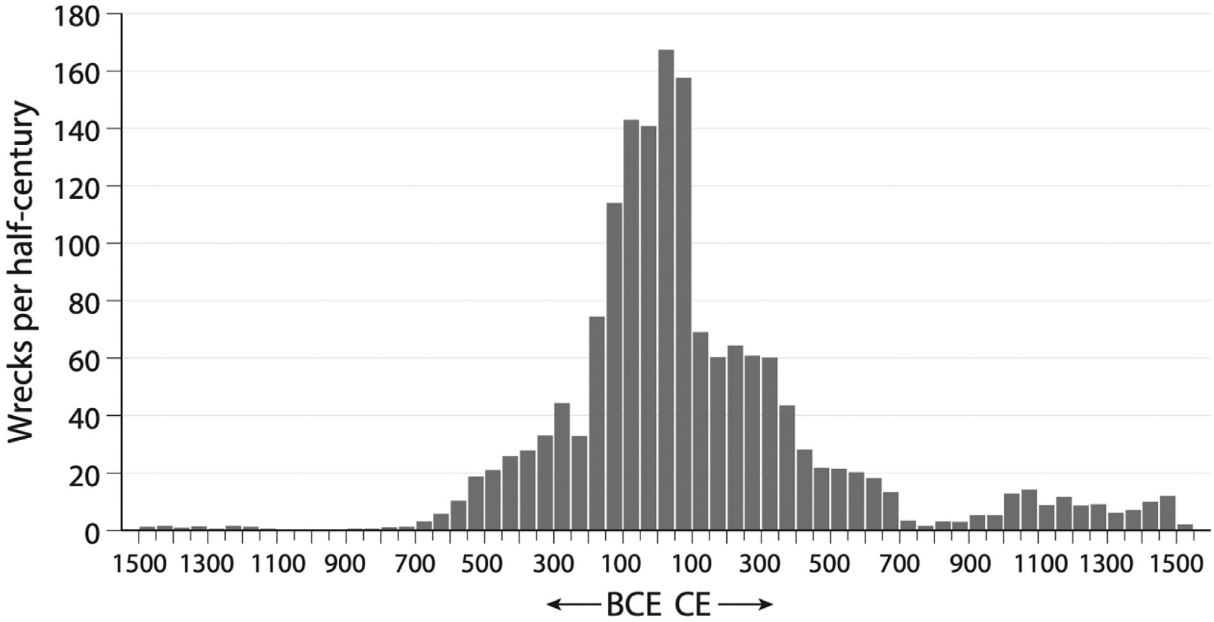

Fig. 1. Mediterranean shipwrecks by half century (image after Wilson, 2011: fig. 2.5).

A different economic proxy records atmospheric lead pollution in the Greenland ice sheet, the result mostly of European silver mining (Fig. 2). Recent, fine-grained Pb pollution data also suggest Roman growth and decline, followed by a marked economic recovery in the early Middle Ages (McConnell et al., 2018; McConnell et al., 2019).

The medieval recovery would continue in the Early-Modern period, ultimately leading into what Deirdre McCloskey (2016) has aptly called the Great Enrichment. The emergence of the modern economy depended on technological breakthroughs that allowed heat to be converted into motion. No such breakthroughs occurred in antiquity, but other advances may have affected economic conditions, and the question of what role technology played in creating Roman growth is worth posing.

2. Technology and intensive growth under Malthusian constraints

There can be no doubt that specialization, economies of scale and long-distance trade account for most of the rise we observe in the ancient data. By implication, Roman growth was chiefly Smithian in nature (Temin, 2013; Erdkamp, 2016; Terpstra, 2019). But was there also Schumpeterian growth? It is now beyond discussion that water-powered grain mills were used widely in the imperial period. There is also some limited evidence to suggest that Roman ore-crushing machines were driven by water and that hydraulic saws were in operation (White, 1984: 56; Wilson, 2002; Brun, 2006). However, Roman water wheels were not the result of entrepreneurs exploiting new ideas and causing a disruptive disequilibrium.[3] Instead, they were the result of the gradual development of existing technology (White, 1984: 196–201; Wilson, 2002: 11). Any Roman growth from mechanization was thus still a Smithian process.[4]

As to the extent of that growth, some Roman historians have argued that hydraulic machinery made a significant contribution. Andrew Wilson wrote that in the Roman empire “the use of mechanical technology … had an important impact on economic performance and the potential for *per capita* growth” (2002: 1). Although he leaves vague what “important impact” means he clearly implies that mechanization created a rise in real incomes. However, that notion is tenuous. It presupposes that hydraulic power increased the marginal output of Roman workers significantly, allowing them to acquire appreciably higher real wages. The problem of slave labor aside, it seems doubtful that in an economy where perhaps 80 percent of the workforce was agricultural, water-driven devices noticeably raised overall labor productivity.

The question of labor productivity is connected to the difference between extensive and intensive growth, a distinction ancient historians have not always been careful in making (Saller, 2002). The long-term proxy data now at our disposal overwhelmingly support the case for extensive growth, lasting until roughly the mid-second century CE. This expansion was in part fueled by population growth, although demography cannot account for all of it (Scheidel, 2007; Jongman, 2007a: 191). Intensive growth thus appears to have occurred as well, and the scholarly consensus now indeed seems to be that it did.

[3] Note that disruptive disequilibria need not be technological in nature: Schumpeter 1934 (1961): 66. Cf. Harley, 2012 for a less disequilibrium view of technological change in the early Industrial Revolution.

[4] Smith was aware of the benefits of mechanization, noting “how much labour is facilitated and abridged by the application of proper machinery.” (1776 [2000]: 9)

