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Abstract

Energy was one of the keys to the remarkable increase in English GDP between 1650 and 1700. Increased per head physical activity and basal metabolic rate led to increased energy consumption. In response, subsistence wages, productivity, wages and incomes increased. Malthusian adjustment explains only 50 per cent of the increase in calorie intake, the other 50 per cent is associated with higher energy consumption. Non-agricultural wages began to differ from agricultural wages. British economic development occurred everywhere, in the city and in the countryside. This approach opens new perspectives to the debate between enclosures and open fields and why underemployment became common among the philosophers' British debates.

JEL Codes: B11, J30, N13, N33, N53, N73, Q43, Q54

Keywords: Energy, physical activity, subsistence wages, incomes, wage gap, Malthusian trap, Seventeenth Century, England

1. INTRODUCTION

In this article we explore English economic history from energy. This approach allows us to open a new perspective and helps us to uncover some debates. Energy equals everything a human or animal needs to meet their energy needs, be it food, heating or related goods such as clothing or housing. Here, key elements were the increase per head in consumption and production of energy. If this need is not met, it affects health or the possibility of being active (one of these activities is working). If it is attended, it implies an improvement in productivity, income and health.

At the beginning of this story, the unusual cold and wet period during the 17th and early 18th centuries was one of the worst climatic depressions in the history of England in the last four hundred years. This climate problem was recognized in many agronomic works of the time (John Mortimer 1712, Robert Plot 1676), or in diaries and registers[1]. The climate crisis negatively affected land yields in the short term, leading to an increase in soil organic matter, but also helped to accelerate change in the agricultural sector and yields. Climate impacts accounted for about half of the variations in wheat yields, the rest came from nitrogen-fixing plants, better crops and seeds, and better work (Allen 2008, Martínez-González & Beltrán, 2020). Farmers' efforts were good enough to withstand the cold phase and continue to make progress in soil fertilization. On a trial and error basis, they discovered that the new methods adopted were more productive and profitable than their old methods. Thus, the slow English agrarian revolution was probably more of a discovery than an invention, induced by a combination of climate challenges and market incentives (Tello et al. 2017).

However, the issue of climate remains a controversial one (Hoyle 2018). Furthermore, there is a small historiographic tradition that has studied its effects on the most obvious aspects such as agriculture and population, but not in human behaviour on energy and labour. Recent research seems to show that a decrease in temperatures and wetter environments generate a significant increase in the metabolic rate of people and their daily activity (a substitutive of thermoregulation; see the following section). But on the other hand, with new agricultural methods and improvements, with the need to ensure

[1] Ralph Josselin's, 1640-1683; Locke 1666, 1667, 1681, 1682 in Oxford, 1669-1675 in London; Robert Hooke, 1672-1673 in London; Phillip Skippon, 1673-1674, Sufflok; Samuel Clarke, 1658-1686, in Norfolk; William Turner Comber, 1808 or Thomas Tooke, 1838, see Joyce Macadam, 2012.

self-sufficiency, political instability, growing urban demand, or with also a declining or stagnant peasant population, farmers and draught animals had to work harder. All this would lead to a sharp increase in the demand for energy per head, productivity and wages.

Nevertheless, in a historical context of climatic depression, these effects have been little studied. The absence of research has led to an omission that overestimates the role of urban and trade demand (although we agree that it was the main factor). Let us analyse for a moment the argument of a growing urban demand, pointed out as the main engine of yields and agricultural production. If in the second half of the 17th century, the population declined, and the foreign sector was still small, the urban demand for food per head had to be very high to compensate for the demographic fall, and even more with the rural demographic fall. However, this is difficult to sustain. Following Wrigley (1981), between 1657 and 1686 the population decreased by 419,205 people. Assuming a per capita consumption of 7.12 bushels per year of bread wheat[2], this implied a decrease in demand by 3 million bushels of wheat (11 per cent of the average annual English production between 1645 and 1700, see estimates by Martínez-González, Jover et al. 2019)[3]. In fact, it was the opposite. According to our calculations, in 1657 there were 32.8 million gross production of wheat bushels, and in 1686, 35.3 million, this is, 2.5 million more. On the other hand, between 1670 and 1700 the English urban population grew by about 170,000 people, 5,667 people per year, a sustained growth thanks to immigration. For national demand to have been maintained (only maintained), the urban population should have increased its consumption of bread wheat by 17.6 bus. per head and year, that is, 2.5 times more than its previous average consumption (going from consuming 7.12 to 24.72 bus.). The differential between the daily wage of a London labourer and one outside London (Southern England) was only 1.5 times greater (J. Chartres 1986, p. 171). With income elasticity less than one unit, any increase in real income especially stimulates demand for secondary and tertiary sector goods more than agricultural ones (Wrigley 1985, p. 684). Thus, this radical increase in wheat consumption, mainly in London, was unfeasible. Furthermore, according to Wrigley, between 1670 and 1700, the English population fell by 5,096 people. If the

[2] Chartres (1985), citing C. Smith, said that wheat consumption for bread was 0.89 quarters per capita per year in London and South-east. One quarter is equal to eight bushels.
[3] Let us assume for now that there is an equivalence between bread and wheat. Later we will develop this difference a little more.

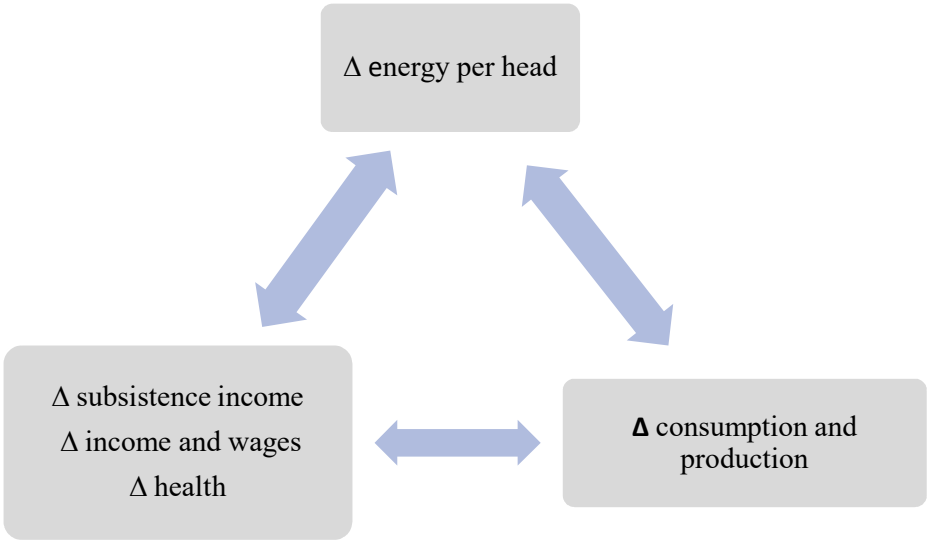
population of London was about 530,000 souls (King gave that figure for 1695), the population in the countryside fell by 175,096 people. That is, in London it grew by 170,000 people and in the rest of the country, it fell by 175,096 people. Logically, all these calculations are certainly very imperfect, but we can see that it is impossible to explain an increase in total demand only from the cities. Consumption per head should have grown everywhere, and in the countryside as well.

As we just said, these calculations are simple, but they illustrate that we cannot entrust everything to the issue of urban demand. This idea is nothing new, although it has been relegated by the mainstream. For example, Everit (1966) criticized the idea that economic change in the southern counties was due exclusively to London: “Even the demands of a town of half a million people were not inexhaustible. Though incomparably larger than other towns, London was, after all, no more populous than modern Sheffield (…) For every person within it, there were ten or a dozen in the provinces to be clothed and fed”. Thus, the increase in productivity and agricultural production cannot be explained by urban development alone between 1650 and 1700. There had to be something else. It also had to come from rural areas or villages. They were less, but they ate more, had more energy or distributed it better, as was the case in urban areas. Exports, although useful, were not a permanent general stimulus factor in the period. The discontinuity of harvests and the government's stimulus policies did not allow a very relevant weight of external demand. Between 1700 and 1709, exports were only 2 per cent of the total produced (John 1968). It was not until the middle of the 18th century that the golden age of cereal exports was reached (Ormrod 1985). If we only have the countryside left, how can we fit an increase in total rural demand for wheat into an environment of declining rural population, greater in proportion to the fall of the nation's population?

The purpose of this study is to learn more about the relationship between climate, energy and work. To be honest, it is a speculative exercise because we do not have much theory or research. In the future we propose new and deeper local explorations to economic historians. For now, to achieve this goal, we use a cross-sectional methodology that combines econometrics, primary sources, historiography and economic thinking, that is, everything we have within our reach.

Low temperatures and higher humidity cause an increase in the metabolic rate and activity of humans and animals. Therefore, the demand of energy per head increases. In rural and urban areas, humans expand their activity as a direct response to lower temperatures (an intrinsic and physical, off-market effect, as we will see later). A greater demand for energy and materials to maintain or protect the body implies more work and changes. Part of the physical work is a part of the sphere of the economy, say labour, because they need money, goods, services, or other mechanisms to increase or maintain their energy. Therefore, subsistence wages rise. The population needs more "goods – energy" and energy flows per head, and the agricultural and non-agricultural sectors require more labour to satisfy the needs (the demand for labour increases), so we conclude an increase in spending and production per head in energy-goods. Moreover, farmers in rural areas can increase the supply of calories, but an increase in nitrogen fertilization in the soil also improves the nutritional quality of the grain (richer in zinc, iron and selenium) and in urban areas gardeners also enrich the diet with new fruits and vegetables. Since the end of the seventeenth century, this has also improved the health of the population, reduced mortality, and increased the consumption of surplus energy for living and working. Until the improvement of health and calorie intake had been stabilized, the population did not re-grow, when the expenditure of energy on women during their pregnancy and lactation had been guaranteed, on average. Of course, all this in turn influenced wages and incomes. If the farmer is a little more productive but the prices of the grain he produces fall slightly, farm wages remain stable or rise a little (this also considering rural institutional constraints). If horses are more productive than oxen and people, horse prices increase more. If the rural sector needs more energy, and the value of the marginal product of the horse is greater than the value of a man's or ox's marginal product, the relative prices between horses (their price or cost) and men (their farm wage or annual income) or oxen (their cost) increase. Moreover, if the prices and productivity of non-food energy goods (cloth, fuel, heat, housing) increase, wages also increase in these sectors. In other words, in this paper, the worsening of the climate is associated with an expansion of per capita demand for "goods-energy", "work-energy", productivity, wages and income (along with other factors that we don't study here). In addition, in this paper we suggest that such an energy shock drives a divergence in wage growth between the agricultural and non-agricultural sectors. Also, it helps us to understand very well why open fields had a special productive role but also why they were in crisis.

