Feeding Rome:
Innovation in the Economy of the Roman Grain Supply

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Introduction

Rome was one of the great cities of ancient times. Builders of much of the foundations of Western society, the Romans brought a vast territorial empire under their control and brought order to a large Mediterranean world. As their empire expanded, the Romans collected more and more wealth and power in their capital city. Yet the nature of Rome's imperial economy is a point of argument among scholars even today. While some scholars claim that Rome was just a large-scale subsistence society with a handful of ultra-wealthy at the top, newer research suggests that the Roman innovation led to higher efficiency in and greater amounts of production. Today we most often think of ways to be more efficient, to produce a surplus, and to maximize profits; but did the Romans also think this way? And although we today enjoy a globally linked economy, was the entire Roman Empire connected in a similar unified economic web? Employing analysis of the grain supply of Rome (from production to consumption), I have found that the Romans did indeed innovate (albeit, over centuries) the economy of their grain supply.

The historiography of Roman attitude toward innovation has changed over the past decades. The first prolific scholar on the subject is Moses Finley, who wrote his "Technical Innovation and Economic Progress in the Ancient World" in 1965.[1] Summing up opinion of ancient innovation at the time, Finley writes "It is a commonplace that the Greeks and Romans together added little to the world's store of technical knowledge and equipment."[2] While Finley's claim is bold, it makes some sense. Finley, writing in the frame of the Industrial

[1] Finley (1965).
[2] Finley (1965), 1.

Revolution certainly sees shortcomings in the comparison. But ancient innovation – and specially that of the Romans – should not be compared to the Industrial Revolution. While the latter centuries of the second millennium certainly demonstrated huge innovation, that should not discount the gradual innovations of the Romans, among others.

Modern scholars have changed their opinion of Roman innovation. Kevin Greene, writing in the same economic journal as Finley 35 years later, states "The absence of revolutionary change is surprising only to those who consider it to have been a regular feature of human development."[3] Modern scholars analyze Roman innovation on its own. By excluding the Industrial Revolution, a highly complex event which we will not discuss here, modern scholars can see Roman innovation for what it is – astounding. While Roman innovation took place over many centuries, these very real advancements improved their world in a variety of areas. In my analysis of innovation in the economy of the Roman grain supply, I will demonstrate that, even in this narrow area, the Romans made huge improvements and demonstrated a desire for greater efficiency.

Once a humble city, Rome grew to be the largest urban consolidation of ancient times, housing approximately a million inhabitants by the early Imperial period. Such a city required a complex economy to sustain itself with enough essentials - especially food. While scholars have long argued about the economic structure of Rome, and whether it changed from Republic to Empire, the sheer amount of grain required to feed the city presents a unique opportunity for scholars of the Roman economy to observe a real example of Roman innovation. Because of the complexity involved in every step of the process, from growing to transporting to storage to

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[3] Greene (2000) 28.

distribution, the grain supply of the city of Rome allows for a deeper dive into questions about the economy of the Roman Empire. Did the Romans seek innovations to improve the yield from agricultural production and to provide for a growing population? Or was the Empire forced to expand its control over even more territory to increase its total agricultural output? An examination of the complex grain system opens up new perspectives for these questions.

Because feeding one million inhabitants of a densely populated city posed enormous logistical challenges, I will focus on the grain supply as a case study to explore broader questions about innovation and the Roman economy. The food necessary to feed the city of Rome was consistent day in and day out, so how did the Romans provide a consistent supply? Assuming no issues with growing enough wheat (although there certainly were), how did the Roman government – which was legally obligated to feed the citizenry – transport the food to Rome from the wide geographic range of imperial bread baskets? And once supplies reached the city, how did the Romans store the unprocessed grain so it would last? And before the raw grain could be eaten, it had to be milled, sieved, kneaded, and baked before it could be distributed as bread to citizens. At each step in this food supply chain, one could imagine there were opportunities for improvement. These were not lost on the Romans. With a massive transportation network, elaborate storage methods, and innovative processing techniques, the Romans did indeed introduce and/or adopt new techniques that improved their food supply economy.

My analysis of Rome's innovation of the economy of the grain supply is organized in the following chapters. In Chapter 1, I will discuss the diet of the Roman people and the ways in which they increased production in their food supply. In Chapter 2, I will focus on the areas of production to gain perspective on the entire grain supply chain. In Chapter 3, I will study the modes of processing grain and the evolution of these processes. Then in Chapter 4, I will be examining the "last five miles" of how processed grain was consumed by the citizens of Rome. In my studies, I sought to find out if the city of Rome relied more on intensification or extensification – that is I ask whether the only way to increase grain production was via an expansion through conquest? Or could innovations in farming, shipping, storing, or milling technology change the game and improve the efficiency of currently available farmland. The Romans certainly did expand their empire and agricultural lands - but innovation in improving their grain supply was equally important.

In writing this thesis, I desire greater understanding of how the city of Rome fed itself. While it can be hard to pin down one exact moment in the history of Rome, I rely on evidence from various points in time to piece together a more complete view of Rome's capacity for innovation. I have therefore decided to focus on the high points, like the population at its height and the maximum grain production of various provinces, which are more frequent in record. These points of maxima provide the most solid numbers on record. By looking at what was recorded and understanding the analytical limits of the historical record, I hope to determine what was possible, even if only at the peak.

An important consideration to mention when discussing the grain supply of Rome is the involvement of the state in the entire process. Starting with Gaius Gracchus' *Lex Frumentaria* in the second century BC, the Roman state had a legal duty to help provide subsidized grain for the citizens in the city. While the laws started as price guarantees only, new politicians eventually expanded the laws into free doles of grain (and later bread) to every male citizen of a certain age starting with the *Lex Clodia Frumentaria* introduced by Clodius in 58 BC. While this dole may not have covered the entire nutritional needs of a Roman citizen and his family, the free grain certainly provided a big supplement to normal wages. Since the state had to provide so much grain (or face the consequences of popular upheaval during scarcity), complex methods of transport, processing, and distribution arose to meet the constant need for food.

While some scholars have argued that Rome had a primitive economy based on subsistence farming, the innovations found throughout the food supply chain indicate movement toward more sophisticated and efficient means of production. The Romans lived in an environment rich for innovation. In the complexities of Rome's grain supply alone, we find evidence for improvements. The diverse diet and heightened efficiency in various parts of the food supply allowed the city of Rome to cater to the nutrition of its huge population. The supply of grain flowed in from all over the empire and was delivered to the city with impressive consistency. The processing of grain demonstrates complex technological innovations in processing that employed animal and water power to make the raw grain edible. And, finally, the last steps of consumption show innovation in cooking, the economy of *tabernae* also indicating a complex distribution network of food within the city.

Diet

The grain supply of Rome was vital to the maintenance and survival of the urban population. Grain comprised the largest share of the consumed calories. The Roman diet, however, also included many other types of food. Since a diet of solely grain lacks the vital nutrients in other foods, such as provided by meat, legumes, and vegetables, the urban dwellers of the Roman world needed access to a variety of food sources. This chapter reviews the various parts of the Roman diet that allowed for the unusually huge population density of the city of Rome. While grain was certainly the most consumed food, the city of Rome would not have been able to feed its people without supplementing this supply with other sources of nutrition. The production of both grain and other foods also highlights important innovations in the food supply that responded to the demands of a burgeoning Roman population.

The processing of grain for the city of Rome was hugely important for the population. Romans had to deal with feeding an ever-increasing density of citizens in Rome. As the majority (around 75%) of calories in the urban Roman diet were from grain, a consistent supply was necessary to prevent famine. Yet Rome as an immensely dense urban population was unique for the time. The diet of the average Roman citizen from anywhere in the empire likely differed immensely from the people of Rome itself, owing to rural access to a wider variety of local foods. While the focus of this chapter will be the diet of the urban population in Rome, certain examples of other urban areas, such as Herculaneum, can provide insight into what was available in the urban environment. The nature of social stratification, however, made for deep differences between the diet of the wealthy and that of the urban poor – with a gradient running between the extremes. There were significant differences between the diets of urban

Romans and rural Romans, rich Romans and poor Romans. This chapter focuses on the "typical" diet of a Roman citizen by discussing the importance of grain in the urban Roman diet as well as the other potential sources of nutrition available in the city.

The first distinction we will make in the diets of various Romans is that of urban versus rural. Since the vast majority of those living in the Roman Empire were involved in agriculture, many people accordingly lived in rural areas. In these rural areas, people had immediate access to the food produced there. As Paul Erdkamp points out, "For most rural dwellers the connection between production and consumption of food was fairly simple: they ate what they (or their close kin) had harvested, gathered, or collected from the nearby vicinity."[4] The average Roman lived in the countryside and generally lived off subsistence farming just like many through history. Any surplus was either used to pay taxes or sold locally. And because a large porportion of foods consumed would perish over the course of long-distance shipment to a place like Rome (with the important exception of grain), "Such foodstuffs mostly reached the dinner tables of the well-to-do, and not so much those of the poor city dwellers. Hence, the diet of urban consumers consisted of a much more limited range of foodstuffs than the rural diet … and possibly resulted in malnutrition."[5] Because grain was one of the few staple foods that could survive shipment to Rome from places as far distant as Egypt, the urban dwellers of the city of Rome had to subsist primarily upon it. The heavy reliance on grain, however, could also lead to diseases stemming from malnutrition.

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[4] Erdkamp (2015) 183.
[5] Erdkamp (2015) 184.

Yet the diet of urban Romans was not necessarily worse than that of their rural counterparts. Because grain was the most efficient food to ship long-distance to Rome and because all grains tended to cost the same to ship, merchants chose to ship higher quality grain (i.e. grain that could be made into bread) that was more cost-effective. Therefore, "urban consumers had access to those kinds of wheat that could be made into leavened bread, while rural people more often ate cheaper kinds of grain that could only be eaten in the form of porridge or flat bread … even those inhabitants of the major cities of the Roman world who were not wealthy by any standard came to be used to consuming cereals in the form of bread."[6] As discussed earlier, leavened bread had nutritional benefits over other ways of preparing grain. While the diet of urban Romans may not have been as varied as that of rural Romans, the quality of their grain was certainly higher. Evidence for the availability of a variety of grains is well documented through Pliny the Elder's *Natural History*, in which he lists over a dozen kinds of grain.[7] Despite such variety, however, only wheat could be processed into high-quality nutritious bread.