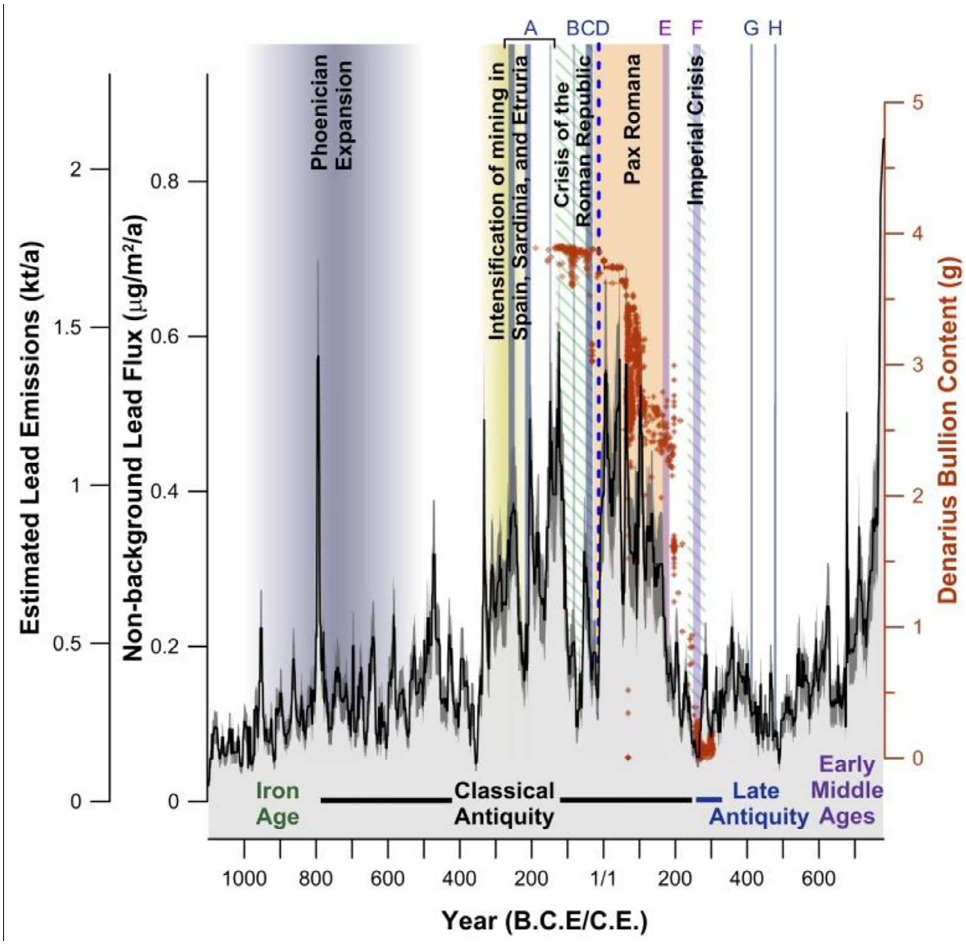

Fig. 2. Nonbackground lead deposition in Greenland ice and estimated European lead emissions, silver bullion content in coinage, and selected historical events during antiquity (McConnell et al., 2018: Fig. 3).

The apparent coincidence of Roman intensive and extensive growth is hard to explain using standard Malthusian thinking. Supposedly within premodern constraints any surplus would be consumed by rising population numbers, and over the long term the result would have been income stagnation (Clark, 2007; 2008; 2013). In an attempt to explain why Rome avoided that outcome, Paul Erdkamp recently suggested that "the predictions of the Malthusian world do not apply to much of the ancient [Roman] world because there were increasing returns to scale in production" (2016: 3). Roman population numbers did not rise with increasing levels of material welfare because of changes in either nuptiality or postnatal intervention (exposure and infanticide). However, this explanation does not warrant the conclusion that Malthusian constraints did "not apply" to ancient Rome. At most, it shows that through allocative efficiency and preventative checks Rome managed not to reach its limits before its economy contracted.[5]

Rohan Dutta et al. (2018) have recently offered a different solution to the problem of intensive growth in premodern economies, including the Roman. If we depart from an economic model with a single composite food-good, extensive and intensive growth can coincide, even under Malthusian constraints. To show how, Dutta et al. model an economy producing two composite goods, "bread" and "circuses," of which only the first is central to survival. The second enhances utility, but has no effect on population growth. If a positive shock to the technology of circus production exceeds a positive shock to the technology of bread production, both extensive and intensive growth will result. An important corollary of this model is that the Industrial Revolution was not in essence different from earlier periods of per capita growth through technological change. The industrializing economy of the nineteenth century became exceptionally adept at producing circus-type goods, far outstripping anything that had come before. But this improvement was a matter of scale, not a departure from the preceding economic fundamentals.[6]

[5] Cf. Chiarini, 2010, who found a negative relationship between real wages and fertility in Italy, 1320 to 1870. That finding does seem to argue against the classic Malthusian model.

[6] By implication, there is no need for a "unified growth theory" (Galor, 2011) to explain how supposedly inevitable, long-term stagnation was followed by sudden, explosive growth after the Early-Modern period.

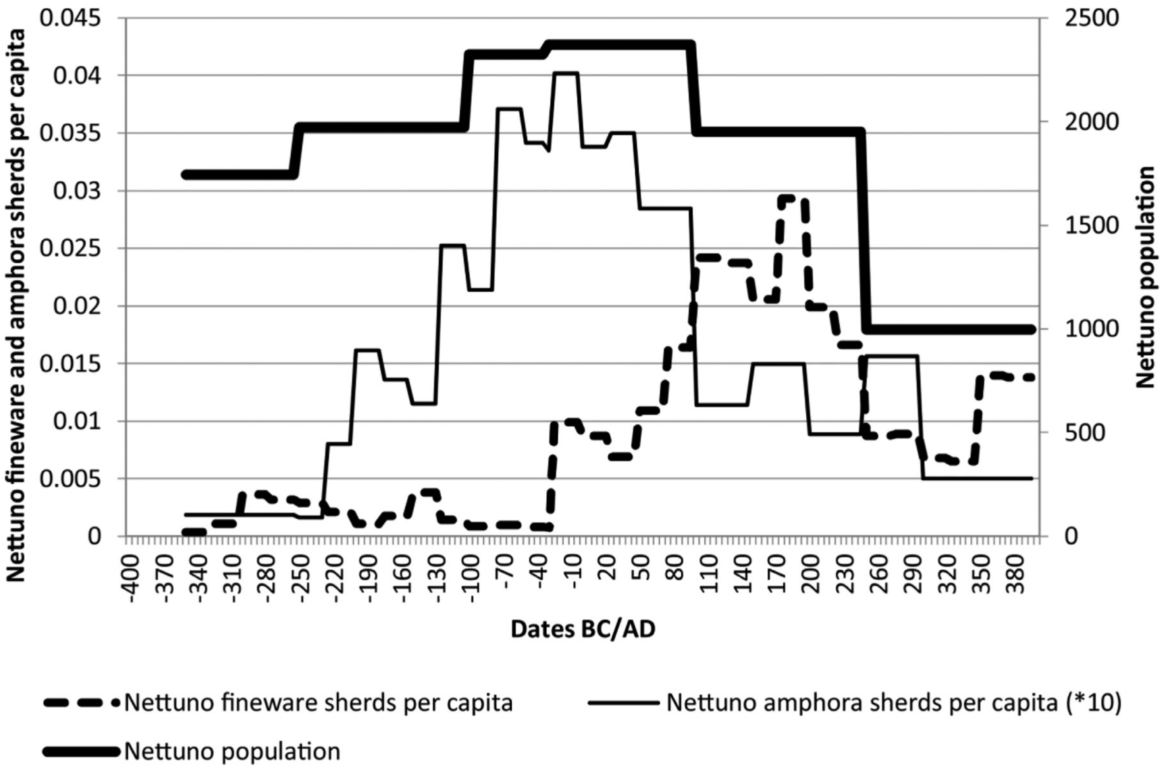

Fig. 3. Nettuno per capita consumption trends (Jongman et al., 2019: fig. 11).

Dutta et al. (2018: 372–73) argue that the Roman Empire saw intensive growth because bread production technology did not keep pace with circus production technology. That proposition is consistent with the historical process usually called Romanization. As Serafina Cuomo has rightly pointed out, one “cannot plausibly identify Romanization with the provision of infrastructure such as aqueducts or roads, and then declare that technical expertise was not essential to run the Roman Empire” (2007: 1). Obviously so. To Cuomo’s list we can add bathing complexes and maritime harbors, both requiring specialized engineering skills that improved over time.

Nor was Romanization a matter solely of the enhanced production of public indivisibles. Miko Flohr (2016) has recently extended the discussion to consumer goods such as glass, ceramics and metal tablewares. Through improved technology, such goods became better, cheaper and more abundant. An in-depth study into Roman economic wellbeing by Willem Jongman et al. (2019) illustrates that point with data from the site of Nettuno, some 60 km south of Rome (Fig. 3).