However, here climate change is not the cause. It only accelerates changes and trends, as well as other reasons, if institutions and other factors allow it. We ignore whether it was an important or secondary factor, but in our opinion, it was at least significant. In any case, the remarkable increase in per capita income and GDP in this period is partly explained by this increase in per capita energy needs (Martínez-González, Suriñach et al. 2019). However, this does not mean that England became a paradise. During the latter part of the 17th century, deviating food consumption to a more caloric basket reduced the consumption of animal protein per head. In the short term, in the countryside, owners knew that it was advisable to increase subsistence wages if they did not want to jeopardize their rents and incomes. For this, they preferred to do so with annual contracts, a sort of "efficiency wage", which guaranteed their profits, and a way not to increase the cost per hour and increase productivity. But on the contrary, "marginalized" daily wages and generated underemployment and inequality, expelling those who were not "better" to seek employment in the city or non-agricultural activities.



The argument seems simple but it has very strong implications. Some contributions are the following. First, it broadens our understanding of how exogenous factors of the economy such as climate (or politics) accelerate the effects on societies in transition. Not only does it influence crops or demographic variables but also a key factor such as energy. In this sense, we used an interdisciplinary approach to advance in the understanding of the problem. Second, it links energy transition to economic

development, a path advocated by Wrigley, Kander, Warde, Malamina (2013) and others. An important novelty is the effort to connect a physical phenomenon around energy with the economic sphere. Third, the agricultural and urban revolution was also a manifestation of something deeper. People needed more energy, either to meet their metabolic needs or to work harder. Yeomen and landowners accelerated improvements to protect their families or their rents. In urban and non-agricultural activities, rising prices and productivity increased incomes, which explains in part the remarkable increase in per capita GDP between 1650 and 1700. It changes the idea of the origin of the economic change (whether it was agrarian or urban-commercial), when in fact it occurred everywhere. Fourth, it explains why and when non-agricultural wages began to diverge from agricultural wages and clarifies the debate between daily wages and annual income. Fifth, it explains very well why during this period a whole debate was opened among mercantilist philosophers on inequality, unemployment or underemployment. Sixth, clarifies that the Malthusian adjustment is only 50 per cent of the story. We agree with Kelly and O'Grada (2012, 2013) in their criticism of Broadberry et al. (2015) on their low calorie consumption valuation. Seventh, it helps us understand the behaviour of each of the actors, based on their energy requirements. There was a phenomenon of "energy seekers" in many aspects, for example, there was a trend to more caloric goods (grains), more energy was sought in the city, the horse became more and more important with respect to the ox. We found signs of energy attraction in London. Ninth, there is an important gap in the debate on enclosures and open fields in the area of wages and incomes. Here we try to understand the logic of this relationship through our approach. The productive success of the open and common fields was at the same time one of the causes of their decline. Tenth, only a general factor such as the increase in energy production and consumption per head could lead to structural change in England. This idea of change from the middle of the 17th century and of a general change, everywhere, from agriculture to other activities, not always urban, is well supported by the findings of Wallis, Colson & Chilosi (2018): in the middle of the 17th century there was a general structural change in England that did not occur in Wales. People left agriculture in most parts of England, both in the North and South, but not everyone went to the cities. The proportion of labour employed in industry and services increased substantially in both rural and urban areas. Most of the transition from agriculture was completed by the end of the 17th century. Above all,

however, this research must be understood as an attempt to capture and bring together the most important pieces of British success, because they must form part of a whole.

This chapter is organized as follows. First, we review the literature and carry out a theoretical analysis of the question. Second, we study the implications of what this literature and theoretical analysis predict. To do so, we use a methodology that combines the use of primary and secondary sources, as well as graphic and econometric support. In this part the results are presented and discussed. Finally, we conclude.

2. BACKGROUND AND THEORY

2.1. Definitions

Total Energy Expenditure (TEE), or total number of calories used per day, is composed of basal metabolic rate, physical activity, thermoregulation, growth, maintenance, immune function, reproduction and digestive costs. The importance of each of these components depends on body mass and height, age, sex, health status, reproductive status, level of physical activity and environmental factors such as temperature (Ocobock 2014, p.10, 30-31; Pontzer 2015, p. 169). Basal metabolic rate (BMR) is the minimum amount of energy required to sustain the life of a non-moving, non-growing, non-reproducing and non-digesting organism (Ocobock 2014, p. 9). In conditions outside the thermoneutral zone (22-26◦C for clothed human subjects) the metabolic rate is increased to heat or cool the body and defend a core temperature of 37◦C. This is thermoregulation. In addition, reproduction requires a lot of energy than usual. A negative energy balance, or failure to meet maintenance needs, can hinder growth and fertility (Froehle, Yokley, and Churchill 2013, in Smith & Ahern, p. 287). In fact, reproduction is very expensive for humans, with an estimated total metabolic cost of pregnancy of 78.000 kcal, and peak lactation costs of 630 kcal/day. The cost of lactation is offset by the mobilization of fat reserves, so that daily energy needs during peak at ~450 kcal/day, like the daily energy cost of pregnancy during the third trimester. Ellison (1990, 2001, 2003) and others have shown that human ovarian function is remarkably sensitive to energy availability and stress, reducing the likelihood of conception during unfavourable conditions. Mothers in traditional farming populations, with physically demanding lifestyles, may reduce BMR during pregnancy and lactation to keep total daily energy requirements in check.

2.2. Metabolic cold effects and short-term effects with mild cold exposure

Acclimatization responses to whole-body cold in humans are classified as hypothermic, insulating, or metabolic. If a cooling of the entire body occurs repeatedly, the main responses of adaptation to cold are to allow a falling core temperature before heat production mechanisms are initiated (hypothermic response), to increase the amount of insulation (insulating response due to a greater amount of subcutaneous fat and/or greater vasoconstriction), or the level of heat production (metabolic response due to shivering or non-shivering thermogenesis) (Mäkinen 2007, p. 158).

A large part of research focuses on exposure to mild cold because exposure to strong cold is very unanimous. Studies find that heat production was significantly higher at the lowest temperature: 7.0 +/- 1.1 per cent (mean+/- SE) between 28 and 22 degrees (Dauncey 1981) and 5.2+/-2 per cent between 22ºC to 16ºC (Westerterp-Plantenga et al. 2002). Claessens-van Ooijen et al. (2006) found a large variation that was around +30 per cent in winter. In Mäkinen (2006, p. 20), a decrease in temperature from 27°C to 22°C increased energy expenditure by an average of 156 kJ-°C-1, i.e. 798 kJ or 186 kcal. This might seem little, but a human spends 2,500 kcal a day, allocating 1,800 kcal to BMR, maintenance and digestive expenses, and 700 kcal to work. So, his working capacity is reduced by 27 per cent.

Van Ooijen et al. (2004, pp. 545-549) investigated the metabolic and temperature response to mild cold in summer and winter in a moderate oceanic climate. The average metabolic response during cold exposure, measured as the increase in kJ/min over time, was significantly higher in winter (11.5%+/-9.1%) compared to summer. The metabolic response ranged to an increase of 30 per cent in winter. Total heat production during cold exposure was inversely related to the temperature response in both seasons.

2.3. Long-term effects of cold exposure on total energy expenditure and activity

In cold conditions, peripheral vasoconstriction, non-shivering thermogenesis, behavioural responses and increased basal metabolic rate have been identified as physiological responses that help to maintain core body temperature despite low environmental temperatures. Ocobock (2014) measured total energy expenditure (TEE)

and compared it in temperate, hot and cold climates. In his research, he found that in cold climate, BMR was 26 per cent higher than temperate climate. Cold activity levels were 67 and 80 per cent higher than temperate and hot climates respectively. Cold thermoregulatory costs were 53 and 71 per cent higher, respectively. Comparisons within each subject for the different climates revealed the same pattern: cold climate thermoregulatory costs were significantly higher than that of temperate climates. The most remarkable difference in allocation breakdown between the climates is the proportion of TEE that is made up by activity cost. Activity comprises 36+3.6 per cent of TEE for cold climates compared to 21+4.7 per cent and 14+4.3 per cent in temperate and hot climates respectively. BMRs from the cold climates were significantly higher than those of the temperate climates. Activity took up a far greater proportion of TEE in cold climates than in either temperate or hot climates. Besides, environmental constraints lead to necessary energy trade-offs. Limited resources could simultaneously demand increased activity levels to gather resources while also reducing reproductive output. Cold climates produced both resource limitation and increased energy demand for both metabolically and behaviourally mitigating the harsh environment. Ocobock found that high levels of activity can mitigate the expected increased metabolic cost due to thermoregulation in cold climates. Estimated thermoregulatory costs without activity costs included were significantly higher than thermoregulatory costs with activity in the cold climates (29 per cent). This suggests that activity helps to lower thermoregulatory costs in the face of cold conditions. When zero activity is assumed, thermoregulatory costs were exceptionally large in cold climates, greater than 2000 kcal day-1. Like the laboratory studies, this suggests that heat produced through activity can be an effective means of maintaining core body temperature and reducing the potential metabolic cost of thermoregulation, particularly in cold conditions. Ocobock's research demonstrated that it is metabolically expensive to live in cold climates. Both basal metabolic rate and thermoregulatory costs were significantly higher in cold climates than in either temperate or hot climates. An unexpected result from this research was the amount of energy spent on activity in cold climates compared to the other conditions. Activity costs comprised 36 per cent of the total energy budget in cold climates compared to 21 and 14 per cent in temperate and hot climates respectively (Ocobock 2014, p. 153). Moreover, Daanen & Lichtenbelt (2016, p. 106), argues that in the cold, physical activity may increase to generate more heat, and according to Mäkinen (2007, pp. 156-

157), extra effort may be needed to complete the same task compared to a warm environment.