Yet grain was not the only food source for urban Romans. Since grain was supplied from overseas and subject to price-controls by the government, local farmers turned their plows to ever more marketable foods. An important look into the diverse diet of urban Romans comes from the excavation of a sewer in Herculaneum. This archeological survey by Robinson and Rowan paints a more complete picture of the Roman diet. While the archeological evidence provides many clues, there is one caveat: "Grain that is ground into flour will not be preserved,

[6] Erdkamp (2015) 184.
[7] Pliny the Elder, *Natural History*, 10.

and the absence of chaff suggests that clean grain was brought into Herculaneum, having been parched, threshed, and winnowed elsewhere."[8] Therefore this archeological survey does not speak much to the grain consumption in Herculaneum, though we can assume grain consumption was likely comparable to other urban areas. The first important discovery of the survey was "that figs, grapes, olives, eggs, and shellfish were very commonly eaten foods. These foodstuffs appear in each stratigraphic layer of every quadrant, demonstrating that they were popular not only over space but over time. Other frequently occurring seeds included apple, pear, and opium poppy."[9] Thus in Herculaneum (and we can assume in Rome) there was a variety of other food options beyond the staple grains. Not only were options available, however – they were eaten all over the city and therefore by people in all walks of life. While the urban wealthy certainly ate better than the urban poor, the average Roman city-dweller still had frequent access to varied nutrition.

The picture painted by these preserved sewer remains is consistent with the analysis of the remains of Herculaneum's inhabitants. Analyzing data collected from 350 skeletons found on Herculaneum's beach, "the medium to high levels of zinc and the high levels of strontium in the bones point to a diet high in marine fish, crustaceans, and legumes but low in red meat … skeletal material suggests a diet that was both diverse and nutritious."[10] While the social standing of these skeletons is uncertain, the sample size leads us to believe that these remains represent a fairly average spread of urban inhabitants in Herculaneum. While these may have been exclusively wealthy people who remained in the city to protect their belongings, they

[8] Robinson (2015) 110.
[9] Robinson (2015) 109.
[10] Robinson (2015) 112.

could easily have been the desperately poor people unable to flee Herculaneum by boat. The "diverse and nutritious" diet found with these remains therefore indicates that urban Romans, for the most part, did have good diets. Urban Romans could appreciate this variety since local farmers did not focus on growing grain, which was already being imported. In fact, "while the cereal grains could have been imported from Egypt, items such as figs, grapes, and herbs would have been cultivated or gathered from the fertile plains around Mount Vesuvius."[11] The supply of overseas grain not only helped the Romans consume enough calories to survive. It also allowed local farmers and fishermen to provide a greater variety of foods for urban Romans, resulting in a better balanced and nutritious diet for the average urban inhabitant.

Other indications of a strong diet for the average urban Roman come from analysis of strong farming and husbandry techniques. Kron claims that "Our literary evidence for Roman cereal yields shows … yields were double or triple those obtained in the Medieval three-field system and could match some of the most productive modern arable farms."[12] Recent analysis of Roman agriculture shows advanced techniques and production that compete with recent productivity. In fact, "the modern Mediterranean diet was, until recently, poorer [compared to Roman diet] in protein from meat and seafood, and in calories from animal fats, as well as significantly poorer in olive oil, an excellent, and healthy, source of calories from fat, and in fresh fruit and vegetables."[13] While bold claims, the evidence for advanced agricultural and husbandry techniques supports the idea that Roman food production was high and Roman food consumption was quality. "Compost and manure were used extensively in arable farming and

[11] Robinson (2015) 114.
[12] Kron (2015) 161.
[13] Kron (2015) 161.

were carefully managed … applied in quantities matching some of the best seventeenth-century Dutch practice."[14] Such fertilizing techniques certainly improved yields. Kron also notes that "seed selection … effective tillage and frequent hoeing and harrowing to destroy weeds … superior metal tools and mechanical reapers … improved crop rotations … substitution of legumes, whether for human consumption, fodder, or green manure, for bare fallow … the introduction of ley farming or convertible husbandry" all made significant impacts on the effectiveness of Roman agriculture. These techniques, including references to the use of greenhouses in the winter,[15] help explain how the Romans could produce high yields from their land and provide good nutrition in urban areas. Such improvements not only increase the supply of fruits and vegetables but also increased the supply of olive oil: "Based on the capacity of the discarded amphorae in the huge dump of Monte Testaccio … an annual consumption in the city of at least 20 kg per year, comparable to modern Italian or Greek rates, and six to seven times as great as the levels attested in Italy at the beginning of the twentieth century."[16] The fact that the Romans maintained such a supply of olive oil - perhaps enough to compare to modern consumption rates - is impressive and indicates advanced agricultural techniques to make it possible.

Higher agricultural yields were not the only improvements that the Romans made in their food supply. Better animal husbandry also allowed the Romans to increase the consumption of meat. The Romans succeeded at animal husbandry to the point that archeological work shows that "the large improved livestock, comparable in size to some of the

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[14] Kron (2015) 162.
[15] Kron (2015) 171 (referring to Martial's *Epigramatta* 8.14).
[16] Kron (2015) 168.

best improved breeds of late eighteenth- and nineteenth-century England, became dominant in Greece and Southern Italy by the fifth or fourth century in Roman central Italy by the third century, and in Cisalpine Gaul and the interior or Southern and Apennine Italy by the first century AD."[17] The Romans were able to greatly improve the size, and therefore yield, of their food animals. Spreading these techniques over the empire over the course of time, the Romans were able to increase red meat consumption followed across the empire.

While not related to animal husbandry per se, game and fish farming also played an important role in the food supply of the Roman world. Game farming, or the protection and feeding of game in a certain area, seems to have greatly improved access to meat. While such meats were usually only accessible to the wealthy of society, "by the time of Diocletian, as is clear from his price edict, venison cost no more than pork; wild boar was comparable to lamb or kid; and duck, goose, and squab were no more expensive than the cheapest meats, beef and mutton. Even guinea fowl, thrushes, quail, partridge, and peacock were well within the means of much of the society."[18] While the transition of such luxury meats as peacock fromMarch the frescoes of the ultra-wealthy into the hands of the average Roman certainly took much time, the greater accessibility to game meat nevertheless indicates improved game farming and an overall improvement in the diet of Romans.

Aquaculture, or fish farming, also improved the food supply of Rome. Using concrete fish tanks with water circulation and other advanced techniques, the Romans had made "more than 82 substantial maritime fish farms … along the Tyrrhenian and Adriatic coasts of Italy

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[17] Kron (2015) 163.
[18] Kron (2015) 165.

alone."[19] Such widespread use of these aquaculture techniques, confirmed through archeology, not only demonstrates the successful adoption of technology by the Romans but also marks an important innovation in the food supply. Aquaculture has made improvements in fish production even today: "The modern transition from extensive to intensive fish farming has seen production rise from around 150 kg/ha to 200,000 kg/ha or more, while significantly reducing the time fish take to reach a marketable weight, using the same critical innovations first securely attested for the Romans."[20] Such successful innovation gave more Romans access to fish and other seafoods and improved the nutritional quality of the average Roman's diet.

We have discussed the wide variety of foods available to the Romans. While access to vegetables and animal protein was very important, we must now return our focus to grain. While the accessibility to such variety, including red meat and olive oil, helped the average Roman achieve a nutritionally complete diet, the mainstay of this diet was still grain. Donahue claims grain could comprise "as much as 75% of an individual's caloric needs."[21] A good example of the diet of an average Roman comes from that of soldiers, who "during [one year] could be expected to consume one-third of a ton of grain."[22] As we can assume that soldiers were fed well in order to keep up their fighting strength, it seems reasonable to conclude that civilians ate similarly. Donahue also points out that "various meats, seafoods, fruits, nuts, and vegetables" were found at military forts.[23] The fact that the Romans could feed their army well

[19] Kron (2015) 166.
[20] Kron (2015) 166.
[21] Donahue (2015) 259.
[22] Donahue (2015) 259.
[23] Donahue (2015) 259.

shows the sophistication of their supply chains and, more importantly, their ability to feed soldiers and citizens alike with a sufficient and diverse array of food.

The variety of foods available to the Romans furnished the city's residents with quality nutrition. But the mainstay of the Roman diet was still grain. But, while calorically the largest part of their diet, grain cannot provide all the nutrients required to survive. The Romans were not able to sustain huge legions and the incredibly dense city of Rome through mass-produced grain alone. The Romans had to innovate (and apply these innovations across their empire) in all aspects of their food supply. Greater supply of grain meant that local farmers could supply foods that would otherwise perish in long-distance shipments. Improved agricultural techniques allowed the Romans to boost yields to impressive heights and increase the food supply. Animal husbandry, game farming, and aquaculture allowed even lower-class Roman citizens to supplement their diets with nutritious sources of protein. All these innovative aspects of the food supply resulted in a complete and nutritious diet for the average Roman that could compete with some diets today. While, as mentioned before, we must take caution with trying to identify the "average" Roman, we can be assured that the vast majority of the population had access to a wide variety of nutrition by the time of early Empire.

Having knowledge of the Roman diet is key to understanding the grain supply. Without the variety and access we have discussed, a diet of exclusively grain would not provide adequate all-around nutrition and would not allow for Rome's population density. The foods we have discussed are, however, the minority of calories needed by the denizens of Rome. In the following chapters we will discuss how the Romans sourced, processed, and consumed the mainstay of the Roman diet – grain.