The graph displays the population trend together with the per capita trends for two types of “comfortable material culture”: amphorae and fineware ceramics. Clearly, material wealth increased while population levels remained mostly flat, ca. 200 BCE - 200 CE. The diffusion of improved consumer goods depended on trade flows, and easily accessible coastal towns close to the imperial capital such as Nettuno may have benefited disproportionately. However, the data conform to a more general picture, familiar to field archaeologists, of a rise in the volume of goods in the imperial period (Ward-Perkins, 2005: 87–102). Fig. 4, for instance, shows the aggregated archeological finds from western Germany.

But while the production technology and availability of consumer goods were advancing, there is no indication that basic Roman agricultural methods were changing much (Greene, 1990: 67–97). There is some evidence to suggest that crop rotation increased at the expense of bare fallowing, but the shift seems not to have been dramatic (Erdkamp, 2005: 41–42). Equally, before the Roman population reached its estimated peak of ca. 60 to 70 million around 160 CE, demographic growth had been leveling off for probably about a century (Scheidel, 2007: 47–48). All this agrees with the new take on technological change, intensive growth and population dynamics proposed by Dutta et al. (2018), which provides a promising way out of some difficult problems.

3. Roman versus medieval technological advancement

The development of water mills especially has been at the heart of the debate about technical improvement in the Roman Empire. But even if it is now clear that the Romans employed water mills widely, they had not adopted what Carlo Cipolla has called a “mechanical outlook.” What he meant by that phrase is a commonly shared appreciation of machines of the kind witnessed in medieval Europe. The Middle Ages’ fascination with mechanical clocks is a case in point. What prompted investment in mechanized timekeeping was not its productive utility. The first clocks told time so imperfectly that they had to be adjusted constantly using

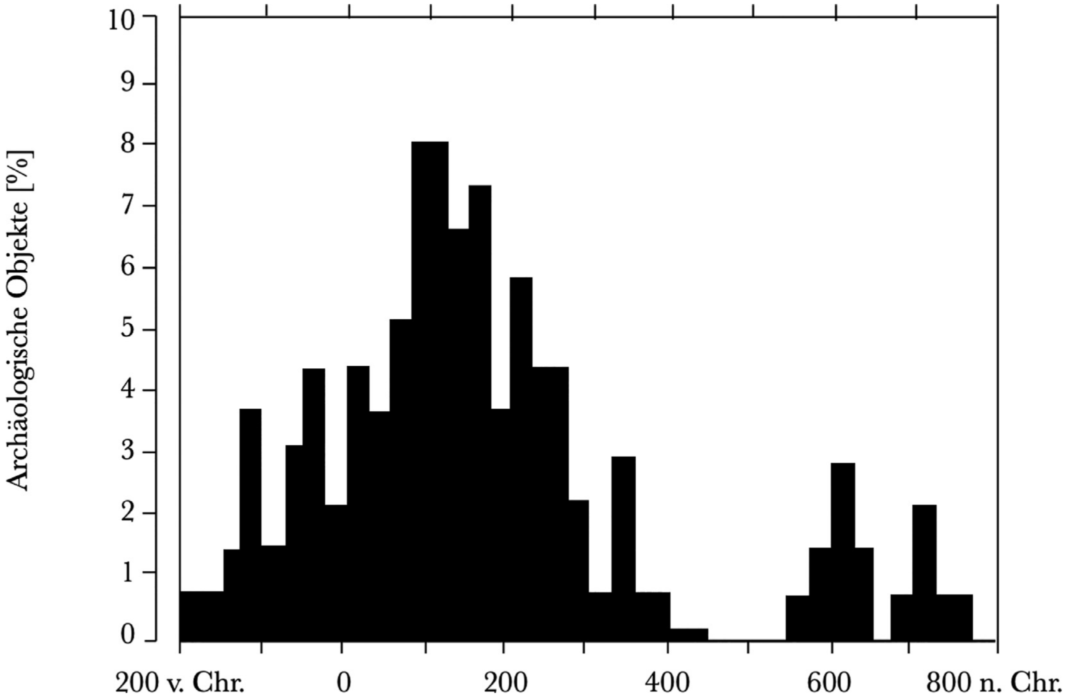

Fig. 4. Archeological finds in western Germany (Jongman, 2007a: Fig. 4).

the tried-and-tested means of sundials and clepsydras. For such devices, “telling the time was almost incidental, accompanied as it was by the revolutions of the stars, and by the movements and pirouettes of angels, saints, and Madonnas. … The men of the thirteenth century thought of measuring time in mechanical terms because they had developed a mechanical outlook” (1994: 152; see also Gimpel, 1988: 147–70). Nothing in our evidence suggests that the ancient world ever developed a similar fascination with machinery, notwithstanding impressive devices like the famous Antikythera mechanism (Mokyr, 1990: 22; Manning, 2018: 3–4). What prevented that development? For the answer to be meaningful the nature of the question needs to be properly understood. Asking why Greco-Roman society never adopted a mechanical outlook does not equate to asking: Why was there no Industrial Revolution in antiquity?

The mechanical outlook of the Middle Ages makes it tempting to project the inception of European industrialization far back in time. Cipolla indeed suggested that the widespread use of water- and especially windmills in medieval Europe “marked the beginning of the breakdown of the traditional world. … It was the distant announcement of the Industrial Revolution” (1994: 144). That notion is debatable. It seems to imply that once Europe’s mills started turning, industrialization would inevitably follow. All the same, Cipolla’s assertion that today, we “represent the final outcome of a centuries-long development” (1994: 153) has much to recommend itself. Technology may not have progressed inexorably and in a more or less linear fashion, as he seems to have thought. But as Walter Scheidel (2019) has forcefully argued, the disappearance of the Roman Empire, and its failure ever to return, created the political conditions allowing Europe to reach escape velocity out of premodern constraints.[7]

However, that world-historically unique process was complex, and asking why industrialization did not occur in Roman times is to oversimplify matters. As Helmut Schneider has warned, wondering why the Romans did not invent the steam engine, despite having discovered the propelling force of steam, wrongly “understands industrialization as the model for a technological development which can serve as a yardstick for other epochs and societies” (2007: 146). More meaningful than industrialization is the application of useful, practical knowledge. As noted, in the Roman Empire such application increased, producing significant material benefits. All the same, those benefits largely accrued from learning-by-doing effects, while innovation remained limited. If framing the question in terms of industrialization is unhelpful, asking why there was not more Roman innovation is justified. Once again, a comparison with the progress made by medieval Europe is illuminating (White, 1962; 1978; Gimpel, 1988; Mokyr, 1990: 31–56).

Unseen in Roman society were the humble wheelbarrow and stirrup, which would not appear until the Middle Ages.[8] Apart from mechanical clocks, medieval Europe invented heavy ploughs, spectacles, windmills, iron-casting, firearms and paper. The first half of the fifteenth century would add the printing press. Well before that time, medieval texts had been published in codex form, a massive improvement on the unwieldy book scroll of Roman antiquity.[9] Along with better carriers of written information, the

[7] See Terpstra, 2019: 228–31 for the expression of a similar idea.