2.4. Effects of caloric intake on health and labour

On the other hand, mounting an immune response to infection requires energy **(**immune function). Muehlenbein et al. (2010), reported an 8 per cent increase in RMR (resting metabolic rate) among nonfebrile men with relatively minor respiratory tract infections. Torine et al. (2007) compared premature infants with sepsis to age-matched healthy controls and found 43 per cent greater TEE among those fighting infection (Pontzer 2015, pp. 176-177). Likewise, cold exposure is a significant health risk, because it is associated with several complaints and symptoms related often to chronic and cardiovascular diseases. Seasonal increases in morbidity from cardiovascular and respiratory diseases have been demonstrated in many studies (Mäkinen 2007, pp. 156-157). If this is what happens today, to the past we must add the multiplier effect of the lack of hygiene and malnutrition. Freudenberger & Cummins (1976, pp. 2-5) explain the abundance of nonworking time in the pre-industrial era because when well-fed workers were deprived of food their output fell relatively much more than their intake of calories. A reduction of 20 per cent in total intake implied a reduction of more than 40 per cent in calories available for other activities, including work. They also added that "conditions of health and nutrition before the Industrial Revolution were such as to restrict seriously people's choices of activities; that subsequent improvements were such as to widen significantly the range of choice; and that the special conditions of the time made it likely that better health would have increased the supply of effort. Moreover, we have reason to believe that the supply of effort could not have increased as it did without improvements in health". On the other hand, it has been found, just since the middle of the XVII century, a decrease in the height of people. This decrease has been associated with the increase in working days, the incidence of child labour, and inequality (Gallofré-Vilà et al. 2018). As we will see below, these phenomena are associated with an increase in energy needs per head.

2.5. Calorie intake, health, productivity and wages. Theorical and empirical perspectives.

So far, a somewhat harsher climate ultimately implies an increase in energy expenditure and activity per head and worsens the health of the population in the short term. This is not a thing of the past. This is also the case today. In the United States, poor and wealthier families increase their fuel costs in response to cold weather. Poor families reduce food expenditures by about the same amount as their increase in fuel expenditures, while wealthier families increase food expenditures. Poor parents and their children spend less on food and eat less during cold weather budget crises (Bhattacharya et al. 2003). Longer-term health is another issue. It will depend on whether this increased demand for energy leads to more real income or not, and here we find the big difference with the rest of Europe.

At this point, we wonder how this situation can affect productivity and wages (income). Recent economic literature argues that there is an inverted U relationship between temperatures and work. A colder and more humid climate causes direct physical effects or psychological discomfort in the short term. It reduces productivity, altering the marginal product of an additional hour of work, or provoking a variation of the effort per hour. However, in a utility model of work, it has been found a greater volume of hours worked and in effort with lower temperatures. In a colder environment, a worker can get warmer, resort to heating (if it is within reach) or consume more calories. They can also decide to work more intensively, rest shorter, adjust the hours worked and the effort according to the compensations they receive, whether in money, in kind, in maintenance or with a more comfortable home (Zivin & Neidell 2014; Seppanen et al. 2006; Heal & Park 2016).

In the previous section, we have seen how a cooling of the climate implies a growth in energy expenditure and generates an increase in activity, the latter phenomenon understood as something strictly physical. But how can we understand this phenomenon in the field of economics, how can we establish a connection between different scientific disciplines? At this point, a more formal analysis may be appropriate. In the short term, the producer only decides, in theory, on the use of the human and/or animal labour factor (figure 1, annex 1). An adverse climate, ceteris paribus, reduces the

number of workers from L" to L', so the product is reduced to Q' (extensive effect). However, there is a second effect that could go unnoticed: it also shifts the marginal product curve downwards, from Pmg to Pmg', because the available energy input per unit of work has decreased, leaving the final output at Z. This means that a climate impact has two effects (first from Q" to Q', after Q' to Z), the second of them being undetectable if we use L in man-units and not in kilocalories. Only with the aggregation of the two effects would the impact of the climate be fully captured. The logic of the above reasoning suggests that measuring (or analysing) labour force in man-units is insufficient: it must be done in energy-units. Can we isolate the effect of the impact on L (reducing Q from Q" to Q', and from L" to L') from the effect derived from the reduction of marginal labour productivity (reducing Q from Q' to Z, and the marginal output from Pmg to Pmg')? That is, can we differentiate the demographic effect (man-units) from the purely energetic (available energy-labour) effect? In this way, the incentive of the producer to improve his situation is even greater, expanding the cultivated surface or making it more productive with new methods, as well as the work force will try to recover its energy by increasing the intake of calories, improving its conservation with more heating and shelter or extending its offer by increasing working hours, compensating for the decrease in productivity. In this context, an excellent solution for the producer is to "imitate" the open fields, "creating community" through annual contracts, guaranteeing stability, higher productivity and a subsistence income for the peasants. But then the problem here is that it generates more unemployment or underemployment.

Let us analyse what happens in the “labour market” in more detail, understood as a partially non-monetary market. First, it is difficult to find a theoretical analysis of the problem. There are no more research studies here. We refer to an economic context in which agriculture is still the main sector and a significant part of the population lives at levels close to subsistence levels.

The basic idea is as follows. Imagine that peasants have a band of comfort in the level of temperatures, say, between 27 and 23 C. As we have been able to read in previous scientific literature, when this comfort band breaks, the human body reacts. If the temperatures are very low, it increases its calorie consumption to maintain the basal metabolism and increases its activity, because this activity compensates for the cost of

thermoregulation. On the other hand, if temperatures are very high, the body tries to maintain the temperature through sweating, inactivity, drinking more and consuming less caloric food. Until now, we have understood this reasoning, thanks also to the fact that there are many research studies. But what happens in the labour market when climate change reduces temperatures in an underdeveloped region, whose main source of economic activity is agriculture?

This is where the problem becomes complicated because it is very difficult to find something seriously reasoned. Searching though, we have found an interesting book by Harvey Leibenstein, an American economist and professor at the University of California, published in 1957. Leibenstein is one of the pioneers of the theory of efficient wages. The central theme of his book was the search for some of the reasons that led some countries to be trapped in underdevelopment. However, what interests me now especially about Leibenstein is that he establishes a clear relationship between income (or wages) and nutrition, on the one hand, and calorie consumption and productivity, on the other. The more income, the better nutrition; the better nutrition, the higher the worker's productivity. Bliss & Stern (1978) also find a clear relationship between calorie intake and work, through various empirical studies. In other words, the intensity of work per hour (effort or work units, as he describes it), depends on his level of energy, health, vitality, etc., which in turn depends on the level of consumption of the worker. Leibenstein then explains in various figures the relationship between wages and productivity, considering productivity per man-hour or per man, on the one hand, and productivity per unit of effort and unit of time (or physical work), on the other. With this he wants to distinguish between the fact that, normally, in the short term, the labourer dedicates a series of daily working hours, but within these hours he can devote himself more intensely to work if the hourly or daily wage is higher and vice versa. In any case, he comes to the conclusion that at very low wages there may be a labour deficit because the units of work (work intensity in our argot) produced by a labourer are very low (i.e. very low work intensity, or little effort), but at higher wages the units of work (intensity or effort) per man increase so rapidly that a surplus of work is created. For underdeveloped areas, this may mean that supposedly observed labour surpluses in agriculture do not exist when wages are very low (it is not worth working), but become a fact when wages increase sufficiently, so that not very high wages coexist

with unemployment or underemployment, something that was difficult to understand according to traditional economic theory.

This idea was the origin of the current theory of the efficiency wage. Some of Leibenstein's proposals were later worked on by Stiglitz (1976), when he studied the "paradox" in developing economies about the coexistence of unemployment with a positive (albeit low) wage for workers. While accepting the idea of rural institutional constraints in the form of "communal pressure", he concludes that there are important conflicts between equity and efficiency. For farms that are poor enough, full equality may not be feasible; maximizing family welfare may entail some degree of inequality. Low-wage individuals are less efficient than high-wage individuals. The presence of a positive wage (and a corresponding positive marginal product) for workers in a competitive labour market cannot be taken as evidence that labour is not surplus (as some authors seem to have done).

Although that is another story. Let us continue with a graphical analysis in figure 2, annex 1. In the vertical axis, we have the wages and the marginal productivity of labour. On the horizontal axis, the number of workers. MP1 is the curve of marginal productivity of the labour, it has this form because at the beginning, when workers are incorporated, the marginal productivity increases, but there is a moment moment when more incorporations no longer contribute more productivity, but it declines (although the total output continues growing). w1 is, on the other hand, the subsistence wage (or the level of real subsistence income, in the case of a poorly monetized economy). Point C where MP1 coincides with w1 represents the demand for labour (we assume that the owner will pay a maximum wage equivalent to the value of productivity, but no more).