The Grain Supply

Rome at its peak sustained a population of probably one million persons and thus required huge amounts of food to feed itself.[24] In order to sustain such a population density, the Roman diet had to include sufficient calories and enough varied nutrition to sustain, on average, active lifestyles. We have discussed how the varied nutrition of the urban populace allowed for a well-rounded diet. Nonetheless, grain remained the most important part of that diet, and its provision will be the subject of this chapter. Now we will discuss how the city of Rome was provided with the mainstay of the average diet – grain. Grain was consumed in huge amount in the city of Rome. Erdkamp suggests that "on average the annual consumption of wheat must have been in the range of 200 kg for an adult."[25] Such heavy requirements became complicated by the passage of laws requiring the city to, eventually, provide a free grain dole to its citizens. As the territory under imperial control swelled and Rome's population grew, the city required new agricultural land beyond its traditional hinterland to produce enough grain. Once these new lands started producing grain, however, the government had to coordinate a tangle of logistics to bring the harvest to the city. Finally, the city had to develop storage and processing methods to ensure a steady supply regardless of possible bad harvests and problematic sea-faring conditions.

Since the city of Rome required consistently immense amounts of food to feed its populace, the city had to have strong control of the origins of all the grain, reliable methods of transporting the food, risk-averting methods of storage and processing, and a reliable system of

[24] Rickman (1980) 10.
[25] Erdkamp (2013) 263.

distribution. All these complications raised the question of whether the Romans tried to improve the efficiency of their grain supply or whether they expanded their sphere of influence in large part to feed a growing urban population in the capital. With the grain supply under constant pressure, the Romans had to either expand production or implement technological advances into their current avenues to keep up. The increase in sources of grain across the empire, the complex transportation network, and the innovative storage methods employed in the grain supply indicate that the Romans did indeed respond to increasing demand by innovating their food economy.

The immensity of the grain demand in Rome is stunning. While Romans did consume other foods, such as olive oil and fish, as already noted above grain comprised the largest portion of foodstuffs in the city with an estimated annual consumption of 150 million kilograms.[26] For reference, the United States produced 2 billion pounds[27] of wheat (specifically durum, which is grown in relatively small amounts when compared to other wheats) in 2010.[28] Annual US production of all kinds of wheat, however, was 27 billion kilograms in 2019.[29] Thus, while the average Roman denizen (women and children included) consumed about 150 kilograms of wheat yearly, the average United States production per capita in 2019 was only about 85 kilograms. While US citizens today have an incomparably large selection in types of foods, including other types of wheat in addition to New World starches such as maize, such a

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[26] Erdkamp (2013) 263.
[27] 72.175 million bushels produced in 2010, each at 27 kilograms. Note: one *modius* is about 6.6 kg.
[28] United States Department of Commerce, *Wheat Data*, (Washington: Economic Research Site).
[29] USDA "Flour Milling Products" report, February 3, 2020.

high consumption of wheat in Rome indicates that citizens depended on wheat for a far greater portion of their diet than US citizens today do.

As the city of Rome, to say nothing of the entire empire, demanded an enormous amount of grain even by today's standards, the question of how to satisfy that need was a pressing issue. With today's modern technology, such as genetically modified plants and an army of farm equipment, and farming techniques, such as crop rotation, the world today has been able to intensify agriculture by making each acre more productive. But without reliable quantitative records of ancient grain production around the empire, scholars today cannot determine if the Romans had the capability of intensifying their own grain fields as the modern world has done. Rickman does reference the province of Africa, where "as in other territories once controlled by Carthage in Sicily, Sardinia and Spain, the Romans took over a sophisticated agricultural tradition."[30] As such, evidence does not exist of the Romans themselves intensifying agricultural techniques around the empire. Instead, they adopted the successful methods of others. The agricultural methods of Carthage, for instance, did seem to be an improvement over others: "Carthaginian influence had been at work in the neighboring kingdom of Numidia, and Carthaginian agricultural techniques had increased the productivity of that area by the time Julius Caesar annexed it to the original province."[31] While no quantitative evidence remains in reference to this supposed improvement in productivity, qualitative observations by contemporary Romans do indicate the possibility of improvement.

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[30] Rickman (1980) 108.
[31] Rickman (1980) 108.

While intensification of land through improved agricultural techniques did help the Romans increase the output of grain necessary to feed their empire, extensification also allowed increased total production by increasing the amount of agricultural lands under the control of Rome. As we will discuss later, the incorporation of new territory through conquest, mainly that of Sicily through victory over the Carthaginians and that of Egypt by victory over Anthony and Cleopatra, meant enormous increases in the output potential of the Roman agrarian hinterland. I will to investigate the growth of the Roman sphere of influence and compare the increase of acreage to the increase of grain demand. Did Romans seek simply plunder from new lands or the ability to grow more in order to feed a growing empire? While there were certainly improvements in the per acre productivity, the sheer scale of the whole supply network, as shown in the map below, indicates that intensification was certainly important to satisfying the demand for grain in Rome.

Figure 1: Map of Mediterranean with important areas for the grain supply noted. https://www.themaparchive.com/media/catalog/product/cache/1/image/b9d24ee63e043d9dae72d8cfeefe8ff8/A/x/Ax00599.jpg.

As Rome started to grow, the lands immediately nearby soon proved insufficient for the city's nutritional needs. While "the fertility and good farming of Campania were legendary from the beginning to end of antiquity," farmers in Italy likely adopted mixed farming "to provide themselves with more valuable cash crops that could be sold at good prices in the expanding city."[32] As sea travel posed a far more efficient mode of grain transportation than that by land, areas nearby the city started to focus on growing other more profitable products. While some areas such as Sardinia and North Africa did produce much grain, logistical issues such as proximity to ports and unreliability in harvests made them less trustworthy grain sources. For instance, if grain production occurred far (over land) from a port, transportation

[32] Rickman (1980) 102-103.

costs would hinder the ability to export. Thus, the bulk of Roman grain came from areas like Sicily, which sent around 50 million kilograms of wheat to Rome at its peak,[33] and Egypt, which purportedly supplied around 140 million kilograms (in other words, almost the entire Roman supply) under Augustus. As these lands could produce enormous amounts of grain and transport it to Rome fairly efficiently by sea, the city's dependence on these provinces grew strong.

The locales from which Rome imported so much grain posed the first hurdle for the city. The first factor in determining the efficiency of imports was the major difference between transportation by land and that by sea. Using figures from Diocletian's Edict of prices from the 4th century, Rickman estimates the price of wheat doubling over a land journey of about 500 km.[34] The 2,720 km from Alexandria to Rome, however, "increased the price by 16 percent."[35] Thus, "the corn trade was therefore necessarily a trade carried on mainly by sea."[36] Transport by sea, however, did take significant amounts of time. Routes differed in their speeds. For example, "a journey from Ostia to Africa is on record as the fastest journey by sea of which we know; some 270 nautical miles in two days."[37] The more vital route to Egypt, however, posed a greater difficulty: "Fast speeds are on record for the journey with the wind from Puteoli to Alexandria, nine days journey of 1,000 nautical miles."[38] While the return trip to Egypt to resupply on grain was quick, "A man congratulated himself on his great good fortune on taking only thirty days to get from Alexandria to Marseilles, a distance of 1,500 nautical miles, with

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[33] Rickman (1980) 105. With 7 million *modii* at 6.6 kg/*modii*.
[34] Rickman (1980) 14.
[35] Rickman (1980) 14.
[36] Rickman (1980) 16-17.
[37] Rickman (1980) 128.
[38] Rickman (1980) 128.

reason, since Lucian says that it could take as much as seventy days to go from Alexandria to Rome."[39] Such long journeys, which were not even certain of success on account of the many dangers, were made more hectic by the short window in which ships could proceed on their routes since all the ships had to make their journey in the same small window.

Short shipping windows posed a huge hurdle for grain transported by sea. "According to Vegetius the seas were closed for four months from 11 November to 10 March, and were very dangerous for eight months from 22 September to 27 May."[40] While storms even in the relatively safe months could sink ships carrying much-needed grain, other factors such as pirates made Mediterranean shipping very risky. With only four months of relatively safe seas, a ship on record time would still only be able to make two trips at most in this window. To make more journeys, a transport ship would have to risk bad seas and potential loss of the entire venture. To overcome this uncertainty, Rome had to employ a great many ships to travel simultaneously. Some ships had a relatively small capacity – Rickman states that in the first century "a 70-tonner was at that time the smallest corn freighter that the state considered useful."[41] At around 63,000 kg, or only 0.04% of Rome's grain demand, many such small ships would need to sail to satisfy the Roman demand. Larger ships, however, did transport grain. Rickman mentions a particularly large vessel, the *Iris*, whose dimensions were approximately those of the Flower-class corvette ships used by the US Navy during World War II.[42] Such a ship, which Rickman suggests was "not unique," could transport around 1300 tons, or around

[39] Rickman (1980) 128-129.
[40] Rickman (1980) 15.
[41] Rickman (1980) 123.
[42] Rickman (1980) 123.

1.2 million kilograms, of grain.[43] Even one of the larger vessels like the *Iris* could optimistically only supply 0.8% of Rome's grain demand. A huge fleet of small and large ships must therefore have supplied the city especially since the short shipping window reduced the number of trips per year.

While sea travel made various areas accessible as suppliers of grain, different areas under Roman control contributed varying amounts to the grain supply of Rome. Growing the grain supply poses a difficult enough question. Even if everything went well, with appropriate soil and enough rainfall, more complex logistical issues arose after the harvest. But even beyond the hectic logistics of transporting grain across the Mediterranean from various provinces, the issue of transportation from the sea to the city of Rome was another issue entirely. Since Rome lay inland up the Tiber, large grain transport ships a deep draft could not navigate all the way to the Roman docks. And since Rome had no nearby port, despite the failed efforts of some emperors to create one near Ostia, grain transport ships could not even stop on the coast nearest to Rome. These ships let off in the bay of Naples, generally at Puteoli, where a natural port protected them at anchor. Then the grain had to be transported along the coast around 100 miles to the mouth of the Tiber from which it was tugged up the river on rafts by draft animals or slaves.[44] These last few miles proved costly and inefficient - but necessary.

[43] Rickman (1980) 123.
[44] Rickman (1980) 19.