[8] But cf. Lewis, 1994: 470–75 who makes the case for an ancient Greek wheelbarrow (though on extremely meager evidence).

[9] The codex was known in antiquity, but only adopted piecemeal in the fourth century CE: Reynolds and Wilson, 2013: 2, 34–37.

Middle Ages adopted a consistent system of graphic symbols, greatly facilitating the readability of the Latin script (Cribiore, 2001: 190; Reynolds and Wilson, 2013: 4–5). Improved ship design in the thirteenth century allowed Mediterranean sailing year-round, unlike in Roman times when travel largely ceased during the winter months (Mokyr, 1990: 46–47; Cipolla, 1994: 145). As mentioned above, the maritime shippers of the Middle Ages rejected heavy, breakable ceramic vessels as transport containers. Instead, they adopted the more practical wooden barrel, which had “a better volume to weight ratio, more efficient stacking capability, and greater maneuverability” (Wilson, 2011: 37).[10]

But if medieval Europe witnessed an impressive spurt in innovational development, its technological progress did not constitute the definitive step leading it toward the Great Enrichment. Its continued progress was determined by an additional and historically unusual variable. As Joel Mokyr (2016) has argued, what produced the decisive breakthrough and the emergence of the modern economy was an understanding of why innovations worked. Engineers and craftsmen could tinker with technology, incrementally improving it by persistent trial and error. But if such efforts were not supported by a sustained rise in the stock of propositional knowledge, they were destined to dead-end because of diminishing returns. Uniquely, the cultural winds that began blowing in Europe around 1600 created an intellectual climate favorable to the pursuit of such knowledge. Early-Modern Europe was not only politically but newly also religiously divided. Its fragmentation hampered attempts by the ruling establishment to suppress new ideas perceived as threatening, such as the heliocentric view of the universe.

But coordination failure by secular and religious authorities was not sufficient for the spread of propositional knowledge. Crucially, new ideas began to be put forward, tested and refined by a collaborative yet competitive pan-European network of Enlightenment *philosophes*. The triumph of this “Republic of Letters” ultimately depended on a deep-seated cultural shift: “The belief that collecting data and facts about the physical world would lead to social progress was born in the seventeenth century and refused to die, even if its tangible results were slow in coming” (Mokyr, 2016: 92).

Here we arrive at the heart of the matter of how Roman antiquity fits into the long-term picture of European technological development. Roman society produced substantial utility-enhancing engineering and craftsmanship, yet fell short of the innovational creativity of medieval Europe. The Middle Ages were inventive, but only the pursuit of propositional knowledge in the Early-Modern period ensured that what followed were the Industrial Revolution and the Great Enrichment. Rather than wonder why there was no Roman Industrial Enlightenment, what we should be asking is therefore: Why did the Roman Empire not go the way of medieval Europe, which saw many practical innovations and the widespread adoption of technological improvements? After all, the Romans were inventive elsewhere - the domain of law, for one - making their lack of progress in technological innovation seem surprising.

With the question clarified, we can turn to formulating an answer. But before any attempt to do so can be made, a persistent misconception needs to be addressed. Ancient historians habitually cast the debate about technological progress in terms of profit motivations and returns on investment, the legacy of Moses Finley and a long-running dispute between formalists and substantivists. Following the work of Hermann Diels (1920: 32–33) and Marc Bloch (1935), older literature argued for the availability of slaves as one of the main impediments to Roman technological progress.[11] Recent scholars have moved away from that idea, recognizing that labor was cheap throughout premodern history - whether servile or free - and that factor prices are of limited value in explaining societal differences. Finley, too, acknowledged that it “is not often that one can point to slaves and say, simply and with confidence, ‘There lies the explanation for a static technology and a static economy’ ” (1965: 43). However, he did tie Roman slavery and technological inertia to a lack of what he called “economic rationalism,” by which in essence he meant capitalism:

It is unnecessary to examine the economic history of the later Roman Empire in detail to make the point … that neither technique nor productivity nor economic rationalism made an advance in those final centuries of antiquity. … Servile and other forms of dependent labor were very profitable. Such changes as occurred in the Roman Empire in the position of the wealthy were political, not economic, and therefore they had no significant incentive to alter the productive arrangements. (1965: 44)

Subsequent scholarship accepted the terms Finley had set for the debate, embracing the idea that “economic rationalism” has to be invoked to explain technological progress. Even Finley’s opponents did not attempt to refute his argument. Instead, they turned it on its head, pointing to the mechanical devices the Roman world did produce, presenting them as evidence for profit-driven investment. Wilson, arguing for a widespread adoption of the Roman water wheel, wrote: “Necessary but not sufficient preconditions for economic take-off are an intellectual climate open to technological development, and the availability of investors and capital. The archeological, literary, and epigraphic evidence … suggests that these factors were available in the Roman world of the early centuries A.D.” (2002: 31).

By now, the view that investors and venture capital are preconditions for technological progress seems to be deeply rooted in Roman economic history. Its depth is suggested by the fact that it has been marshaled also to explain the stalled application of mechanical devices later in the imperial period. Jean-Pierre Brun wondered why the use of hydraulic energy under the Empire “did not have ripple effects on the whole of agricultural and artisanal production: tanning mills, iron forge hammers, oil mills, etc.” (2006: 123). Topping his list of explanations is a supposed gradual disappearance during the second century CE of an adventurous and inventive middle class of entrepreneurs.

However, in studying the pace of Roman technological progress we are at bottom not addressing a question of “economic rationalism.” Claiming that if only the Romans had been more economically rational they had advanced further technologically or, conversely, that they did in fact advance technologically because they actually were economically rational is misguided. We need to discard such notions if we want to make any headway in our understanding of the subject.

[10] Barrels were used in Roman times, but never became the standard; Wilson, 2011; Bevan, 2014.

[11] Surprisingly, even some modern economists adopt this argument: Acemoglu and Robinson, 2012: 172.

4. Roman disincentives to innovation

If economic rationalism is not the factor to consider, what is? To date, much of the discussion has centered on disincentives to Roman technological progress. The disdain for non-agricultural activities of the Empire's landed gentry is commonly touted as one of the main hindrances. Finley (1965; 1999) was an early exponent of that view, which lives on in modern scholarship. The idea requires some qualification. Large-scale hydraulic projects like aqueducts were acceptable as a topic of interest, as were villa architecture and military engineering, see the writings of Frontinus and Vitruvius (White, 1984: 165–68, 185–88). But it is true that more mundane economic pursuits such as tools manufacturing and shipbuilding were below the dignity of the Roman upper classes (Humphrey, 2006: 130–31; Greene, 2008: 803). Slavery was not a major disincentive to developing technology, but because slavery linked physical work to unfree status it undoubtedly heightened the elite's contempt for such endeavors. All the same, we should be careful not to overstate the case. The attitude toward manual labor of Roman and medieval aristocrats was not dissimilar.

Another disincentive to innovation is deliberate suppression. Opposition of that nature can produce serious impediments to progress and has done so widely in human history (Mokyr, 2002: 218–83). For good reasons of social stability and public order, the psychological pull of conservatism is strong. But although conservatism prevents chaos and anarchy, it can put a sealed lid on innovation. Reactionary forces are frequently represented by religious officials and political powerholders. But resistance can also come from artisans, whose skills are rendered obsolete, and whose livelihoods are threatened, by productivity-enhancing innovations. Technological progress, after all, creates losers as well as winners and is rarely Pareto superior (Mokyr, 2002: 232).