Let us suppose now that the supply of labour SS (vertical in the short term) is also in C. We therefore have a first equilibrium point in the labour market where OS labourers receive the subsistence wage w1. Imagine that temperatures are falling. The labour supply is reduced to OS' because it worsens the health of some workers. On the other hand, now each worker must devote more calories to maintain his basal metabolism and has fewer calories to work with. Therefore, their productivity per unit of effort is reduced and produces less than before per unit of time and therefore the marginal productivity curve shifts down to MP2. Let us suppose now, for the sake of simplicity,

that the decrease in productivity is offset by the reduction of peasants to work at OS', so that subsistence wages are maintained at w1.

But here is a problem. w1 stays below the subsistence level, and here we have the main difference with the Malthusian adjustment, which argues that we will always return to the natural wage rate. w1 is no longer the subsistence wage. Now every labourer needs a higher wage to get the extra energy he needs, say w2. However, the consequence of all this is that with w2, employers do not need so many workers, reducing their number to OS", so that unemployment is generated even at subsistence levels (the difference between OS' and OS"). The difference in C", is that they are fewer workers than before, there is unemployment, they earn the same in real terms to subsist. But here the employer has two problems (which we will see later). First, open and communal fields are increasing their marginal productivity and therefore workers' incomes. Second, off-farm wages are increasing. So, the supply of labour shifts a little more to the left, so in the end we stay at C", with OS"' workers and a higher wage rate w3, which goes very well with the employer to prevent worker losses. The conclusions are, if we compare the starting point with the end, first, that a cooling of the climate tends to generate more inequality, combining a lot of involuntary unemployment and a little voluntary unemployment. Second, wages would be a little above subsistence wages, but with a more productive workforce than before. And third, the Malthusian circle is broken (which defends a tendency to return to the subsistence wage), simply because the subsistence wage is now higher. If later energy needs per head are reduced because the climate improves or because the economy is moving closer to works that require fewer calories, it is very difficult for them to fall back. As David Ricardo rightly said, the subsistence wage had a lot of habits and customs. Some readers might add here that a worsening climate surely reduces agricultural production. Well, this would imply that labour supply would shift more to the left because of the demographic crisis, and that marginal productivity would shift even more downwards (there is less agricultural production per worker than before). This would lead to results like the previous ones even worse, depending on the movements of both curves.

All this analysis would be applied to a farm that maximizes profits. But is this really the case in an underdeveloped country? Surely, the answer is no. For example, we may find common fields (what matters is equality in the community, that everyone has work). In

this case, all labourers have the right to obtain the new w2 subsistence wage (or real income), without any of them losing their jobs. For this reason, the community is forced to increase its marginal productivity up to E, keeping the labour supply in OS'. At this point, it is very interesting to see how both the capitalist and the common farms remain. In the first, MP is lower, productivity is achieved by reducing the workforce and paying a slightly higher wage than the new subsistence wage. On the common farm, they are forced to innovate or increase marginal productivity, so that the same number of workers are more productive (the only way to be able to keep everyone on a higher w2 wage).

The problem here is that in the common farm the innovation effort is more intense and possibly the peasants will have a wage a little lower and closer to subsistence, which could cause them to migrate to the capitalist farm or to the city. Broadening the horizon, if the common farms are not able to innovate, they will disappear. If they can innovate, they will resist, although everything will depend on their innovative capacity and the existing alternatives; the greater the degree of innovation and the lesser the alternatives, the greater the resilience. But it is to be expected, on the one hand, that their innovations will also be transmitted to capitalist farms, or that new alternatives will appear (migration to places with better living conditions), or even that, in many common areas, the properties will be bought, and therefore they will also end up languishing.

We must also include in this point the variations in the food demand and prices. Productivity growth adjusts very well to the increased demand and tends to maintain prices over the long term. On the other hand, there is competition with wages outside the countryside, which are higher, and this pushes them up. Finally, rural institutions control wages. The difference between the desired wage and the actually paid wage is even greater. All this causes the annual income of workers to rise more than the daily agricultural wages, but in any case, less than in sectors outside the countryside.

Let us extend the argument to non-agricultural labour markets, for example building. There are no "bad building harvests" here that in the short term will put downward pressure on marginal productivity or slow down the upward trend in wages. So, the effects of the climate are concentrated on the labour factor (most of them work outdoors). Here there are no reports of innovations and productivity gains in building

during the 17th century. Thus, adjustments almost always occur through changes in the number of workers, wages and housing prices. We always move on the MP2 curve. In addition, there are no "housing cooperatives" or similar common institutions in this sector (we are not sure if the guilds had this function, because they did not play a leading role in urban expansion), and we assume that the demand for housing is growing steadily. In comparison, all these differential elements make building wages rise more than agricultural wages (towards w4 and beyond).

As we mentioned earlier, too low a wage was a good reason for some to think that it was not worth working "honestly" and thus reinforcing some of the existing "reprehensible" social habits, such as the presence of frequent holidays. According to Petty, a "moderate worker" was equivalent to 10 to 12 hours of work per day, except on Sundays, and needed about 20 meals per week (1687 p. 57, 1691, p. 110). Depending on the characteristics of the European and English family structure (De Vries 2008, pp.29-31), we can segment people's reactions in two ways. Firstly, in cases of greater "family weakness", the net energy balance could be negative (the difference between wasted energy at work and insufficient energy intake through food, clothing and heating). As G. Becker rightly says, poor health "reduces hourly earnings because a lower level of energy reduces the energy spent on every hour of work or household chores. It was not always a problem of a lack of demand for labour, but of control over the weakest by not allowing wages to rise or to move and start a new life: you could only free up work in big cities like London or in new sectors, embark on an uncertain future overseas or join the army. This is seen in the evolution of the building/agricultural wage ratio, favourable to the former (figure 19, annex 1). Secondly, the most resistant family nuclei would react differently. According to Becker, income in some jobs is very sensitive to changes in energy consumption, while others are more sensitive to changes in the amount of time. People who devote a lot of time to strenuous household activities (childcare) would try to save their energy consumption by looking for strenuous and intensive work and the opposite would happen to people who devote most of their time at home to leisure (Becker 1985). These more consistent household units would be the origin of the launch of the family. Thirdly, another alternative they had was to secure their annual income. If they were not part of common fields, many found a solution with annual contracts. In this way, they guaranteed the growing consumption of energy they needed, and on the other hand it was a good business for the owners, as they continued

to pay the equivalent of a better subsistence wage that allowed them to increase labour productivity, a strategy of "efficient wages" that left many peasants with daily wages and relocations to the city. According to several authors (Woordward, Kussmaul, Foster, Whittle, see Humphries & Weisdorf 2017), the traditional service contract made it easier for employers to harmonize incentives, ensured the availability of labour at the demand peaks of agricultural cycles, reduced supervision and meeting costs, travelling expenses to and from work, and protected workers against rising rents and food prices.

In conclusion, the main theoretical points are here: 1) if the energy need per head increases, the demand for food, heating and other goods related to the maintenance and conservation of energy (clothing or housing) rises; 2) this produces an upward adjustment of subsistence wage (or income), in all sectors, from w1 to w2; 3) henceforth, the productivity and wages (or income) of the two sectors (agricultural and non-agricultural) begin to grow differently, and there is a divergence in favour of the related non-agricultural sector (w4 relative to the w3-w2 range in agriculture); 4) common farms (at one end) make the increased productivity adjustment in order to maintain everyone; capitalist farms (at the other end) increase efficiency wages (incomes) and reduce the number of labourers; 5) wages (or incomes) in the non-agricultural sector are easier to diverge from those in agriculture because a) there are no "bad harvests" that limit wage improvements, b) long-term demand for these energy-goods increases, and c) adjustments are concentrated on prices rather than technical innovations; 6) there is a growing phenomenon of unemployment, underemployment and inequality; 7) daily or hourly wages are a good indicator of what happens to prices and productivity in each sector, as well as labour movements between them, and annual incomes respond instead to the final outcome for the workers of this whole struggle (Humphries & Weisdorff , 2017).

3. IMPLICATIONS

3.1 Implication one: demand increase of energy-goods.

3.1.1. Food-energy for humans and animals

Here, the key is the increase in the demand for energy per head. One of the main conclusions of all previous research is that a mild drop in temperatures drives energy demand and activity level. These results are obtained in investigations of the present, not the past, in developed countries, with people who are well fed, heavier, taller and healthier. However, with a colder climate, Broadberry et al's estimations (2015) capture only an increase of 13 per cent of daily intake of calories per head during the second half of the seventeenth century. This estimate confirms the previous studies summarized here, but given their conclusions, this figure could be low. The same conclusion is reached by Kelly & Ó'Gráda (2012, 2013). They found that calorie intake should be higher, because the GDP and the agricultural output per head increased notably and there was an improvement in health and a disappearance of mortality crises, *inter alia*. Now, the problem with these arguments, no doubt right, is that they are "circular" in the sense that we can say: "Okay, but then tell me why the agricultural output increases, or why health, heating, insulation improve, and so on".

Although it seems low to us, let us now accept the estimate provided by Broadberry et al. (2015). According to them, between 1650 and 1700 the daily consumption of kcal in grain increased from 1,576 to 1,777 kcal, or about 201 kcal more. Suppose that 200 kcal comes from 100 grams of bread (old bread, wholemeal and with many impurities) and that these 100 grams are equivalent to 75 grams of flour (you needed at least three parts of flour for 4 parts of bread, Petersen 1995). These 75 grams are in turn obtained from 100 grams of grain per day (the degree of flour extraction with respect to the grain was 75 per 100). We obtain a consumption of 36.5 kg per year, i.e. 1.34 bu/year (1 bu=60 pounds, 1 pound=0.454 kgs, so 1 bu=27.24 kgs). Therefore, we could say approximately that there was an additional consumption of grain at 1.34 bu/year. Taking an average population in the 1700s of 5,145,531 inhabitants (or Gregory King's 1695 figure of 5,500,000), this increase in per head consumption implied 6.9 million additional bushels of grain (7.37 million, taking King's population). If of this total grain consumption, only 40 per cent was wheat, the increase in wheat consumption caused by

higher per capita energy demand was about 2.76 million bushels (3 million with King's data).