Figure 2: Map of the Tiber from Ostia to Rome. https://2.bp.blogspot.com/-is6hhD4mFyc/UdVsi6TIfyI/AAAAAAAAI1Q/SFGOZrapOf8/w1200-h630-p-nu/Ostia-Antica-map.jpg.

While Romans enjoyed grain shipments from all over the empire, the system of grain transportation was unstable. On the one hand, as Erdkamp points out, "The high relief of the peninsulas [in the Mediterranean] breaks [Mediterranean lands] up into small micro-regions. Hence, if harvests failed, they did not do so everywhere at the same time."[45] While rural areas were highly dependent on yearly conditions – and had to stockpile reserves accordingly – the city of Rome could still get grain from areas that performed well. While a logistical challenge, the wide availability of regions did provide some stability. The grain markets in Rome, however, were still subject to the economic effects of surpluses and shortages: "Moreover, several sources indicate that the price of grain on the urban market normally went through an annual cycle, with low prices after the harvest, which gradually rose during autumn and winter to

[45] Rickman (1980) 185.

reach a peak just before the new crop was harvested."[46] Since shortages naturally occurred as more time since the harvest passed, prices naturally rose. These rising prices may not have severely impacted most urban dwellers, but the poorest subsistence earners certainly had trouble.

After the grain arrived in Rome, the state had to store it before distribution to its citizens. As storage required sturdy structures that kept the grain in a certain temperature and humidity range, considerable design went into these so-called *horrea*. To accommodate so much grain, *horrea* were huge like the *Horrea Galbana*, which covered 225,000 sq. ft.[47] Such a *horrea* could hold up to 15 million kg of grain at a time.[48] Such large buildings required thoughtful design and proficient engineering to ensure the grain for the city of Rome remained safe and fresh for consumption. Because grain still respires after harvest, giving off heat, carbon dioxide, and water, much of grain storage aims at reducing these outputs through proper ventilation and temperature control. Additionally, the grain must be maintained at an appropriate environment to avoid spoilage by insects and fungi. Finally, the design of the storage facilities must dissuade ravaging by birds, rodents, and thieves.

Standards for grain storage today are moisture percentages between ten and fifteen percent along with a temperature below 60 degrees Fahrenheit. While the Romans were certainly not as precise when measuring these factors, "Roman writers on agriculture were clearly aware of the need to keep stored grain both cool and dry, and to control pests, whether

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[46] Rickman (1980) 185.
[47] Rickman (1980) 23.
[48] Assuming grain stacked at 6 feet across the entire square footage. With 1.25 ft^3/bushel and 27.3kg/bushel. Resulting in 30 million over entire square footage, divide in half for other non-storage footprint.

weevils or rodents."[49] While the Roman military employed different storage methods, namely sealed pits that better suited the mobile nature of an army, civil granaries were more permanent and sturdy. Pliny the Elder goes to great length to describe an ideal grain storage building, recommending everything from wall thickness to building orientation.[50] Grain storage was a well-thought-out feat of engineering – and it still is. As grain produces around 240 pounds per square foot of pressure,[51] "the buildings were strong, sometimes massively, constructed of the finest materials current in their day."[52] With complex layouts that maximized the transfer of grain into and out of the facility while preventing thievery and the spread of fires, "all was so built as to facilitate the carrying of goods by men."[53] In order to keep the grain cool and ventilated to reduce vermin, "the floor of each room was raised upon dwarf walls 1 ft (30 cm) wide and 1 ft (30 cm) apart … which allowed air to pass into the tunnels under the floor.[54] By keeping the grain covered and cool, these *horrea* could prevent spoilage of grain and allow for months of viability. As the transport of grain from agricultural areas was never consistent or reliable, the storage of grain for months at a time smoothed out distribution - preventing wastage during a glut and famine during a scarcity.

After the grain arrived in the city, the final step remaining to feed the citizens of Rome was distribution. While later in the imperial period the state provided citizens with milled grain and bread, in some places employing singular mills large enough to feed tens of thousands, the earlier doles consisted only of grain, which had the upside of lasting longer but downside of

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[49] Rickman (1980) 135.
[50] Pliny, *Natural History*, 18.73.
[51] Rickman (1980) 135.
[52] Rickman (1980) 136.
[53] Rickman (1980) 137.
[54] Rickman (1980) 137.

leaving milling to the consumer. When the government later took on the burden of baking the grain into bread, they took on the whole problem. Such an expenditure of time and money 6explains why the government so readily jumped through all these logistical hoops. The Romans sought to find any innovation in these processes to cut down on the already bloated supply chain that fed the city of Rome.

As the government of Rome was legally obligated to supply a consistent source of grain to the citizens of the city, enormous expense went into the securing, shipping, and storing of the grain on its way to Rome. Such a complex process made for a situation ripe for innovation. In addition to improved growing techniques, engineers could design better boats that could hold more grain and more safely traverse the Mediterranean to improve the chances of a successful (and profitable voyage). Ideas to increase the efficiency of transport from the coast to Rome (including the abandoned idea of digging a canal from the Bay of Naples to Rome as well as the realized construction of a successful port at Portus) indicated a desire to improve the grain supply. And, finally, complex and evolving grain storage designs show that the Romans improved their technology to protect a greater portion of the shipped grain. This initial stage of transport and storage only comprises the first of many in which the Romans innovated the grain economy. Next we will analyze innovations in milling that brought more of this raw grain onto the tables (or, perhaps, into the *tabernae*) of Roman cities.

Mills

After production, shipping, and storage, how did the Romans consume their grain? At this point, the grain has been parched, threshed, and winnowed, leaving dry grain kernels. In poorer areas, porridge was made from these kernels. Although Romans had access to other types of foods like vegetables and meats. The vast majority of the diet consisted of grain. While cooking the grain as porridge did give the grain superior nutrition and digestibility, there were drawbacks to consuming this un-milled form of grain. Leavened bread stands out as the most desirable (in terms of enjoyability and nutritional value) method of consuming grain among the Romans. But to make this bread, the Romans needed to mill and carefully sieve the resulting flour. A variety of milling methods existed in ancient times. While the Romans certainly employed most of these methods at some time or other, their development of water-driven mills is the best example of Roman advancement in food technology. In this chapter, we will establish the superiority of leavened bread and proceed to discuss the innovative methods the Romans adopted and developed to produce the necessary grain (and from there, flour) for the city of Rome.

Various grains have been a staple part of the diet of humans (and many animals) from prehistory. The consumption of grains, however, has changed over time. After the grain has been reduced to kernels, the easiest form of consumption is porridge or gruel, made by heating the kernels in water. And cooking grain this way was effective - Thurmond states that "Above 140˚F, a mixture of water and cereal starch gelatinizes to form porridge or gruel, which is both palatable and reasonably digestible but very unstable microbiologically and always more or less fluid."[55] Any Roman with access to a brazier or similar fire could make this porridge, but the resulting food spoiled quickly and was difficult to store. Once milled, however, bakers could turn the grain flour into bread. Yet there are large differences in types of bread - the differences between leavened and unleavened bread specifically being significant. Thurmond points out that "High consumption of unleavened, whole-wheat breads high in bran content is associated with such deficiency diseases as iron-deficient anemia, dwarfism and rickets … phytate acid in the bran and germ of cereals … impedes the absorption of essential minerals."[56] Thus, unleavened and poorly sieved grain made for a poor bread.

Leavened bread, in addition to having a superior texture, has the benefit of "yeasts and lactic bacteria [which] predigests some of the complex sugars in wheat starch and [makes] them somewhat more digestible for humans."[57] Because it had significant nutritional and other advantages, leavened bread likely was the most efficient form of grain consumption in Rome. These advantages also help explain why the dole much later consisted of bread instead of unprocessed grain. Other forms of grain consumption did, however, persist, as the Romans did not "abandon completely their taste – or need – for porridges, especially, we may suspect, among the poorer urban class and peasantry."[58] We will therefore proceed with the knowledge that a significant amount of Roman grain (at least before the offering of bread as part of the dole) was consumed in the form of porridge, which did not require the milling process. Now we focus on the other form of consumption – bread – and the processes necessary to produce it.

[55] Thurmond (2006) 15.
[56] Thurmond (2006) 16.
[57] Thurmond (2006) 16.
[58] Thurmond (2006) 16.

Sourcing and transporting the grain was only the first part of the puzzle. In order to access the nutrition locked in raw grain, various processes had to take place. While humans have processed grain for eons, "Historically the earliest true mill, that is, an instrument for grinding rather than pounding grain, was the saddle quern, of almost universal provenience and still very much a part of traditional cultures."[59] The saddle quern used a side-to-side motion of a rock over a devoted "saddle" to crush the grain.

Figure 3: Irish woman grinding grain with a saddle quern in the early 1900s (https://www.mediastorehouse.com/mary-evans-prints-online/grinding-corn-saddle-quern-co-antrim-14365257.html?nochkip=1&pid=7046)

Mechanical additions allowed for easier use of this type of mill, including levels and hoppers. The hopper, seen in the picture below near the fulcrum of the lever and above the milled grain, supplied a steady source of grain without the user having to replenish it as often (like with the saddle quern). This upgraded type of mill is referred to as an Olynthian mill, "so-called because a number of such millstones were recovered from a shipwreck off the Greek site of Olynthus."[60] While the Olynthian mill allowed for "regulating the flow of grain … and,

[59] Thurmond (2009) 38.
[60] Thurmond (2009) 38.

perhaps more importantly, eliminating the necessity of stopping the operation and lifting the top stone to feed in grain by hand," it nevertheless required a side-to-side motion that could not easily be powered by a more common circular motion (Thurmond, 38).