Deliberate obstruction either by ruling elites or workmen seems not to have been a major hindrance in the Roman Empire. To be sure, there are the widely cited stories about Tiberius and Vespasian, respectively executing and dismissing a man who had come to them claiming a practical invention. These stories are not unbelievable at their core. A papyrus text dated to the third century BCE presents us with documentary evidence for a seemingly comparable case. It contains a letter to the Ptolemaic king by a man seeking a financial reward for an unspecified "machine," allegedly capable of alleviating an ongoing drought.[12] However, the literary passages about the two Roman emperors bear all the hallmarks of fictional just-so stories, part of retrospective character sketches by later authors (Greene, 2000: 46–47, 49–50). In any case, they cannot be taken as evidence that Roman emperors were cracking down on innovation as a public policy.[13]

As for resistance by laborers, no evidence exists for rioting or sabotage. With a bit of effort, the argument could be made that Roman slavery was a beneficial institution in this regard, as it helped prevent such obstruction. Slaves displaced by some novel device lacked the power (and presumably the desire) to protest violently like the Luddites did between 1811 and 1816. Regardless of what one thinks of that argument, the matter is ultimately not of great consequence. Resistance at the lower social level is mostly futile in the long run. At the end of the day the Luddites, though protesting vehemently, lost the fight against gig mills and shearing machines (Mokyr, 2002: 264–65).

With regard to religious opposition, before the triumph of Christianity the Roman Empire was a polytheistic state where no institutional establishment dictated faith and censored contrarian views. It is of course possible that Rome's animistic cults imposed religious orthodoxies that were inimical to innovation. We can well imagine voices warning against attempts to control the forces of nature, seen as the exclusive domain of divine spirits (White, 1978: 146, 237). Still, opposition did not emanate from a centralized, powerful and all-pervasive organization like the medieval Catholic Church.

Potentially more harmful to progress than obstruction was a perhaps widespread lack of belief in progress to begin with. A Greco-Roman notion of "ages" - a descent in steps from past greatness to current inferiority - may have slowed technological advancement (Humphrey, 2006: 132–33; Cuomo, 2007: 107). The educated classes, and thereby the upper tail of human capital, would have been most exposed to the poets peddling this negative worldview.[14] Still, the pessimistic perception of time found in the ancient authors reflects a view mostly of morality, not technological knowhow. Ovid described a four-stage history in which man's virtue had regressed while his technological capabilities had steadily increased, from sailing to land surveying to mining and metallurgy. That view left open the possibility that man's command over nature would continue to grow, even if his moral value would sink ever deeper. It might with some justification be asked how much of a brake on innovational development such a perception of regressing ages represented. As a second note of caution, antiquity was not alone in entertaining negative views of the future. In the Middle Ages, Christian eschatological philosophy cannot have been any more helpful in inspiring a societal sense of progress.[15]

Yet the idea of a mythical Golden Age, long gone, seems to be related to a more pernicious influence on Roman innovational development: a reverence of the past and a professed belief that the ancestral ways were best. Such notions informed the many stories about great men of old such as L. Quinctius Cincinnatus and Scipio Africanus, held up as role models for the supposedly decadent present.[16] Respect for the achievements of the past also strongly influenced Roman schooling, although there the focus was on Greek exemplars. Direct evidence for Roman education comes from papyri found in the province of Egypt. They show that schooling in all its stages was characterized by rote learning and slavish imitation, centered on a fixed set of poetic, dramatic and rhetorical texts. Numeracy, meanwhile, was given only cursory treatment. As Raffaella Cribiore summed up the state of Roman schooling:

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[12] *P. Edfu* 8, on which see Manning, 2018: 166–67. Unfortunately, the king's response is unknown.

[13] As Acemoglu and Robinson, 2012: 171–72 seem to have thought.

[14] Explicitly: Hesiod *Works and Days* 107–78; Ovid *Metamorphoses* 1.89–150. The idea of a vanished heroic age is also strongly present in Homer's *Iliad*, e.g., 1.247-72.

[15] Eschatological thought: Barbezat, 2018. Cf. White, 1978: 235–50 on Christianity's positive effects.

[16] E.g., Columella *Praef*. 13; Seneca, *Moral Epistles* 86.1-7.

The horizons of a student who was reaching the top of the educational hill were much broader than they had been, but the principles that inspired his learning were identical: imitation of a model, honor paid to the written word, reverence for the literary authors and the world of mythology, a strengthening of mnemonic skills in order to retain a patrimony of information, and the application of sets of rules that imprisoned his freedom and inspiration. (2001: 221)

It is obvious that this state of affairs was not conducive to innovation and technological progress. To be clear, it was not just the way the curriculum was organized that was deleterious.[17] The main problem was the propagation of the idea that learning anything useful meant looking to the past, accepting as authoritative what one found there and then emulating it. Education thereby instilled and legitimated the proposition that received wisdom should not be challenged and that new ways should not be attempted. There were doubtless individuals willing to take on such backward-looking cultural norms; there always are. But anyone desiring to do so was swimming against a strong current of traditionalism, making the successful emergence of heterodox ideas unlikely. Nevertheless, we should once more be careful not to draw too stark a distinction with medieval Europe. There, the "top of the educational hill" - universities - were for the most part highly conservative places where "critical learning" meant poring over classical texts to detect copying errors (White, 1978: 329–38; Mokyr, 2016: 172–73).

5. Political fragmentation and technological progress

It appears that disincentives are insufficient to explain the difference in innovational outcomes of the Roman Empire and medieval Europe. Ultimately more important than what kept people from innovating is what drove them to do so. Historical periods of flourishing, classical and otherwise, show that if the incentives were strong enough, the forces of social conservatism, elite prejudice and even reactionary suppression could be overcome. In one key aspect of its incentive structure the medieval world was at a distinct advantage: it was extreme politically fragmented.

Its fragmentation was recognized as a force for social, economic and intellectual progress already by Enlightenment thinkers, including David Hume (1742 [1985]: 119–20), Montesquieu (1748: XVII, ch. 6) and Immanuel Kant (1784 [1914]: 333–35). The idea has subsequently figured prominently in the work of modern scholars, including Douglass North (1981), Cem Karayalçin (2008) and, most recently and comprehensively, Scheidel (2019).[18] But to date it seems not to have been used to explain why medieval Europe experienced more creativity and a greater application of useful knowledge than the Roman Empire. Mokyr (1990: 193–208), who addressed the question directly, acknowledged that the Roman and medieval worlds differed in their political structure. Yet he ultimately turned to Roman animistic religions and elite social values as the main explanatory factors. Such disincentives may have had some limited influence, but I propose instead that medieval Europe's political pluralism provides the solution to the problem.

After states began to reemerge around 900 CE, Europe was a motley patchwork of states and statelets, municipalities, principalities, duchies, counties and bishoprics. Over time a process of coalescence occurred, yet fragmentation remained the norm (Scheidel, 2019). Europe's self-governing polities were in a constant struggle for survival, and the result was fierce interstate competition. Eric Jones has labeled this political setup a "states system," pointing out that it encouraged prudent behavior and penalized doctrinaire folly: "In its states system Europe had a portfolio of competing and colluding polities whose spirit of competition was adapted to diffusing best practices" (2003: 115). Not in the last place, best practices meant attracting human capital and shielding individuals with heterodox ideas from persecution by rivals. Refugees seeking asylum were frequently skilled craftsmen, and their physical movement across Europe's borders greatly aided the diffusion of efficiency-enhancing innovations.