It is quite surprising to see how this calculation fits with what we calculated in the introduction of this paper. The demand for wheat would have fallen by 2.9 million bushels because of the decline of the entire population in England, if it had not changed its diet. We have also just seen how a higher per capita energy demand for wheat, according to the conservative estimate by Broadberry et al., causes an increase in wheat consumption of between 2.76 and 3 million bushels. This surprising coincidence of values could indicate a simple Malthusian adjustment, a higher real income in terms of wheat, that is, the increase in calorie consumption occurred simply because there were fewer people and they had higher real wages. This is what has been believed so far. The problem here is that wheat production did not remain stagnant but output increased. That implies something intrinsically new: an increase in energy demand per capita, very different from eating more for being less. According to our estimates, between 1657 and 1686, wheat output grew by about 2.5 million bushels. The average for the 1650's was 32.89 million and the average for the 1700's was 35.76 million (+2.87 million bushels). Therefore, we should expand the range of possible options in increasing calorie intake from 13 per cent on Broadberry to about 25-30 per cent, if per head consumption also increased in the rest of the cereals. As we can see, this 30 per cent fits very well with the results of much of the current research on the effects of a coldest climate, summarized in the first part of this paper. Half is due to Malthusian adjustment and the other half to an exclusively energetic phenomenon, and here is the novelty. It is not necessary to assess now that demographic oscillations could also be associated with changes in the weather.

The worsening of the climate remains today a phenomenon not well understood, but the general nature of its effects fits well with two of the conclusions obtained. First, that general per head consumption, not just urban consumption, offset the decline in demand caused by a smaller population. The increase in consumption occurred everywhere, in the countryside and in the city. It is unlikely that urban demand was the only stimulus for agricultural innovation. We suggest that a fundamental part of the origin of British success is located in the countryside and that it had much to do with the different behaviours of its actors, open fields, yeomen and landowners. Secondly, without the

increase in per head energy demand, England would not have been able to open the "little convergence" gap any further. That was the key factor, and it could not have been otherwise than a general phenomenon. Another thing is that the increase in demand was more noticeable in the city because the population was tilting towards the urban perimeters, so there was also a displacement of the most productive areas oriented towards London, but it must be clear that in the countryside per head consumption also grew, and that in absolute numbers it was the highest. On the other hand, Wrigley (1985) proves that urbanization is for the first time a general phenomenon since 1670, not only in London, so the causes must have had a common denominator.

English farmers needed their families and communities to eat more, landowners needed to protect their rents, and from urban areas more food was demanded because there were more of them and because each person needed more energy. In figure 3, annex 1, we can see how between the 1650s and the 1700s consumption per head of wheat increased. This conclusion is not incompatible with the idea that urban demand was a stimulus to increase productivity, especially in nearby and better communicated regions, but it does not explain 100 per cent why wheat production increased throughout the country. Not only did they ask for more wheat because they were more and more in the city (while in the countryside they were less) but also because they needed more energy-wheat per head. In addition, the productive improvement of peri-urban areas was not unrelated to supply factors related to the environment. During the 17th century, London was already a highly polluted city (R. Fouquet 2008, p.57). Increased emissions of carbon dioxide and other wastes should have increased the yields of the land in the surrounding regions. And the high productivity of black soils, which fed on soot to fertilize the soil, is well known (Mingay 1984, p. 97; B. M. Short 1984, p. 290; R. C. Richardson 1984, pp. 242-248).

Table 1 (annex 1), shows how consumption/output per head of wheat is associated with temperatures and rainfall. In the short term, a drop in temperatures worsens the outcome (3-4 lags). Conversely, in the long run, colder temperatures are associated with better harvests because farmers can manage the situation (6-10 lags). With summer rains the same thing happens. In the short term, excessive rainfall worsens the consumption of calories-wheat per head. In the long run, farmers react, and people “eat” more calories. And so, it is with spring rains. We observe the same rule with rye and oats. The

conclusion is that, while in the short term, a cooling climate reduces the consumption/output of wheat calories, in the long-term consumption/production increased. At this point we must say that we are not interested in developing a complete model, our goal is to find a meaningful relationship in the variables of interest. The slowness in reacting is explained by the low predictive capacity of farmers. And even if their capacity had been higher, they would have tended to underestimate the risks and would have believed that they were incapable of solving the problem in the short term. These two aspects have been well studied in modern and developing economies (Grothmann & Patt, 2005). For this reason, the reaction is slower when two factors (land and work) come into play instead of only one (work).

Another evidence that relates the increase in wheat consumption with a higher energy demand per head is the higher energy capacity of wheat compared to other cereals. Campbell et al (1993) reported that the kcal per bushel content of barley and oats, relative to wheat, was 82 per cent and 74 per cent of the caloric content, respectively (among ground grains). For this reason, just in the cold period, it is well visible how the preference for wheat in relation to rye increases its price (figure 4, annex 1). The old sources obviously do not speak of calories, but we did find references to preferences for bread and wheat: "*he that tilleth his land, shall be satisfied with bread, and shall have plenty*" (W. Blith, 1649). For Blith, the greatest incentive for agricultural improvements was that farmers and the poor could eat more bread. Surveys conducted by the Royal Society in 1667 collected testimonies of the farmers' preference for wheat and how they tested new varieties "*...They sow noe winter corne (nott butt that theire ground would produce Good-Dod-red wheat as hath beene tried of late yeares att Kilham, with great success*" (Lennard 1968, p.168)[4].

Seed improvement is a little-known subject. It was a resource for farmers with little capital. It is known that English farmers rotated their seeds between different fields and lands. An example is *Pendule Wheat*, a variety grown in Oxfordshire, which was very useful the first year (twenty to one). After two years, the seed was no longer productive, and farmers were forced to source their produce from outside Berkshire at the Abington

[4] Direct testimonies like this are scarce, but very valuable and reliable. For example, the Martínez-González, Jover et al. series (2019) for that year provides an estimate of 18.45 bushels per acre, and in this survey the average production was 18.1 acres.

market. Another variety, *Double Ear Wheat*, although widespread, was also not to the satisfaction of the farmer because its yield on the same soil fell rapidly (Plot 1676, p. 155).

There may be many reasons for the improvements in seed profits, but without a doubt, the ability of farmers to improve them was crucial. Allen has failed to solve the "mystery" of the 1650-1750 production increase, especially in open fields, even with a nitrogen-centred approach (2008). His "something else" is still alive (1999, p. 227). One of its "escape routes" has always been to point out, in a very generic way, the improvement of seeds. This was one of the main causes of the increase in land yields during the Modern Age, thanks to interregional trade and grain selection. These actions "perhaps improved" the genetic characteristics of the English seed, regardless of the level of nitrogen in the soil (1999, 2008). Overton, before Allen, already said: "random mutations must have productive varieties of cereal crops and it is likely that farmers would have selected these in preference to others" (1989, p. 90).

The writings of the period reveal an important movement of seeds. The *Red Stalk Wheat* was a wheat variety introduced in 1626 until it "proved marketable" (Plot 1676, pp. 153-156). If in 1676 it was still not known in many places, in 1712 it was already a common cereal (Mortimer 1712, pp. 94-96). The *White Eared Red Wheat*, also called *Mixt Lammas*, was also introduced into Oxfordshire successfully because it was more productive than most (twenty to one), and much coveted under the Chilterns. However, it remained a very localized seed: even in some parts of the same territory, such as Banbury or Burford, little was known about it. The *Lammas* (Red and White) varieties had a great capacity to combat smut, thanks to their early ripening, which hardened the grain and prevented the entry of the fungus. Added to this was its great longevity. This made them become the most appreciated, especially in open fields (Plot 1676, p. 153). One fact was confirmed by John R. Walton: before the 19th century, the most successful native autumn varieties were the *Red Lammas* (1999, p. 47). At the other extreme was the Cone Wheat. High yielding in clayey soils, birds could not easily attack it, so it did not require much manpower. This made it more of a good seed for large landowners than for yeomen and bakers, who found it too thick and sensitive to mould (Plot, 1676).

Two hundred years later, on Oxfordshire farms there were only seven or eight local varieties, including the *Red Lammas*. This was no longer the most productive (37.8 bu/acre according to experiments carried out in Rothamsted between 1871 and 1881) but maintained one of the highest percentages of gluten among British seeds (25.2 per 100 out of an average of 18.6, while foreign wheat gave an average gluten of 22.3). Another English variety, the *Rivet*, yielded much more (45.8 bu/acre), but barely had traces of gluten. *Lammas* were still, at the end of the 19th century, the champions of resilience, and *Rivets* were just the opposite. Faced with an adverse climate, *Lammas* yields were among the best. And while the flours of the Rivets were not used to make bread, the *Lammas* provided good quality. But times had changed. Climate problems had been reduced and agricultural techniques had improved, and there was not much interest in producing bread wheat, in an agricultural sector more concerned with maximizing yields than the destination of production, well guaranteed by the demand for livestock and the British cookie industry. Thus, many of the autochthonous seeds were residual in 1852, surviving in marginal crops where adaptation to the environment was the problem to be solved. As there was no cereal capable of having high yields in stems and seeds at the same time, there was a tendency for the harvest rate to fall in favour of the Straw (the stem), with animal consumption taking precedence over human consumption (Walton 1999, pp. 39-50).