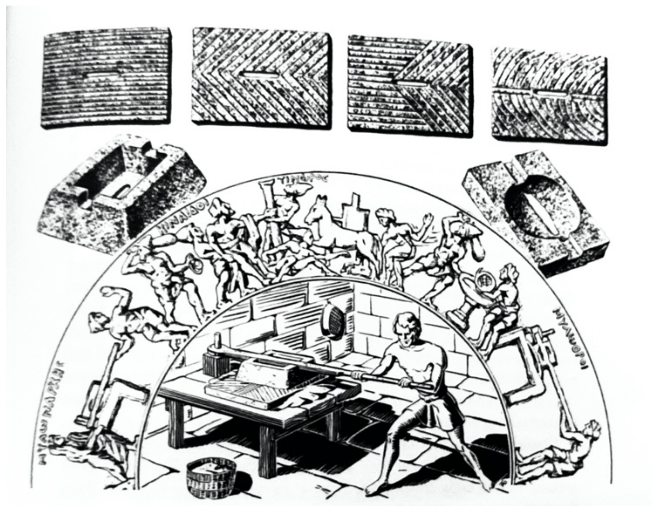

Figure 4: Diagram of an Olynthian Mill with hopper.[61]

The next innovation reflects a desire to achieve greater efficiency by harnessing circular motion. The resulting mills, conventionally called the Pompeian type because of the many examples found at Pompeii, were at first powered by beasts. The Pompeian mills consisted of a bell-shaped *catillus* (or spinning part) and a conical meta (or stationary part). By hooking up a donkey to the spinning *catillus*, the rubbing of the stones together would then grind grain fed from the top.[62] These types of mills, so called because of the many examples found at Pompeii, were probably not developed by the Romans, however. Probably originating from the Eastern Mediterranean, "The rotary donkey-mill was certainly known by 160 BC and probably about 185 BC."[63] While the donkey-mill may not have been first made in Rome, the Romans definitely

[61] Thurmond (2009) 39.
[62] Moritz (1958) 87.
[63] Moritz (1958) 74.

spread this technology far and wide in the centuries after its first appearance. While these animal-driven mills required more sophisticated equipment, millers could employ them even in small places like cities: "animals were in antiquity harnessed so close to their mills that their use could only be ruled out if the distance between wall and mill were smaller than the width of the animal."[64] Thus, such mills occurred in dense cities such as Pompeii.

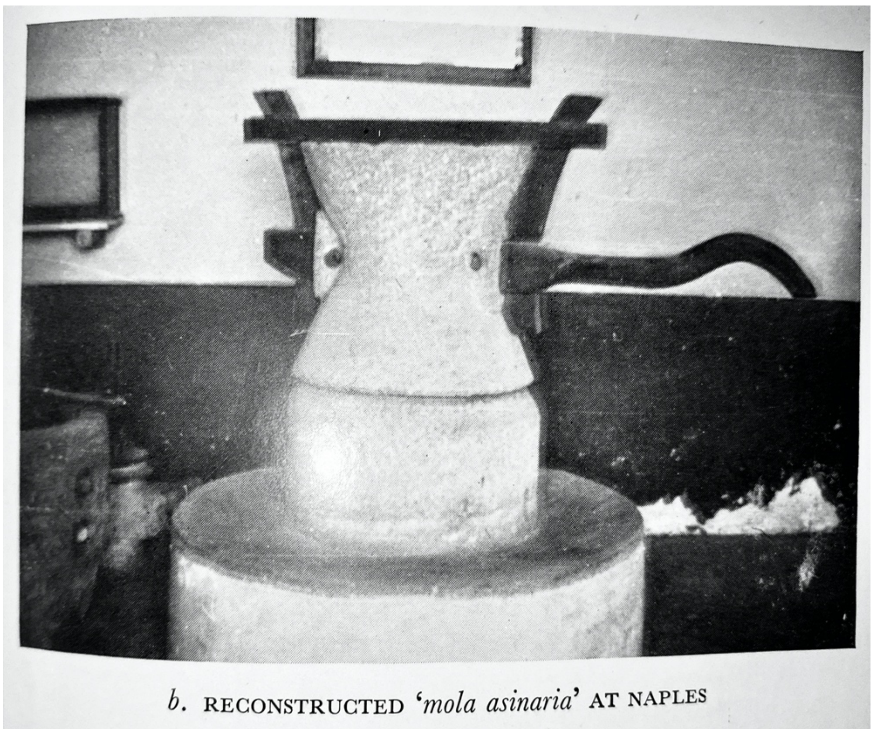

Figure 5: Reconstruction of a Pompeian Mill with harness for donkey.[65]

While the Romans may not have invented the animal-driven Pompeian mill, they certainly became the most important adopters of this technology. Williams and Peacock point out that while "Roman households may have had one or more small rotary querns for domestic use, … the Pompeian style mill was essentially a piece of specialized equipment used to produce

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[64] Moritz (1958) 98.
[65] Moritz (1958) 64.

commercial-scale quantities of flour."[66] Now, instead of people relying on small saddle-querns, the sue of Pompeian mills allowed for the "commercial" production of flour – meaning citizens could have their grain milled at a centralized place instead of having to do it themselves. The Romans used these larger, more efficient mills to provide flour to their dense population centers across the empire. The design did not spread across the empire alone: "The existence of Pompeian mills in Narbonese Gaul is no longer to be doubted … Orvieto appears to be the source of the Pompeian mills found in the metallurgical sites of Languedoc at Froges."[67] While the mills in this case was used for the metallurgical purpose of crushing mined ore, they nevertheless demonstrate that the technological ideas (and even the materials required to make it) spread from areas near Rome to more distant provinces.

Despite the prevalence of Pompeian mills across the empire, the hand-quern still persisted – because, as noted already, the larger Pompeian mills were more efficient for densely populated areas. Roman hand mills have been found in many places, likely because "While Pompeian style mills or water mills have a long life, the hand mills would not and a relatively short life might explain the fresh appearance of milling on many of the [saddle] querns."[68] Despite the facts that hand mills are more likely to appear in the archeological record because of their frequent replacement, hand mills still had important use cases for the Romans. In the legions, for instance, a portable mill "could process 4 kg of wheat in an hour (4.71 ration-equivalents); in other words, it takes almost an hour and forty minutes to process the daily ration of the *contubernium*, or 6.8 kg" (Jodry, 87). Thus, one hundred minutes of work

[66] Williams and Peacock (2011) 117.
[67] Jaccottey and Longepierre (2011) 103
[68] Williams and Peacock (2011) 120.

per day could feed a squad of eight Roman soldiers. Twelve and a half minutes per person per day (not including cooking, however), is a fairly efficient use of time. While the Pompeian mill became vital to the high-demand dense cities of Rome, the use of smaller hand-held mills persisted along side.

Thus was the landscape of Roman milling – the use and propagation of various technologies, new and old, across the empire. We know that Romans likely preferred to consume leavened bread, the product of milled grain. But to answer the question of how the Romans consumed their grain in the city of Rome, we must delve deeper into the use of geared mills. The efficiency of such mills, especially in densely populated areas, is clear. It was "found in practice that a long handle was needed at which four to six men could work, who could then grind 100 kg of grain in an hour."[69] Such a mill is about five times more productive (in terms of man-hours) than the legionary hand mill discussed above. Yet the most dramatic innovation of the mill came with waterpower.

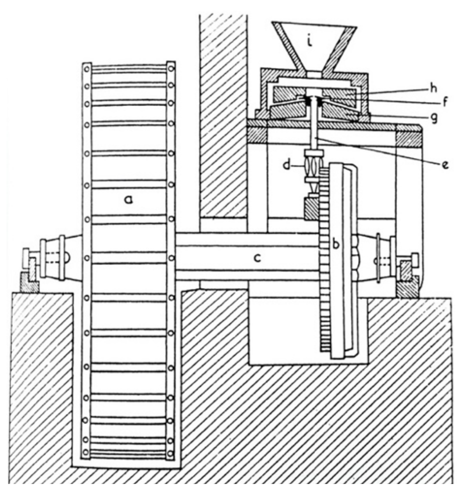

Figure 6: Diagram of a watermill described by Vitruvius.[70]

[69] Moritz (1958) 126.
[70] Thurmond (2009) 47.

While earlier scholars have dismissed the innovative capabilities of the Romans, citing "that the cheapness of human labor, and the wide social gulf between those who had work done for them and those who did it, meant that there were few incentives for finding methods of easing such work or making it unnecessary for human beings to do it at all," the Roman development of the water mill indicates a strong culture of innovation.[71] The origin of the water mill is not set to an exact time or place, but "must have existed by Augustus' time, and probably half a century earlier."[72] The area of invention is also unclear, as "The earliest archeological evidence points to a western, even Italian, innovation, but the (slightly earlier) literary evidence argues for an eastern origin."[73] As with the invention of Pompeian mill, the credit cannot necessarily be given to the Romans. Nonetheless, the Romans certainly became early adopters of the technology and later spread it across the empire.

While we have archeological evidence of water mills in the form of mill wheels, we know of the entire configuration from the historian Vitruvius. In *De Architectura*, Vitruvius describes the mill sketched in the above figure: "Mills are turned on the same principle, except that at one end of the axle a toothed drum is fixed … Adjoining this larger wheel there is a second toothed wheel placed horizontally … Thus the teeth of the drum which is on the axle, by driving the teeth of the horizontal drum, cause the grindstones to revolve."[74] This account of a water mill by Vitruvius not only serves as evidence of water mills as a technology but also highlights the use of gearing in these mills to transfer motion – another huge innovation.

[71] Moritz (1958) 143.
[72] Moritz (1958) 134.
[73] Robert (2001) 350.
[74] Vitruvius, *De Architectura*, 5.2.

Beyond the water mills appearance in the empire, the progress of its widespread acceptance and use is also unclear: "The earliest literary evidence, therefore, dates to the first century BC and portrays the water mill as a novelty."[75] Like all new technology, the water mill took a while to become mainstream. For instance, Moritz refers to Suetonius' *Caligula*: "In AD 39 or 40 Caligula could still endanger the city's bread supply by commandeering the mill-animals," indicating that the animal-driven Pompeian mill still held a vital place in the Roman food supply.[76] Yet at some point, the use of water mills surpassed the use of animal-powered mills: "in Rome at least there were by the sixth century not enough of them to fulfil the needs of the population when the water-supply of the Janiculum was cut by the Goths."[77] Literary evidence therefore indicates that the watermill became an essential tool in feeding the city of Rome during the period of the empire. And eventually the water mill became a huge enterprise. For instance, an archeological find near Arles, France revealed a huge mill – the Barbegal Mill. With sixteen mills fed by a river diversion, this huge complex could mill grain for tens of thousands.