The states system allowed European polities as a collective to escape what Mokyr, (1990: 207, 261–69; 1994) has called Cardwell's Law, the widely observed phenomenon that technological progress tends to stall after an initial period of flowering. Instead of progress occurring more or less evenly across the fragmented European political landscape, a small number of states were usually in the vanguard.[19] But the leading states were constantly changing. After some time, whichever one was ahead had to cede first place to another. But although creativity might slow in one place, as a process it never stopped. Political decentralization and interstate competition ensured that there was always a nation ready to pick up the torch. As a result, "some light source illuminating the landscape has been glowing in Europe more or less continuously since the eleventh century" (Mokyr, 2002: 276).

In sharp contrast to Europe's collection of small, competing polities, the Roman Empire was a single state with a central government and one supreme ruler. Of course, cities and regions enjoyed a large degree of autonomy because for practical reasons Rome could not be in charge of their day-to-day running. Still, the Empire's defining characteristics were those of a unified state, from its external borders to its military apparatus, coinage system, legal organization and fiscal regime. Ruler worship as an imperial ideology held sway throughout. No Roman city or region, no matter how much autonomy it might claim for itself, was truly independent. Besides, none felt the danger of being incorporated into a larger state, as that had already happened. There were several great centers of learning, including Athens, Alexandria and, later, Beirut. But neither those cities nor any other were in cutthroat competition for human capital and productivity-enhancing advantages. The elements that defined the incentive structure of Europe's states system and that ensured its forward motion were therefore lacking.

Yet we are still not there. During the Tang and Song dynasties, China was about as technologically advanced as medieval Europe, falling behind only during the first century of Ming rule. China's enormous technological success had taken place in an imperial context and cannot be attributed to a political dynamic analogous to that of the European states system. It is thus clear that although political

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[17] Although content does matter; see Yuchtman, 2017 on educational change in late imperial China.

[18] See also Van der Beek, 2010 for a case-study showing the positive relationship between political fragmentation and water mill construction in medieval France.

[19] The reference is to Cardwell, 1972.

pluralism and technological creativity are correlated, “pluralism is neither a sufficient nor a necessary condition for technological creativity” (Mokyr, 2002: 279). That observation leads to the question: Why did the Roman Empire not display the kind of progress that China did under the Tang and Song? The answer is that unlike in the Roman Empire, in China technological change was largely the result of state intervention:

The Chinese imperial government generated and diffused new technologies in rice cultivation, including better (drought-resistant) varieties, owned the great foundries that were central to its iron industry, developed and built the great junks with which the Chinese sailed along the African East Coast in the fifteenth century, and encouraged the use of cotton, better implements, and hydraulic techniques. Clockmaking technology was wholly monopolized by the emperor. The authors of the great treatises on agriculture such as Wang Chen and Hsii Kuang Chhi, as well as the inventor of the use of mulberry tree bark in papermaking, were government bureaucrats. (Mokyr, 2002: 223 n. 3; see also 1990: 233–34; 2016: 300–01)

In the Roman Empire, no state sponsorship on anything like that scale occurred. If anything, rulers seem to have been uninterested in technological solutions to everyday problems. Here, the stories about inventors approaching Tiberius and Vespasian *are* relevant. It does not matter that these stories are all but certainly fictional. What matters is that they appear to reflect a general indifference to technological progress by at least members of the Julio-Claudian and Flavian imperial courts. Other emperors may well have been more receptive, but if they were we do not know about it. One way or the other, Roman rulers did not invest in the development, application and diffusion of practical technology as the Tang and Song did. Instead, they invested their resources elsewhere. Hadrian and Marcus Aurelius instituted chairs of rhetoric and philosophy at Athens, supported by generous state stipends. Such gestures better fit the ideological framework of Roman politics and better served an imperial program of rule legitimization (Lauwers, 2015: 83–92).

Chinese state sponsorship was greatly beneficial to technological progress, but as a source of support it was less sustainable than the competitive force of the European states system (Mokyr, 1990: 231, 236–38; 2016: 301–02). In monarchical regimes, advancement under state management ultimately depends on single individuals and their views on how to govern. A ruler might be a great promoter of technological development, but if his or her successor is not, progress will slow to a halt. The observation has wider implications for technological progress in world history. The changeable nature of ruler support goes a long way toward explaining why the stunning mechanical and scientific advancements of the Hellenistic age stalled. Some of the greatest mathematicians, inventors and natural philosophers of antiquity worked under Hellenistic royal patronage. In Ptolemaic Egypt, Euclid wrote the *Elements*, Ctesibius reportedly invented the force pump and Eratosthenes near accurately calculated the circumference of the earth (Lloyd, 1973: 3–5, 34–40, 49–50, 100–01; Luce, 1988). But in the end, ruler sponsorship turned out not to be a substitute for the states system. Hellenistic scientific and mathematical production ultimately fell victim to Cardwell’s Law.

If political pluralism is correlated with technological creativity, what about the classical Greek world? In antiquity, the political constellation that came closest to the European states system was the collection of city-states of ancient Greece. Fiercely independent, Greek cities were in constant competition. Their rivalry regularly turned violent, but the damage seems to have been limited for agriculture, the foundation of the Greek economy (Hanson, 1998; Rawlings, 2007: 144–76). Interstate competition led not only to warfare but also to intellectual one-upmanship. As in medieval Europe, thinkers with heterodox ideas could move to a neighboring polity if their position became too awkward. Socrates could almost certainly have avoided execution if he had pursued a defense aimed at exile as a penalty (Panagiotou, 1987: 41–44). In classical Greece, the right conditions for creativity and innovation thus seem to have obtained.

Needless to say, the Greek world did indeed make intellectual strides, displaying an impressive flowering of freethinking and philosophizing. In the fifth century BCE, the groundbreaking theory of atomism was proposed by Leucippus and his pupil Democritus. The idea of atomism was itself a reaction to propositions about the nature of existence, chiefly those of Parmenides. Subsequently, Aristotle would criticize the theory, formulating his own hypothesis (Lloyd, 1970: 45–49, 107–09; 1973: 22–24; Warren, 2007: 153–73). Such metaphysical dialectic suggests that Greater Greece had an open, competitive market for ideas with low barriers to entry. Why, then, did it not advance further in innovation and its practical application? I am hardly the first to ask that question.[20] The matter exceeds the parameters of this paper, but I propose that two points are of particular relevance.

First, it needs to be remembered that Iron-Age Greece started out at a much lower baseline than Europe ca. 900 CE. The collapse of the Roman Empire caused a tremendous decline in socioeconomic complexity, certainly in the west (Ward-Perkins, 2000; 2005). Still, the early medieval world did not have to invent or rediscover such basic practicalities as coinage and the alphabet. Second, from early on Greek cities had to contend with peers harboring hegemonic aspirations such as Sparta and, especially, Athens. Outside threats also quickly manifested themselves. In the mid-fourth century BCE, the Macedon of Philip II loomed over the horizon. In the subsequent century the Romans arrived on the scene; in 146 BCE they left no doubt that they were in charge by destroying Corinth. As Jones (2003: 108) has pointed out, the states system is fragile and its equilibrium easily disturbed. Arguably the states system of ancient Greece was tipped off-balance too soon to see a development similar to that of medieval Europe.