Another question is how the farmers managed to improve them and why between 1650 and 1750. The primary sources consulted point to possible avenues. First, increasing the rotation of seeds between plots and territories, reserving the best to sow and the rest to eat or sell. Before 1750 improved seed selection was such a regional phenomenon that many varieties became alien to English travellers from other regions (Walton 1999, p. 32). Mortimer clearly describes how they moved from South Staffordshire to the North, and from "North to South", except in Moor-lands where farmers "always took the best seeds to avoid being left in nothing". For Mortimer, this racking was the "greatest advantage". But this argument was certainly descriptive. Why did local and regional rotation increase right then? The answers can be many. The 17th century was a period of great internal migrations, motivated by the political crisis of the monarchy. Before 1640, most of the male population could not legally leave without a certificate, but between the fall of the political reconciliation and the establishment of new and greater restrictions deriving from the Residence Act of 1682, there was a period of greater

labour mobility, thanks to the increased movements of armies and soldiers, which surely increased the trafficking of ideas and things (C. Hill 1961). Second, regarding why between 1645 and 1700, one of the answers is that the climate became colder, wetter and more variable. The environmental pressure on farmers multiplied. In Mortimer's book, the disadvantages of weather, storms, rain or frost, the dangers of humidity and how to avoid *smut*, were a constant threat. It was no coincidence that at that time the *Lammas* varieties flourished, some of the most resilient, productive and best accepted by bakers. It was the Yeomen and small farmers who were looking for more daring solutions, since seeds are a much cheaper resource than drainage or water meadows. Thirdly, in addition to land rotation or regional rotation, part of the solution also focused on post-harvest treatments and the storage and conservation of wheat. By treating with brine, powdered chalk, and drying the seed well, farmers reduced the risk of *smut.* They also did this by dissolving sheep dung in water by adding salt, soaking the grain in the formulation eighteen hours for wheat and thirty-six hours for barley, then drying with powdered chalk, and adding wormwood to avoid birds. According to Mortimer, the best barns were made of stone and brick. In this way, rodents and humidity were better avoided, in a century characterised by the substitution of wood by stone, a process intensified by the fire in London in 1666 and the diversion of wood towards the Navy. Likewise, it seems that the greater diversity of agricultural practices and the pressure of the climate modified some guidelines in agricultural constructions. Adaptations were made by heavy rains in the western highlands or by the cold winds of the eastern counties, all to minimize the exposure of humans and animals to the worst of the weather. Combinations were sought between grain and feed storage with housing and feeding of horses and livestock. In the *Penine Counties*, cold and wet winters determined the management of stabled cattle, giving rise to a practice that became very popular since 1650: a barn, separated from the house, with accommodation for livestock. Barns with stables were also extended to grazing areas, or they were used to store grain as well as for fodder and hay (M.W. Barley 1985, pp. 667-671).

We can also see in figure 16, annex1, that seed yields have fallen since 1760. This fact confirms Walton, when he detects a *turning point* in the seed during the second half of the 17th century, as Allen did in 1750 (1999, p. 225). The triumph of parliamentary closures and the increasing inflow of foreign wheat may have implied a relative slowdown of improvements with local seeds. While in Thirsk, Thick or Ambrosoli there

is hardly any mention of foreign seeds between 1650 and 1750, in the second half of the 18th century scientific curiosity towards European seeds began to be recorded in writing. It is therefore not unreasonable to suggest that business and livestock principles, based on profit, were gradually being imposed in the field, while English food sovereignty and living standards suffered (Walton 1999, pp. 32-37).

On the other hand, milk production fell from 72.52 million gallons in the 1650's to 59.10 in the 1700's. Milk prices, except for a few short periods, remained fairly stable. Beef production fell from £24.83 million to £21.16 million. The price of beef also remained stable. The overall conclusion is that per head consumption of meat probably remained stable. The increase in consumption was redirected to more energetic food and more energy in this period, rather than protein, so the population's height probably had to remain stagnant or fall (Galofré-Vilà et al 2018).

If in wheat there was a relative productive success, in the case of rye this success was even more spectacular, as we can see in figure 4, annex 1. The preference for wheat could only be converted into consumption in those social groups that could afford it, regardless of their level of income or their proximity to production. For this reason, in the 1650-1700 period, rye consumption increased much more in proportion, doubling from 3.7 to 6.7 million bushels (Broadberry et al. 2015). If we look at the immediately preceding periods (1600-1650, decrease from 7.8 to 3.7 million) and subsequent periods (1700-1750, decrease from 6.7 to 1.5 million), we observe that 1650-1700 was clearly anomalous, the only one where the demand for rye increased again. The fact that cereal consumption grew, especially rye, proves a greater demand for calories, but also a period of food crises, where rye bread and other inferior breads played an important role in preventing famines (Appleby 1979, 1980; Hoyle 2013).

Not only were adaptations made via energy. Thirsk (1990) claims about the importance of poor harvests and food shortages to increase the production of grains and others crops. This fact had also the effect of stimulating interest in food crops other than grain, and vegetable growing meant food and work for the poor. Vegetables were consumed in London in such quantities that in some seasons the gardens feed more people than the fields. It was even suggested in the 1670's that so much were the poor substituting grain by vegetables in their diet that it was a cause of the deadness of the markets for corn. On

the other hand, recent studies have shown that increasing nitrogen fertilization is related to a much higher dose of zinc, iron, copper and protein in wheat, in the order of 50-80 per cent more, which significantly improves health. Zinc and iron are essential nutrients that contribute to human health, the immune system, and the formation of haemoglobin, which spreads oxygen throughout the human body. These nutrients are also key players today, as it has been found that zinc, iron and protein levels are likely to be reduced by up to 10 per cent in wheat and rice to the expected levels of CO2 in the atmosphere by 2050 (Myers et al. 2014). Other research has shown that ancient cereals (landrace seeds) are richer in nutrients than modern varieties because modern plant breeding has been historically oriented toward high agronomic yield rather than the nutritional quality (Zhao et al. 2009, Shi et al. 2010, Gómez-Becerra et al. 2010, Kutman et al. 2011). Farmers, especially yeomen, got better seeds, more resilient, with better gluten for bread, and more nutrients. Thomas & Frankenberg (2002) find that a nutritional deficit, especially a deficit of iron and a lower intake of energy reduce work capacity and the opposite.

In conclusion, the needs of peasant communities and urban horticulturists drove the slow agricultural revolution, resulting in more calories measured in cereals, but also in more and better nutrients, which had a second effect through improved health, further favouring the ability to work and choice among people.

3.1.2. Firewood, charcoal and coal

Wood, firewood and charcoal were used for heating, cooking, producing bricks, boats, horse-drawn carriages, housing, iron, salt, pottery and many other everyday items. An important part of the firewood (in its different forms, faggots, bavins, billets or turf), was consumed in the countryside. The costs of transport prevented its distribution more than 20 miles away from where it was produced (Clark 2004 (Rackham (1980)). Coal was consumed in a much more concentrated form, especially in London, and was largely used for household consumption (heating). For any of these variables, we do not have annual or monthly data on physical amounts spent. This forces us to work with price estimates (figures 5, 6. 7 and 8, annex 1). Analysing those provided by Clark, we see that the price of firewood increased until the last quarter of the seventeenth century, where it remained at peak levels. If in this period the peasant population decreased (due

to demographic stagnation and urban migration), the price of firewood should have decreased. However, prices rose, indicating a higher per head demand for firewood and a greater need for energy. It has been pointed out that there was an energy crisis in Britain during the 17th century, caused by increased demand for shipbuilding (the demand for iron, could only be met with imports, Thomas 1986). With firewood, however, we cannot go much further. Clark's series does not explain in detail how the sources used have been combined or what their characteristics were. Furthermore, if the market was markedly regional, we would find many local prices, not just one (Hammersley 1957, 1973; Hatcher 1993; Allen 2003). It is possible that many families did not pay for firewood with money, and it is hard to believe that the demand for wood and iron derived from the construction of boats and other materials ceased. Therefore, it is risky to draw conclusions from a single series because it might not be representative.

Looking at figures 5, 6, 7, 8, annex 1, it seems that the supply of coal successfully meets the growing urban demand until the 1690s, when its price seems to overflow, just like wood, wood or charcoal. This general increase in the price of energy, in a depressed demographic environment and absence of external demand, can only indicate a strong increase in per head demand for energy-heat. Unlike firewood, coal consumption was concentrated in London and industries. In fact, London's growth was determinant (Allen 2003). Therefore, we can be reasonably sure that the price series is more reliable (figure 6, annex 1). Going into detail, we observe that coal supply successfully meets urban needs until the 1690's, where prices seem to overflow, probably due to intense energy demand. We can also venture some more conclusions from figures 9,10 and 11, annex 1. The per head expenditure on coal increases steadily and has several important peaks in situations of extreme cold or supply failure[5]. On the other hand, the real expenditure per head on coal (in terms of wheat) has a similar evolution. Coal consumption, in real terms, became more expensive. That is, the population devoted more and more resources to coal. This idea is well taken up in Martínez-González, Suriñach et al. (2019). Lower temperatures would accelerate the consumption of coal, in contrast to the warmest period, when temperatures would lose importance in favour of other demand factors (urbanisation and population).

[5] The calculation of coal expenditure can be found in Martínez-González, Suriñach et al 2020.

In the previous pages we have commented how the greatest need for energy per head had different responses depending on the context of each person or family. One of these answers could have been in the migration to London, what we can call a temporary or permanent migration of "energy seekers". In our opinion, a greater ease in heating was a powerful attraction. At this point it would be ideal to do a simple quantitative exercise on this "attraction", for example, linking the variation of the London population with the price of coal. We are in “collision” again with the absence of data or estimates. However, we can make a first attempt. Based on the calculations provided by Petty in 1686, we have a short series of baptisms between 1665 and 1682. This series could be a proxy for the population, since much of the emigration consisted of women of childbearing age. In figure 12 and table 2, annex 1, we see how population growth in London was associated with coal prices. If these went up, the baptisms descended, that is, population grew less. Another surprising finding, using two primary sources from more than three hundred years ago and without any relationship between them (Petty's series of baptisms and the Newcastle coal shipments, which we explain below), we observe a strong correlation. Coal availability was a very significant factor in births and child survival (figure 13 and table 3, annex 1).