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[75] Robert (2001) 349-350.
[76] Moritz (1958) 135.
[77] Moritz (1958) 139.

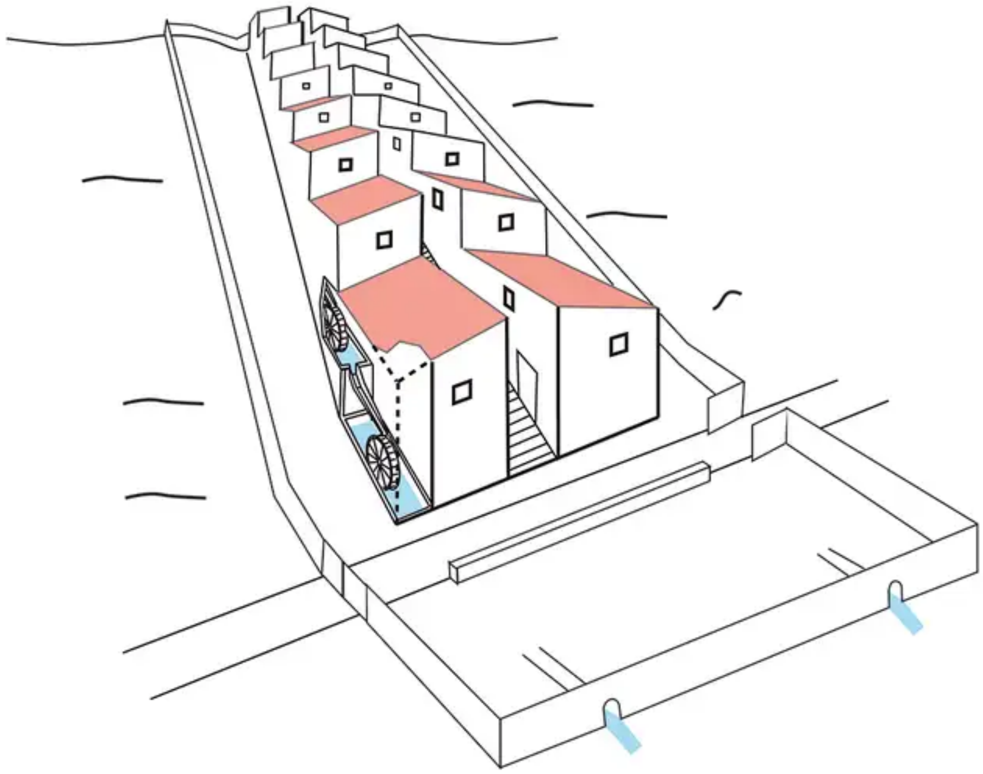

Figure 7: Diagram of the Mill at Barbegal. https://www.newscientist.com/article/2178696-a-huge-water-powered-factory-helped-make-food-for-roman-sailors/.

The importance of the watermill to the Romans is clear. But the water powered mill took many forms and went through various stages of development. The three main types of wheels are horizontal, undershot, and overshot. Horizontal watermills were horizontal wheels driven by the movement of water coming from the side. Undershot and overshot mills were vertical wheels driven by water on the lower side for the former and water over the top for the latter. These differences in setups came about as adaptions to what water sources were at hand: "Horizontal and overshot wheels are better suited to a limited water supply and a high head; the undershot wheel to a larger supply and a lower head."[78] The efficiency differences

[78] Wikander (2000) 378.

are small but still significant, with horizontal watermills having about 8% greater power than undershot mills and overshot wheels having about 10% more power than horizontal mills.[79] Horizontal mills have the least efficiency since they only utilize the power from the water flow – but their horizontal configuration creates large friction loses at the axis. The undershot vertical mill gets rid of this problem by allowing an ideal axis configuration, but it still only harnesses the power of water flow. The overshot vertical mill then improves the power of the water by using the energy from its movement as well as converting its potential energy into kinetic energy though the vertical drop of the water. Regardless of the small differences between types, however, the average horsepower of these mills is about 5.4 hp.

Regardless of type, therefore, the replacement of manpower (with a human able to maintain 0.1 hp consistently) or animal-power (with a donkey able to produce 0.3 hp consistently) in favor of waterpower marked an enormous increase in efficiency. Water, a power source fifteen to fifty times more efficient than previous sources, also had fewer maintenance costs despite probably higher up-front costs. While engineers had to spend a lot of time and money to make these mills, the completed construct could passively work by harnessing the power of water. The saddle quern and donkey-powered mills had lesser construction costs but required the maintenance of a living being to operate.

Interestingly, the construction of water mills seemed to follow a similar set of measurement constraints. "Most powered stones from Antiquity have dimensions between 55 and 85 cm."[80] These measurements were probably constrained by output on the low end of

[79] Wikander (2000) 378.
[80] Wikander (2000) 392.

sizes and weight of the stone on the high end. The water wheels also seem to have fallen in a range: "No actual remains of overshot wheels have been preserved, but at four sites their diameters can be ascertained … 1.95/2.01 m (Baths of Caracalla, Rome), 2.20 (Barbegal), 2.60 m (Ephesos), and 3.24 m (Agora II, Athens)."[81] This range, again, was probably bounded by the wheel having to be large enough to mill a practical amount of grain and the inability of water to move a behemoth wheel. While we now can explain the similar sizes of both millstones and water wheels, it is also possible that a spread of knowledge for sizes accompanied the spread of the water mill technology itself.

Milling became an essential step in the Roman grain supply. While the cooking of un-milled grain into porridge sufficed as a food source, the eventual move of the dole to bread indicates that bread became the main food source for the city of Rome. The benefits of bread over porridge is clear, but the milling of so much grain into flour for bread posed a problem. Thus, developments in milling became very important for the Romans. While hand-powered smaller mills remained in use, the larger commercial mills started to move on from animal power to waterpower. With waterpower yielding orders of magnitude more efficiency to the milling process, their incorporation into the Roman food supply was an enormous innovation. The use of waterpower to process grain in the Roman Empire marked a large-scale adopting of innovation that indicates a desire to increase productivity – and a willingness to invest in infrastructure.

[81] Wikander (2000) 388.

Consumption

Thus far we have discussed the Roman diet (with a large emphasis on grain), the locales from which Rome sourced grain, and the methods by which the grain was processed on a large scale. So, the final question is how did the Romans consume their grain? And in analyzing how they did so, we will also look into the way in which the Romans innovated these modes of consumption to provide for an ever-growing urban population. In our discussion of grain mills, we covered why mills existed in the first place – leavened bread had obvious benefits over porridge and other forms of edible grain. In this chapter we will discuss further why leavened bread was the ideal way to consume grain (and likely was the most common form of grain in urban Rome). We will also discuss where the Romans procured this food – and how the institutions built around distribution were innovative. To make bread, large mill-bakeries consolidated production and increased efficiency - but required a large start-up investment. After the bread was baked, most Romans received their ration at local *taberna* shops in the city. These *taberna* in turn were supplied by large-scale bakeries (and thus the large-scale mills as well). We know these mill-bakeries produced bread in large quantities from evidence of carbonized loaves in a Pompeian bakery.[82] The movement of these loaves from the bakery to the mouths of urban dwellers then proceeded through the *taberna*.

After the arrival and milling of grain at Rome, there remained a few steps before the result became edible. Two sources of archeological evidence shed light on the subsequent processes: the tomb of Eurysaces and a mill-bakery discovered in Ostia. The find of the tomb of

[82] Thurmond (2009) 71.

Eurysaces, a Roman mill-baker, sheds light onto the whole process. The relief shows the receipt of the grain in Rome and the subsequent milling (after the receipt had been recorded by an official). The next steps necessary to turn the milled grain into bread were sieving, kneading, and baking. After the baking of bread, the last step was distribution to the public. After the grain arrived in the city, officials recorded what arrived to account for the upcoming grain dole. Then the grain was milled and sieved to assure the production of bread-quality flour. The flour was made into dough, kneaded (mechanically!), and made into loaves before being baked. After the bread was baked, the bread was moved and weighed so the same officials could ensure a proper yield before the bread moved on to the final steps of consumption. To get a better idea of how the milled grain was transformed into bread, this chapter will begin by focusing on sieving.

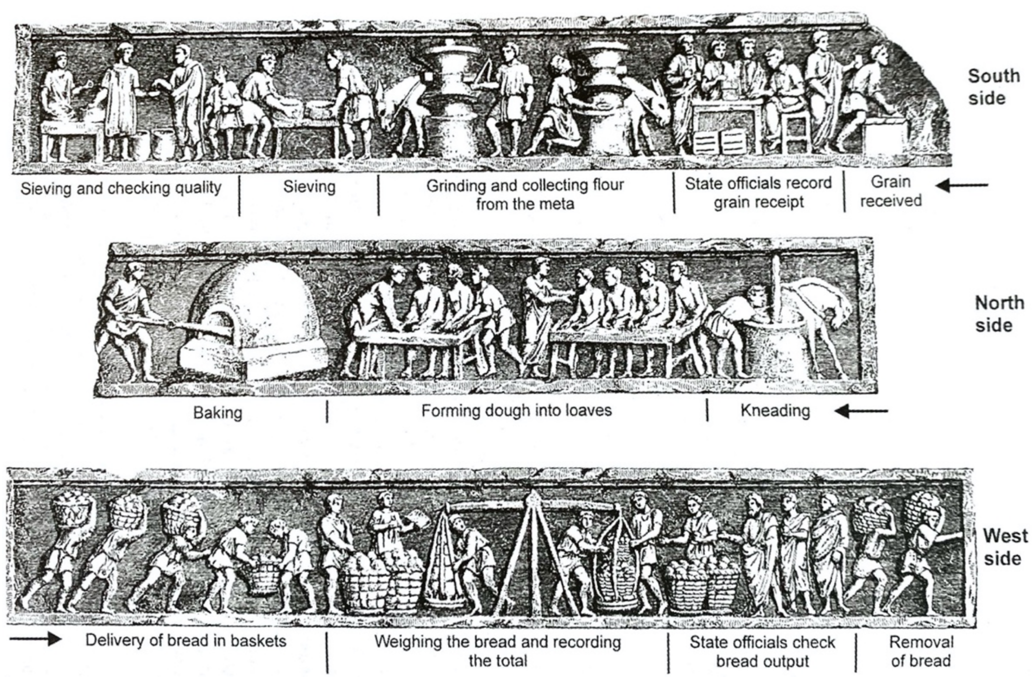

Figure 8: Tomb Relief of Eurysaces.[83]

[83] Thurmond (2009) 58.