The cases of stalled technological progress in the states system of ancient Greece and the monarchical regimes of the Hellenistic world fill out the story of limited innovation in the Roman Empire. Of course, telling that story does nothing to detract from Rome’s awe-inspiring achievements in engineering, for instance in water management. Still, we should be careful to distinguish innovation proper from the incremental development of existing technology. With that distinction in mind, we should have no illusions about the fact that the innovational progress of the Roman Empire was insignificant compared to medieval Europe and imperial China. What explains the difference is that the Empire possessed neither the ruler sponsorship of Tang-Song China nor the competitive drive of

[20] Vernant, 1957 is an early example. Folded into the larger context of Greco-Roman antiquity, the question is even older: Lombroso-Ferrero, 1920.

polycentric medieval Europe. Rather than disincentives such as slavery, animistic religions and elite biases, a weak incentive structure holds the key to understanding the Roman Empire's limited innovational advancement.

Series and Periodicals

AHES = Annales d'histoire économique et sociale	
CAH = The Cambridge Ancient History	
Curr. Anthropol. = Current Anthropology	
EEH = Explorations in Economic History	
EHR = Economic History Review	
EREH = European Review of Economic History	
Eur. Rev. Econ. Hist. = European Review of Economic History	
IER = International Economic Review	
JOIE = Journal of Institutional Economics	
JRS = Journal of Roman Studies	
PNAS = Proceedings of the National Academy of Sciences of the United States of America	
Res.Policy = Research Policy	
RHS = Revue d'histoire des sciences et de leurs applications	
Technol.Cult. = Technology and Culture	

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References

Acemoglu, Daron, Robinson, James A, 2012. Why Nations Fail: The Origins of Power, Prosperity, and Poverty. Profile Books, London.
Barbezat, Michael D., 2018. Burning Bodies: Communities, Eschatology, and the Punishment of Heresy in the Middle Ages. Cornell University Press, Ithaca, London.
Bevan, Andrew, 2014. Mediterranean containerization. Curr. Anthropol. 55 (4), 387–418.
Bloch, Marc L.B., 1935. Avènement et conquêtes du moulin à eau. AHES 36, 538–563.
Brun, Jean-Pierre, 2006. L'Énergie hydraulique durant l'Empire romain: Quel impact sur l'économie agricole? In: Lo Cascio, Elio (Ed.) *Innovazione tecnica e Progresso Economico Nel Mondo Romano*. Edipuglia, Bari, pp. 101–130.
Cardwell, Donald S.L., 1972. Turning Points in Western Technology: A Study of Technology, Science, and History. Science History Publications, New York.
Chiarini, Bruno, 2010. Was Malthus right? The relationship between population and real wages in Italian history, 1320 to 1870. EEH 47, 460–475.
Cipolla, Carlo M., 1994. Before the Industrial Revolution: European Society and Economy 1000-1700. W.W. Norton & Company, New York.
Clark, Gregory, 2007. A Farewell to Alms: A Brief Economic History of the World. Princeton University Press, Princeton.
Clark, Gregory, 2008. In defense of the Malthusian interpretation of history. Eur. Rev. Econ. Hist. 12, 175–199.
Clark, Gregory, 2013. 1381 and the Malthus delusion. EEH 50, 4–15.
Cribiore, Raffaella, 2001. Gymnastics of the Mind: Greek Education in Hellenistic and Roman Egypt. Princeton University Press, Princeton.
Cuomo, Serafina, 2007. Technology and Culture in Greek and Roman Antiquity. Cambridge University Press, Cambridge.
De Callataÿ, François, 2005. The Graeco-Roman economy in the super long-run: lead, copper, and shipwrecks. JRA 18, 361–372.
Diels, Hermann A., 1920. Antike Technik: Sieben Vorträge. B.G. Teubner, Leipzig, Berlin.
Dutta, Rohan, Levine, David K., Papageorge, Nicholas W., Wu, Lemin, 2018. Entertaining Malthus: bread, circuses, and economic growth. Econ. Inq. 56 (1), 358–380.
Erdkamp, Paul, 2005. The Grain Market in the Roman Empire: A Social, Political and Economic Study. Cambridge University Press, Cambridge.
Erdkamp, Paul, 2016. Economic growth in the Roman Mediterranean world: an early good-bye to Malthus? EEH 60, 1–20.
Finley, Moses I., 1965. Technical innovation and economic progress in the ancient world. EHR 18, 29–45.
Finley, Moses I., 1999. The Ancient Economy, 2nd ed. with a foreword by Ian Morris University of California Press, Berkeley.
Flohr, Miko, 2016. Innovation and society in the Roman world. Oxford Handbooks Online doi:10.1093/oxfordhb/9780199935390.013.85.
Galor, Oded, 2011. Unified Growth Theory. Princeton University Press, Princeton.
Gimpel, Jean, 1988. The Medieval Machine: The Industrial Revolution of the Middle Ages, 2nd ed. Wildwood House, Aldershot.
Greene, Kevin, 1990. The Archaeology of the Roman Economy. University of California Press, Berkeley, Los Angeles.
Greene, Kevin, 2000. Technological innovation and economic progress in the ancient world: M.I. Finley reconsidered. EHR 53, 29–59.
Greene, Kevin, 2008. Inventors, invention, and attitudes toward technology and innovation. In: Oleson, John P. (Ed.), *The Oxford Handbook of Engineering and Technology in the Classical World*. Oxford University Press, Oxford.
Hanson, Victor D., 1998. Warfare and Agriculture in Classical Greece, 2nd ed. University of California Press, Berkeley, Los Angeles.
Harley, C.Knick, 2012. Was technological change in the early industrial revolution schumpeterian? Evidence of cotton textile profitability. EEH 49, 516–527.
Harper, Kyle, 2017. The Fate of Rome: Climate, Disease, and the End of an Empire. Princeton University Press, Princeton.
Hume, David, 1985. Of the rise and progress of the arts and sciences. In: Miller, Eugene F. (Ed.), David Hume, Essays: Moral, Political and Literary. Liberty Fund, Indianapolis, pp. 111–137.
Humphrey, John W., 2006. Ancient Technology. Greenwood Press, Westport CT, London.
Jones, Eric L., 2003. The European Miracle: Environments, Economies, and Geopolitics in the History of Europe and Asia, 3rd ed. Cambridge University Press, Cambridge.
Jongman, Willem M., 2007a. Gibbon was right: the decline and fall of the Roman economy. In: Hekster, Olivier, de Kleijn, Gerda, Slootjes, Daniëlle (Eds.), Crises and the Roman Empire. Brill, Leiden, pp. 183–199.
Jongman, Willem M., 2007b. The early Roman empire: consumption. In: Scheidel, Walter, Morris, Ian, Saller, Richard P. (Eds.), The Cambridge Economic History of the Greco-Roman World. Cambridge University Press, Cambridge, pp. 592–618.
Jongman, Willem M., Jacobs, Jan P.A.M., Klein-Goldewijk, Geertje M., 2019. Health and wealth in the Roman empire, economics and human biology. Econ. Hum. Biol.. https://doi.org/10.1016/j.ehb.2019.01.005.
Kant, Immanuel, 1914. Idee zu einer allgemeinen Geschichte in weltbürgerlicher Absicht. In: Herder, Johann Gottfried (Ed.), Ideen zur Philosophie der Geschichte der Menschheit mit Kants Rezensionen der "Ideen" und seiner Abhandlung Idee zu einer allgemeinen Geschichte in weltbürgerlicher Absicht. Deutsche Bibliothek, Berlin, pp. 321–338.
Karayalçin, Cem, 2008. Divided we stand, united we fall: the Hume-North-Jones mechanism for the rise of Europe. IER 49 (3), 973–997.
Koepke, Nikola, Baten, Joerg, 2005. The biological standard of living in Europe during the last two millennia. EREH 9, 61–95.
Kron, J. Geoffrey, 2005. Anthropometry, physical anthropology, and the reconstruction of ancient health, nutrition, and living standards. Historia: Zeitschrift für Alte Geschichte 54, 68–83.
Lauwers, Jeroen, 2015. Philosophy, Rhetoric, and Sophistry in the High Roman Empire: Maximus of Tyre and Twelve Other Intellectuals. Brill, Leiden.