However, we have carried out an additional exercise (Table 4, annex 1). First, we took as a variable to explain, Clark's London coal prices, a proxy indicator of coal demand. Second, we took two primary sources as explanatory variables. The first source is coal shipments from Newcastle from mining accounts. According to Hatcher, 75 per cent of these shipments were to London (Hatcher 1993). According to Broadberry et al 2015, these shipments are an excellent indicator of the increase in coal consumption in England. The second source are seasonal temperatures. The main message of the model is that London coal prices increased when coal shipments fell and when autumn and winter temperatures were lower. In Table 4, 72 per cent of the London coal price is explained by autumn and winter temperatures, and Newcastle coal shipments. The colder the temperature, the more expensive the coal and vice versa. A 1ºC reduction in temperature resulted in a price increase of 2.13 shillings, 15 per cent in the average price of coal for the period studied. Knowing that the 1645-1700 period was especially cold, we understand that it was an important added stimulus to the demand of fuel per head. The lower the coal shipments, the more expensive it was. On the other hand, Hatcher (1993) has shown that shipments were radically reduced when the weather

worsened, especially in autumn and winter. Therefore, the increase in prices reflects two things, an increase in the demand for heat, and an increase in the relative scarcity of coal. At that time, it was not easy to increase total winter energy consumption in proportion to low temperatures. According to this, total consumption could be more related to average temperatures based on forecasts and expectations. Thus, we have seen before that the 1645-1700 period was very cold and humid. Therefore, cold was an important stimulus in demand, which is in line with the conclusions of our work.
Our conclusion is, firstly, that we find signs of "energy attraction" on the part of London and, secondly, that the price of coal is directly linked to the worsening climate.

3.2 Implication two: higher energy, therefore higher and divergent wages.

In the previous sections we found a relationship between temperature, energy need and demand for food or goods related to energy maintenance. On the other hand, we have predicted, based on theoretical analysis and empirical studies, that this causal line will lead to increased productivity and wages (incomes) and divergent growth between wages (incomes) in the non-agricultural and agricultural sectors. Figure 14 seems to show how our prediction is met. Right at the beginning of the climate crisis (1646) the daily wages of both sectors begin to diverge for the reasons explained in section 2.5. Furthermore, if we put the real daily wages estimated by Clark and the real annual income estimated by Humphries & Weisdorff in the same chart (figure 15), we observe how they begin to grow just after 1645, as the theory predicts.

Regarding productivity, table 1 (annex 1) suggests how the output of wheat per labourer is affected in the short term by a more adverse climate, but in the long term it rises. This fits quite well our forecast of "jump" from C to C' and then to E, C" in Figure 2. Second, Malthus and David Ricardo's wages theory argues that the "natural wage" is marked by the subsistence level. Therefore, if the basic need for energy per head increases, the "natural wage" also increases. Otherwise, there would be a demographic and migratory crisis. A current, more settled argument defends the idea that the wage adjusts quite well to the value of the labourer's marginal productivity (the value of marginal productivity is equal to the result of times the marginal productivity by the price of the goods produced). Greater availability of energy per hour for work implies an increase in productivity. If the price of the produced goods remains stable or rises, the value of the marginal productivity rises and therefore wages rise as well. Labour employers are

inclined to pay more. If the price of what is produced decreases in the same proportion as the marginal product increases, the value of the marginal productivity remains stable and the wage also increases. Returning to theoretical section 2.5, it predicts an increase in agricultural wages from w1 to w2-w3, depending on whether it is a farm that maximizes profits or rents (adjusting the number of workers and wages), or if they are common fields (adjusting productivity), if there are no additional institutional constraints. A higher increase in non-agricultural wages (w4) is also expected. In other words, in the cold period a direct relationship between wages and temperatures must be found in the short term, and the opposite relationship in the long term. The relationship is expected to be weaker in the agricultural sector, because 1) the effects of climate on harvests play a corrective role, 2) agricultural labourers are both producers and consumers, and 3) a whole series of institutions and operating rules moderate these effects.

Let us now make a comparative exercise between agricultural and building day wages (skilled or unskilled workers). The logical line begins, let us remember, in a worsening of the climate and the political situation, and an increase in energy consumption per head. More energy per hour means more productivity. From this point, there is a divergence between the countryside and the city. Agriculture would be able to improve or maintain its productivity (especially in open and common fields) and agricultural prices would tend to fall in the long term. Therefore, the value of productivity should be stable or slightly higher (the rise in productivity is offset by the fall in prices). Thus, daily wages would remain stable in the long run (or rise smoothly), ranging from the highest levels on "capitalist" farms (paying more with fewer labourers) to the somewhat lower levels on common and open fields (because more workers and families are being maintained).

On the other hand, in the building sector (craftsmen or unskilled), the increase in energy consumption per head is achieved by adjusting the number of labourers, wages and prices. As the price of energy-housing rises, so do the wages of building labourers (we do not know whether there is a substantial improvement in marginal productivity). The consequence of all this is that (1) there should be a stronger relationship between climate variables and wages in non-agricultural sectors than in agricultural sectors, and (2) adjustment is faster in the non-agricultural sector because poor harvests slowed the

growth process, rural institutions limited wages through wage and mobility controls between counties. In urban areas, on the other hand, guilds lost power.

The results of table 5 (annex 1) are close to our intuitions. The parameters of the explanatory variables are significant. As predicted, the relationship between temperatures and real agricultural wages is weaker (R2 lower) and adjustment is slower. At first, declines in temperatures mean lower real wages. In the long run, these end up rising because the subsistence minimum and productivity increase (a process that can take nine years to complete). In any case, the relationship is significant but weak. However, in building wages, the ratio is stronger (R2 higher) and this adaptation is faster (between two and three years). Obviously, these results are still quite speculative. The only way to prove this is with local comparative studies.

A similar exercise can be done with animal force. It also had to increase the need for energy in bullocks and horses. This meant higher costs and higher requirements for production. Horses were much more versatile as draught animals in the transport of people, goods or coal. In an environment where more energy-work was required to obtain more energy, the value of the marginal productivity of horses was higher than of oxen. Therefore, the price of the former rose in relation to the latter. Table 6 (annex 1) offers an empirical approximation to this idea. We observe a significative relationship between the increase in the price of the horse and the fall in temperature, and vice versa with bullocks. In fact, the number of draught bullocks was halved, from 80,000 to 40,000, and beef and milk productions were also reduced. On the other hand, in food-animals such as pigs or cows, their price increased as their energy requirements and maintenance costs increased.

3.3. Implication three: If the open fields were successful, why were they disappearing?

In order to cope with a higher need for energy and minimum subsistence, section 2.5. concludes that common farms are obliged to effect productivity improvements in order to maintain the number of working families and individuals. This theoretical prediction has long been demonstrated in Allen and others. An increase of energy requirements of the rural families was a stimulus for the agrarian communities, because they will protect calories intake for their women and children or to increases energy to attend the market

demand. We know by Allen (1992) that yeomen and open fields were the key protagonists in the increase of agricultural yields and output, between 1650 and 1750. How can we harmonize this success in a more adverse environment? Dyer (2018) explains that the basic characteristic of peasant communities was the need to achieve a certain degree of self-sufficiency, so that open fields were specially designed to minimize the risks of bad harvests, with a landholding structure and social balance between arable and pasture managed by by-laws. McCloskey (1972) explains "that strips were scattered by villagers to reduce risk and they were driven to hold land in scattered strips to hedge against disasters befalling only one type of soil and to diversify their crops, holding land in each of the open fields of the village, to hedge against disasters raising the price of only one part of their food". Allen (2001) talks about this again, admitting the efficient management of climate risks and high productivity. "Land was not uniform, so the productivity of different parts of a village's land responded differentially to variation in the weather. In years of high rain fall, low lying land might have been waterlogged and given low yields, while higher land might have been productive. Conversely, when rainfall was light, the upland might have been too dry to produce well, while yields might have been high in the low land".

In our opinion, the cost-benefit ratio was well managed in that they did not need a high capital investment individually, because this capital was shared as investment in horses, diversification into furlongs and strips, and the contribution of new seeds. According to John (1968), small farmers did not benefit from poor harvests. The profit depended on two years of tenure, the fallow year and the year in which the crop grew, while the third was devoted to what we call the Quaresma grain, such as oats, or with legumes, intended for the subsistence of horses and cattle. This precariousness explains, in large part, the rapid turnover of small tenants in many arable areas of central England. On the other hand, where animal husbandry was the predominant activity of the small farmer, the effects of harvest conditions were somewhat different. Here grains were grown mainly for on-farm consumption and affected the economic survival of the farmer less directly. However, as in the case of the small farmer, a farmer suffered severely when the crops were bad. When he had money, he appeared in the markets as a food buyer; more often, however, he and his family went hungry.

Therefore, here urban demand was not an important pull factor for them. A drop in temperatures and more humidity, together with an increase in the variability of weather,

implied a greater demand for energy to protect the needs of peasant families, who were forced to sharpen their ingenuity. This fact is confirmed by Allen (2001) and McCloskey (1972) when they mention that common and open fields were organized in dispersed plots, very suitable for managing climate risks. In a period with greater probability of risks, the response capacity could be significant in the farmers, hence also their productive success. Allen (2001) has also pointed out that in open fields, small farmers had an adequate system to increase yields, something necessary to maintain their families, and they also introduced turnips, clovers, new rotation systems and new seeds. All this also explains why there was an incentive to the enclosures. The increased value of the land generated renewed interest from landlords and landowners, so many did not renew tenure contracts. On the other hand, as we have already discussed in section 2.5, the pressure to be more productive was greater, and wages were probably lower. These factors made their long-term viability more difficult. More productivity for a lower wage could lead to a process of depopulation in some of the open or communal fields. This phenomenon (and others) are what Walter Blith (1649) notes, defending enclosures to avoid the loss of rural population.