While the relief on the tomb of Eurysaces gives a good overview of the whole process, the archeological find of a mill-bakery in Ostia offers an even more detailed insight into these large-scale facilities. The figure below shows a floor plan for the mill-bakery in question. While all archeological finds of mill-bakeries are not the same (and even the one in question demonstrated changes throughout the centuries), the floorplan demonstrates a very large scale of production. The large space contained five kneading machines (marked k1 through k5), eight mills (marked m1 through m8), and a massive oven (marked 9). [84] The enormous scale of the building indicates a large through-put of grain and the ultimate production of a large quantity of bread. Mill-bakeries such as this example in Ostia demonstrate that the Romans made innovations in their grain economy by consolidating bread production to increase efficiency.

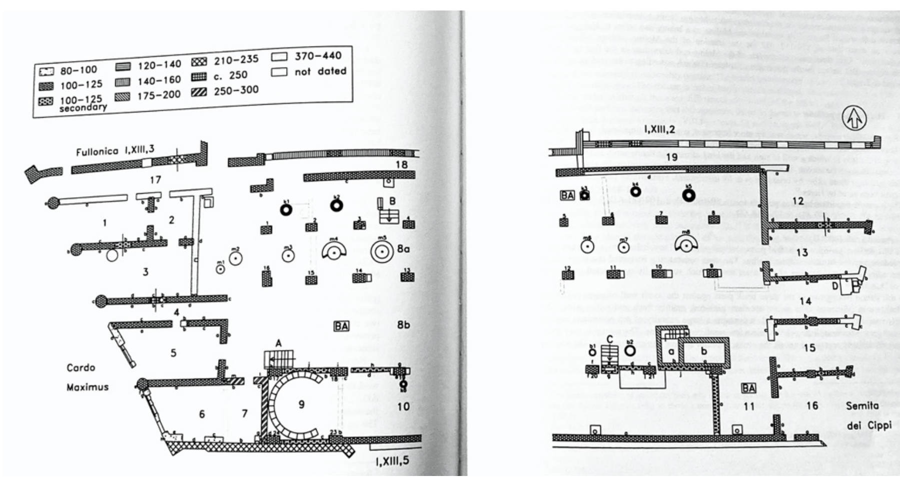

Figure 9: The floorplan of a mill-bakery in Ostia (Bakker 62-63).

The difference between porridge and bread is the method of cooking. But with a huge variety of breads and cooking methods, further steps had to be taken to reach the ideal form of grain consumption. Even after the winnowing and threshing, the first milling may not have been enough. In fact, a second milling of the resulting grain was likely to achieve a finer

[84] Bakker (1999) 62-63.

quality.[85] By further grinding of the grain, sieving could achieve a much finer flour, which reduced impurities and improved the resultant leavened bread. The final flour may even have been supplemented with the flour of legumes and other crops. The result of such supplements, while perhaps aiming at increasing the weight (and therefore value) of the grain), had the effect of improving the nutritional quality of the flour as well. In fact, "the principle of combining cereal and leguminous flours to produce more 'composite' flours has been understood empirically for millennia … provide an adequate balance of protein precursors in the human diet."[86] Thus, flour was no simple matter. The granularity of the flour, its combination with other flours, and other variables made a huge difference in the resulting bread's quality and nutrition.

Another important aspect of flour, which we hardly notice today, is its color. Normally, "freshly milled wheat flour has a pale yellow or cream color."[87] While starting out as pale yellow the flour bleaches naturally through aging. Color may appear as only aesthetic in purpose, but the change in color after aging also effects quality of the flour. During aging and bleaching, "improvements in baking properties accrue gradually over time until they reach a peak and begin to decline."[88] Issues with newly milled flour, such as bad odor or flavor, are removed through aging because of certain chemical changes that take place over time. While it is uncertain if the Romans took the time to age their flour – a process today which takes place

[85] Thurmond (2009) 55.
[86] Thurmond (2009) 56.
[87] Thurmond (2009) 57.
[88] Thurmond (2009) 59.

over a period of six months – we can assume they did because of the obvious benefits to color, taste, and overall quality in the bread that Roman bakeries produced.

After making the ideal flour through multiple millings, sieving, and the application of an aging process, the next step involved the leavening of the bread. While bakers today make white bread through the mixing of bread dough as a mixing of flour, water, and pre-packaged yeast (among other things), the Romans likely instead made a kind of sourdough bread.[89] The main difference – in preparation - between white bread and sourdough is the origin of yeast and the rising process. While white bread comes from a specific source (today packages in powders from one strain of yeast), sourdough uses yeasts that exist simply in the air. By exposing the flour and water mixture to air, yeasts from the air start to grow in the mixture. The process of making sourdough was accessible to – and therefore likely the only form of bread for - the Romans.

But ease of production was not the only benefit that sourdough gave to Roman consumers. Sourdough gets its sour flavor from the production of higher lactic acid production through naturally occurring airborne yeasts. The higher acid content does impact the flavor, but "In addition to lowering pH [i.e. making it more acidic], sourdough ferments make the minerals of wheat doughs more available to human digestion and also inhibit spoilage ferments."[90] By creating a more acidic bread, these yeasts actually make available more nutrition for human consumption while also creating an environment that is less hospitable to bacteria and other spoiling agents. Therefore, when we think about Roman bread, we cannot

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[89] Thurmond (2009) 59 (referring to Pliny the Elder's *Natural History* 18.27).
[90] Thurmond (2009) 59.

imagine quickly degrading Wonder Bread. We have to imagine a stauncher, longer lasting, and denser sourdough bread.

The next step in the process, as demonstrated by the relief on the tomb of Eurysaces, is kneading. Interestingly, the depiction of kneading is unlike the modern-day conception of hand-kneading on a table. In fact, the depiction of kneading demonstrates the use of a mechanical kneader. And such a device did actually exist in Roman times. The kneading machine used in Roman mill-bakeries was animal-powered and pushed the newly formed dough through a rotating motion of teeth in a process upon which "Modern commercial kneading machines are based."[91] Pictured below is a plan of the Roman kneading machine.

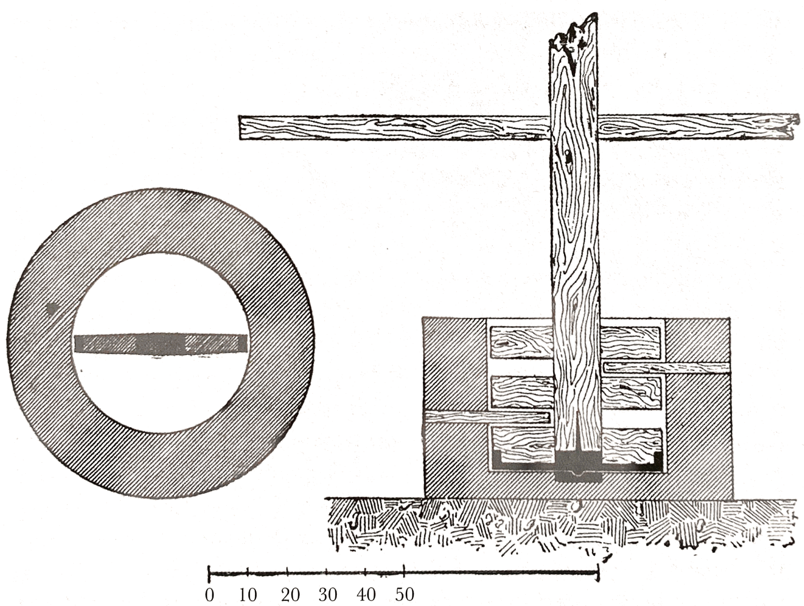

Figure 10: plan of the Roman kneading machine.[92]

By using such a kneading machine (the earliest evidence for them originating from a Pompeian mill-bakery) the Romans were able to innovate the grain supply by more swiftly transforming

[91] Thurmond (2009) 66.
[92] Thurmond (2009) 67.

their grain into bread at much larger scales than was achievable by hand-kneading.[93] The mill-bakery in Pompeii had eight such kneading machines.[94] As the kneading space was approximately a cylindrical volume of two feet in diameter and two feet in height, we can remove the approximate volume of the kneading parts (let's say half the total volume conservatively) to find each kneading machine had a little over three cubic feet of capacity for dough.[95] Kneading by hand, alternatively, can take even longer and can only process a fraction of the volume (around 0.3 cubic feet in my experience). Therefore, kneading machines proliferated during the Roman Empire, with eight such machines appearing in one bakery alone in Pompeii. The use of such machines represents an increase in productivity by a factor of ten or more. And if animals drove these kneading machines (and there is in fact evidence that the same animal drove the grain mill and the kneading machine simultaneously by rotating a common drive shaft),[96] then the savings in labor were immense. The Romans invested heavily in innovation of kneading technology.