Lewis, Michael J.T., 1994. The origins of the wheelbarrow. Technol. Cult. 35, 453–475.
Lloyd, Geoffrey E.R., 1970. Early Greek Science: Thales to Aristotle. Chatto & Windus, London.
Lloyd, Geoffrey E.R., 1973. Greek Science after Aristotle. W.W. Norton, New York.
Lombroso-Ferrero, Gina, 1920. Pourquoi le machinisme ne fut pas adopté dans l'antiquité? Revue du Mois 21, 448–469.
Luce, John V., 1988. Greek science in its hellenistic phase. Hermathena 145, 23–38.
Manning, Joseph G., 2018. The Open Sea: The Economic Life of the Ancient Mediterranean World from the Iron Age to the Rise of Rome. Princeton University Press, Princeton.
McCloskey, Deirdre N., 2016. Max U versus humanomics: a critique of neo-institutionalism. JOIE 12, 1–27.
McConnell, Joseph R., et al., 2018. Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. PNAS 115, 5726–5731.
McConnell, Joseph R., et al., 2019. Pervasive arctic lead pollution suggests substantial growth in medieval silver production modulated by plague, climate, and conflict. PNAS 116, 14910–14915.
Mokyr, Joel, 1990. The Lever of Riches: Technological Creativity and Economic Progress. Oxford University Press, Oxford.
Mokyr, Joel, 1994. Cardwell's law and the political economy of technological progress. Res. Policy 23 (5), 561–574.
Mokyr, Joel, 2002. The Gifts of Athena: Historical Origins of the Knowledge Economy. Princeton University Press, Princeton.
Mokyr, Joel, 2016. A Culture of Growth: The Origins of the Modern Economy. Princeton University Press, Princeton.
Montesquieu Baron de (Charles-Louis de Secondat), 1748. De L'esprit Des Lois. Barrillot & fils, Geneva.
North, Douglass C., 1981. Structure and Change in Economic History. W.W. Norton & Company, New York, London.
Panagiotou, Spiro, 1987. Socrates' 'Defiance' in the Apology. Apeiron 20 (1), 39–61.
Rawlings, Louis, 2007. The Ancient Greeks at War. Manchester University Press, Manchester.
Renberg, Ingemar, Bindler, Richard, Brännvall, Maja-Lena, 2001. Using the historical atmospheric lead-deposition record as a chronological marker in sediment deposits in Europe. The Holocene 11, 511–516.
Reynolds, Leighton D., Wilson, Nigel G., 2013. Scribes and Scholars: A Guide to the Transmission of Greek and Latin Literature, 4th ed. Oxford University Press, Oxford.
Saller, Richard P., 2002. Framing the debate over growth in the ancient economy. In: Scheidel, Walter, Reden, Sitta von (Eds.), The Ancient Economy. Routledge, New York, pp. 251–269.
Scheidel, Walter, 2007. Demography. In: Scheidel„ Walter, Morris, Ian, Saller, Richard P. (Eds.), The Cambridge Economic History of the Greco-Roman World. Cambridge University Press, Cambridge, pp. 38–86.
Scheidel, Walter, 2019. Escape from Rome: The Failure of Empire and the Road to Prosperity. Princeton University Press, Princeton.
Schneider, Helmuth, 2007. Technology. In: Scheidel, Walter, Morris, Ian, Saller, Richard P (Eds.), The Cambridge Economic History of the Greco-Roman World. Cambridge University Press, Cambridge, pp. 144–171.
Schumpeter, Joseph A., 1961[1934]. The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle. Oxford University Press, New York translated by Redvers Opie.
Smith, Adam, 2000[1976]. The Wealth of Nations. The Modern Library, New York.
Temin, Peter, 2013. The Roman Market Economy. Princeton University Press, Princeton.
Terpstra, Taco T., 2018. Neo-institutionalism in ancient economic history: the road ahead. In: Ménard, Claude, Shirley, Mary M. (Eds.), A Research Agenda for New Institutional Economics. Edward Elgar, Cheltenham, pp. 233–240.
Terpstra, Taco T., 2019. Trade in the Ancient Mediterranean: Private Order and Public Institutions. Princeton University Press, Princeton.
Van der Beek„ Karine, 2010. The effects of political fragmentation on investments: a case study of watermill construction in medieval Ponthieu. EEH 47, 369–380.
Vernant, Jean-Pierre, 1957. Remarques sur les formes et les limites de la pensée technique chez les Grecs. RHS 10 (3), 205–225.
Ward-Perkins, Bryan, 2000. Specialized production and exchange. In: Cameron, Averil, Ward-Perkins, Bryan, Whitby, Michael (Eds.), *CAH* vol. 14: *Late Antiquity: Empire and Successors, A.D. 425-600*. Cambridge University Press, Cambridge, pp. 346–391.
Ward-Perkins, Bryan, 2005. The Fall of Rome and the End of Civilization. Oxford University Press, Oxford.
Warren, James, 2007. Presocratics. University of Berkeley Press, Berkeley, Los Angeles.
White, Kenneth D., 1984. Greek and Roman Technology. Cornell University Press, Ithaca, New York.
White, Lynn T., 1962. Medieval Technology and Social Change. Oxford University Press, Oxford.
White, Lynn T., 1978. Medieval Religion and Technology: Collected Essays. University of California Press, Berkeley, Los Angeles.
Wilson, Andrew I., 2002. Machines, power and the ancient economy. JRS 92, 1–32.
Wilson, Andrew I., 2011. Developments in Mediterranean shipping and maritime trade from the Hellenistic period to AD 1000. In: Robinson, Damian, Wilson, Andrew I (Eds.), Maritime Archaeology and Ancient Trade in the Mediterranean. Oxford Centre for Maritime Archaeology, Oxford, pp. 33–59.
Yuchtman, Noam, 2017. "Teaching to the tests: an economic analysis of traditional and modern education in late imperial and Republican China. EEH 63, 70–90.