Next comes baking. In terms of baking, the Romans use much of the same equipment that is familiar today. Large brick ovens heated with burning wood to create large, quite hot cooking spaces capable of cooking many loaves at once. An important factor in Roman baking, a factor which is still important today, is the amount of rising that the bread does before baking. Using various techniques, like coating the mound of risen dough in water, Roman bakers could achieve "as much as 30%" increase in volume of their bread.[97] While the Romans

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[93] Thurmond (2009) 65.
[94] Bakker (1999) 7.
[95] Robert (2001) 362.
[96] Thurmond (2009) 66.
[97] Thurmond (2009) 71.

still measured the market value of bread in terms of weight, the volume and airiness of the bread were, as they are today, highly valued. Another interesting technique to achieve such rising was the cutting of the bread using "a mode still practiced in craft baking today: lines are incised with a knife in the top of the risen loaf, first in the form of a cross, then in the interstices of the cross. Such lines facilitate division of the crusty loaf and assist over spring [i.e. the amount of rising during baking].'[98] The baking process for the Romans was very important. While the preparation of the dough ensured the nutritional and baking potential of the bread, proper baking resulted in palatable, properly cooked breads that made bread an appealing way to consume grain.

The process of baking we have discussed thus far was undertaken on a large-scale, commercial level. While private ovens may have existed for baking bread (and private braziers for making porridge certainly did), "Ovens in private houses at Pompeii are uncommon, likely due to the existence of public bakeries, which provided much of the bread consumed by the city."[99] We can assume the same for Rome. Such commercial baking certainly has the merits of efficiency and low costs. Since ovens were so expensive to make and operate, such consolidation was necessary to produce large quantities of bread. The innovation of consolidating baking was thus an important development in the Roman food supply. While it unclear where the grain came from to provide for these bakeries (specifically whether the grain was purchased by the bakery or was collected from various citizens from their grain dole), the result is clear: the majority of urban dwellers lived off bread that was produced in large-scale

[98] Thurmond (2009) 71.
[99] Ault (2015) 210.

mill-bakeries. And while these bakeries may have been privately owned and operated, we can see evidence of state involvement in baking from the tomb of Eurysaces. The relief depicts officials recording the received grain before sending it through its transformation into bread and then recording it again at the end (likely to confirm it was all baked). The involvement of state officials in this relief indicate that the mill-bakery depicted in the tomb of Eurysaces likely processed grain destined for the public dole.

The final step in the food supply was the actual selling of the bread to the Roman people. Just as most of us today do not buy our bread (along with any of our other food) directly at the source (or bakery), Romans did not procure their bread at the source of the bakery. Enter the *taberna*. The Roman *taberna* started perhaps in Athens as "the permanent, usually rectangular, module in which storage and negotiation took place besides the private life."[100] These shops were intermingled into residential areas of the city and therefore provided services such as food very close at hand. Usually attached to the *domus* of rich urban dwellers, the *taberna* was the modern-day equivalent to a small restaurant, bar or convenience store, their array of products varying widely. While these *taberna* initially started as more luxurious shops, "By the last days of the Republic, however, the *tabernarii* [those who frequented the *taberna*] had become almost synonymous with the urban population."[101] The shift from higher class personas to lower-class "urban" peoples marks an important shift in the purpose of these establishments.

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[100] Purcell (1994) 660.
[101] Purcell (1994) 661.

The sheer number of *taberna* in urban centers is intriguing. Monteix, studying *taberna* in Pompei, identified 158 *taberna* in the city.[102] While he notes that there were differences in what these different *taberna* likely sold (with 24 likely serving exclusively beverages), we find a density of around 125 *taberna* per person in Pompei.[103] If such a density of *taberna* was consistent in Roman cities, Rome would have a staggering 7,900 *taberna*. These vendors of food were highly innovative because they brought a food source extremely close to many people in the city.

The shift of *taberna* from the shops of the wealthy to those of the ordinary urban public meant an important shift in the food supply of Rome. Purcell claims that freed slaves started to work the *taberna* and that such movements to the *taberna* "preserved both the stigma of the servile associations of his employments and with it the minutely subdivided tasks characteristic of slave households [i.e. baking] … baking became a trade rather than a domestic service."[104] The shift of the city of Rome from a concentration of wealthy and powerful aristocrats to a larger population of urban dwellers meant that centers of trade started to shift to providing for this growing population. As the population of the lower strata burgeoned, the *taberna* served as an important source of nutrition for urban dwellers. And the flow of freed slaves (which at this point may have comprised one third of the population of Rome) into this profession also the stigma of being a freed person also stuck. But this social shift also marked an important change in the food economy that allowed the lower classes to access a consistent and nearby food supply.

[102] Monteix (2015) 220.
[103] Using the accepted population of 20,000 in Pompei at the time of its destruction and preservation.
[104] Purcell (1994) 663-664.

Furthermore the distribution of bread at *taberna* may also have taken on a political twist. In a Pompeiian fresco, a politician hands out loaves of bread.

Figure 11: "Sale of Bread" fresco in Pompeii.[105]

This fresco portrays a politician in a toga handing out loaves to common people. When *taberna* certainly provided much of the bread consumed in Rome for a price, there are also examples of politicians giving out bread. Such distributions could promote a politician's career while also supplementing the normal dole provided to citizens. Some grain may have been provided free by the state, and some may have been purchased at local *taberna*. These structures in the food supply allowed the lower classes to receive the quality diet we discussed earlier.

The "last five miles" of grain consumption in the city of Rome was an important area of innovation for the grain economy. We have interesting archeological evidence that shows the flow of delivered grain through complex mill-bakeries. These large-scale facilities could mill the

[105] Nguyen (2019).

grain, knead the dough, and bake the bread at far greater efficiencies than any individual. This concentration of labor indicates an important innovation in the food supply that freed the citizens of Rome to attend to other business. After leaving the mill-bakeries, the bread was then normally sold to citizens through an enormously dense network of *taberna*. These food shops, paired with bread distributions by politicians, allowed the citizens of Rome to have food close at hand. The final steps of distribution in the grain economy of Rome supported its enormous population by allowing for efficient bread production and easy access to distribution centers.

Conclusion

The Romans made a variety of remarkable contributions to world history. Their culture, organization, and language still impact us today. But in order to make such a strong impact on the world millennia later, their population needed food. The city of Rome at its peak was at a point of unprecedented population density. And the demand for bread from the city was answered by a complex and productive grain supply. And in order to improve the efficiency and productivity of this grain supply, the Romans innovated. While these innovations may have taken place over centuries, they nevertheless demonstrates a productive drive in the Romans.

The first innovations discussed in this paper are those of diet. The Roman diet was remarkably good. A well-rounded diet led to the sufficient nutrition that sustained the huge population of Rome. Various innovations to improve productivity, such as farming techniques, animal husbandry, and aquaculture, improved the variety and quantity of foods available to the Romans. All these factors added to the supply of foods that rounded the grain heavy diet of urban Romans.

And the Roman diet was grain heavy. Since grain was around 75% of the caloric intake for an urban Roman, the city required huge quantities to keep the populace fed. The Romans were able to source their grain from all over their empire, meaning they could choose the most productive breadbaskets as their main bread sources. Farmlands in Egypt and Sicily provided much of the grain in Rome. This transportation was made possible by a huge fleet of ships consistently making the journey across the Mediterranean. This trade network alone is an example of Roman innovation. Once the grain reached Italian waters, technological innovations, such as improved ports and complex storage, made the last part of shipping into

Rome possible. The innovations in the flow of grain into the city demonstrate a Roman desire to improve a complex system.

After the grain arrived in Rome, the transformation into bread began with milling. The Romans applied the innovation of animal power across their empire, saving large amounts of human labor. But the shining example of Roman innovation in milling came with the advent of waterpower in geared mills. Using gears to convert the water's energy into milling power is a huge innovation, saving even more human labor. With the concentration of mills in complexes (such as the Barbegal Mill), efficiency was improved further. The technological applications and innovations employed in milling is another area exhibiting the Roman drive for improvement and innovation.

Finally, after the transportation and milling of the grain, the "last five miles" included the baking and distribution of the bread. The Romans consolidated milling and baking into large complexes to improve efficiency. They invented kneading machines to vastly improve the productivity of kneading. They introduced state-sponsored grain (and later bread) doles that helped urban Romans received enough food to survive. And they cultivated a system of *taberna* to provide local access to the food supply for all denizens of the city. The combination of technological and logistical innovations in the consumption of grain in Rome demonstrate a drive for improvement.

This paper discusses a wide variety of innovations in the Roman world. From production to consumption, the Roman grain supply went through a series of improvements over times that allowed the dense metropolis of Rome to flourish. These improvements occurred over the course of millennia, but they nevertheless establish a trend of innovation by the Romans. And the grain supply is one small aspect of the Roman world. While grain had important roles in many aspects of Roman society, many more papers are written on the innovations of a plethora of other areas (the military, roads, architecture to name a few). The grain supply of Rome is an example of an area of innovations for the Romans and showcases their ingenuity, creativity, and drive for innovation.

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Illustration Sources

Figure 1: Map of Mediterranean with important areas for the grain supply noted. https://www.themaparchive.com/media/catalog/product/cache/1/image/b9d24ee63e043d9dae72d8cfeefe8ff8/A/x/Ax00599.jpg.

Figure 2: Map of the Tiber from Ostia to Rome. https://2.bp.blogspot.com/-is6hhD4mFyc/UdVsi6TIfyI/AAAAAAAAI1Q/SFGOZrapOf8/w1200-h630-p-nu/Ostia-Antica-map.jpg.

Figure 3: Irish woman grinding grain with a saddle quern in the early 1900s (https://www.mediastorehouse.com/mary-evans-prints-online/grinding-corn-saddle-quern-co-antrim-14365257.html?nochkip=1&pid=7046)

Figure 4: Diagram of an Olynthian Mill with hopper. Thurmond (2009) 39.

Figure 5: Reconstruction of a Pompeian Mill with harness for donkey. Moritz (1958) 64.

Figure 6: Diagram of a watermill described by Vitruvius. Thurmond (2009) 47.

Figure 7: Diagram of the Mill at Barbegal. https://www.newscientist.com/article/2178696-a-huge-water-powered-factory-helped-make-food-for-roman-sailors/.

Figure 8: Tomb Relief of Eurysaces. Thurmond (2009) 58.

Figure 9: The floorplan of a mill-bakery in Ostia (Bakker 62-63).

Figure 10: plan of the Roman kneading machine. Thurmond (2009) 67.

Figure 11: "Sale of Bread" fresco in Pompeii. Nguyen (2019).