3.4. Implication four: inequality, involuntary and voluntary unemployment

However, depopulation on capitalist farms was more general, due, as we have seen before, to a decline in the number of workers per acre in the face of rising energy requirements. Fortrey (1663), another supporter of enclosures, acknowledged the prevailing view of the moment. Enclosures were a problem because they generated depopulation, unemployment for families and grain shortages. That is why the old parliaments opposed them. The land would become pasture. One hundred acres would barely maintain a shepherd and his dog, while "now many families and employees are maintained on the farm, and from experience one finds that many families, now in enclosures, do not have as many inhabitants on them". Therefore, it matches the theoretical prediction that the "capitalist" farms generate less employment and that part of it is forced to change occupation as the manufacture of wool, as Fortrey defended.

Another important conclusion of our research was the prediction that higher per head energy requirements led to more unemployment and underemployment. In this sense, during the second half of the 17th century a whole body of evidence emerges, around a growing concern of British philosophers and intellectuals for these issues. If with the

emergence of classical economics (18th century) leisure was harshly criticized, during the 17th century mercantile economic philosophers believed that involuntary underemployment predominated over voluntary underemployment. William Petty concluded in his *Treatise of Taxes and Contributions* (1662) that the government should not allow mendicity. It was far costlier to tolerate than to provide money to the less fortunate. Petty believed that it was unfair to starve people with wage controls when they wanted to work and prosper. This has been corroborated by Christopher Hill: in most counties the official wage rates set by the judges remained almost unchanged from around 1580 to 1640, while prices kept rising. Even workers who earned more than the officially marked wage or those who attempted to leave their parish without permission could be punished with a terrible fine and imprisonment (Hill 1969).

A common idea developed by almost all English thinkers was that the prosperity of the nation would be achieved by combining low prices and wages. Although there was no unanimity on the desirability of keeping wages low, almost all views pointed in this direction. Petty believed that wages should be competitive, but he also criticized the fact that wage ceilings were so low as not to allow workers more prosperity. Against such a backdrop, it becomes very difficult to think that the workforce had an "irrational" propensity for leisure. Petty had a positive view of work: people wanted to work and prosper, it was unfair to limit wages. On the one hand, he believed that the market always tended towards a natural subsistence wage, but he also agreed with the unstoppable phenomenon of migration for the sake of a better life. According to Petty, wages were limited by the Law (1662, p. 52), hence the good reasons to go to the city: more equitable taxes, better justice, accessibility to consumption and commerce, a greater division of labour with more opportunities and more educational possibilities (1683, pp. 470-75).

Josiah Child (1630-99) published an 18-page pamphlet called *Brief Observations*, in which he analysed Dutch prosperity. He insisted on the importance of increasing the population and facilitating work for the poor, but above all he thought like Petty (there was a lot of involuntary unemployment), although he also emphasized the strong tendency of the workers to leisure as their real wages increased as the poor,

"will no provide for a hard time, but just work so much and no more, as may maintain them in that mean condition to which they have accustomed"[6]

George Berkeley, an Irish bishop and author of *The Querist* (1735), was concerned about several issues, especially chronic and widespread unemployment or underemployment. For him, there was no doubt that unemployment in England, Scotland and elsewhere was largely involuntary, but there was also a component of idleness (in modern terms, the supply curve pulled back once a wage level was reached). To solve both types of unemployment it was necessary to apply a carrot and stick policy: forced labour houses (those who do not work do not eat) and "wants",

"Whether the creating of wants be likeliest way to produce industry in a people? And whether if our peasants weve accustomed to eat beef and wear shoes they would not be more industrious? Whether comfortable living doth no produce wants, and wants industry, and industry wealth?"

Berkeley was very clear that there was an involuntary part of employment and leisure, so there was a tension between the two extremes, because he could even see poverty face to face. For the bishop, fiscal policy was a good solution to reduce luxury spending and bring the poor into employment. Income inequality was undoubtedly a real brake on development:

"Whether as seed equally scattered produces a goodly harvest, even so an equal distribution of wealth doth not cause a nation to flourish?"[7]

Underlying here is a rational explanation of "voluntary unemployment". Any exogenous impact that reduced the demand for labour in the short term caused downward pressure on wages. If the maximum wages were already at the subsistence threshold and the workforce was not free, it was a perfectly rational choice not to work and live on charity, to escape the forests, to go on an overseas adventure, to break the rules or to migrate to the city. "There was a large movement of surplus labour from villages to forest settlements in many parts of England" (Hill 1969). Faced with the weakness of European family networks (nuclear family units), the only alternatives available to them were, in addition to "an escape" in the case of the less consistent ones, the extension of the work force with women and children either by extending the number of working hours, or even diverting their time and energy in seeking sustenance through other alternative systems (De Vries 2009).

[6] Hutchison, 1988.
[7] Hutchison, 1988.

Inequality, the distribution of time and energy within family units, wage and non-wage levels, the existence of social benefits and coverage, or restrictions on labour mobility may have been influencing factors. For Edmund Halley (1656-1742), a pioneer in the development of population statistics, Fellow of the Royal Society and widely known for his work *Degrees of Mortality of Mankind* (1693), inequality was the main cause of demographic and economic stagnation. The population size was maintained not by disease and hunger but because people considered marriage an adventure. Taking on the burden of supporting a family could be an insurmountable problem. The population did not grow so much because of hunger and disease but because of decisions not to marry, a kind of "moral" restraint. Halley's argument connects with Clark's "Law of Social Mobility" (2014). If wealthy social groups maintained their marriage and fertility rates, but the lower strata did not (and so globally the number of marriages fell), the "winning genes" of the future Industrial Revolution spread to the lower layers for several generations, which could help to understand the progressive shift in British economic thinking between the 17th and 18th centuries, as well as other factors such as Dutch immigration or the economic boom of the early 18th century.

In a context where the per head need for energy grew, the fact that this need was much greater during pregnancy and lactation (see above) had to slow down the rate of nuptiality and births, especially among the poor.

Be that as it may, from everything we have seen up to now we can see a clear concern of "modern" thought in promoting employment (industries and businesses were judged for their capacity to absorb labour or stimulate employment), where the discourse of the "idle" is also making its way, according to the declarations of writers and pamphleteers, the preambles of a long series of laws, writings of statesmen or reports of public bodies. There was a preoccupation with seeking work rather for reasons of wealth than for the existence of a certain sensitivity in improving the welfare of the population. Did all these elements reflect a destruction of the collective or communal spirit of the Middle Ages, the beginning of the triumph of the individual over the collective in a century of transition? This is obvious to Hill, as feudal relations were already in clear retreat from the sixteenth century: "villainy ends, tenure leases and wage labour extend," "scruples did not prevent owners from expelling settlers who were no longer obligated to serve

them. The law was strongly inclined against the poor", or quoting Professor Richard H. Tawney, "the villainy ends, the law of the poor begins", when feudal protection of agricultural work gave way to welfare protection (C. Hill 1969). Be that as it may, a large part of the references in social matters come from the studies of the Law of the Poor, and on the other hand at the level of labour force, peasants and workers, there is very little. The writings of the mercantilists distil analysis of political economy but little of the labour market and genuine social history. And in no case did they speak of the role played by women, children or servants.

In this general context, the strategies followed were different. The increase in calorie intake was a slow and gradual process, as well as the improvement in health. Neither sooner nor later did this benefit everyone. Gregory King's population distribution in 1688 shows that a very large proportion lived at levels close to poverty. In a time of such controversial change, many could not benefit. Gregory King (1648-1742), genealogist, accountant, social and economic statistician, wrote two works that have had much influence in this field, the *Natural and Political Observations and Conclusions upon the State and Condition of England*, not published until 1802, and *Scheme of the Income and Expense of the Several Families of England calculated for the Year 1688*, where he presented a table that was well recognized and accepted by later economic and social historians. King's research showed a grim history. He classified 23 per cent of the national population as "working people, servants apart" and another 24 per cent as "cottagers and poor," estimating that both groups had an annual family expenditure greater than income. The sum of both groups was no less than 47 per cent of the total population. These accounts may have been clearly falsified to avoid paying taxes, but Coleman (1956) was inclined to accept King's figures: a quarter and half of the population was below the poverty line, including the skilled and semi-skilled working class, farm workers, the poor, day labourers, and the most modest weavers.

It is certain that a greater need for calories weakened many people. All those who did not find ways to increase their need for energy reduced their work capability. Freudenberger & Cummins (1976) insist that before "losing" calories to survive, many of these people preferred to keep sacrificing work for leisure, this leisure being largely voluntary. The question of the poor and their "aversion to work" became fashionable in the field of political economy. Therefore, there seemed to be an association between a

greater need for calories and the growing situation of vulnerability in a part of the British population.

4. CONCLUSIONS

It is clear that there are several factors associated with an increase in energy needs. In this article we focus on one of these factors, climate. A worsening climate means more energy expenditure in a variety of ways. The English population was mostly poor and with subsistence wages (or income) concentrated on food, clothing, housing and energy to burn. Thus, to spend more energy they needed higher subsistence incomes. The increase in the wage fund may then be one of the causes of the remarkable growth of British GDP per capita in the second half of the 17th century. The Malthusian argument is incomplete, it would only explain about half of the increase.

From this central message (energy as a key element) come other issues that should be studied in the future. Some of these issues are as follows. Economic transformations occur everywhere, in the countryside and in the city. We can connect physical energy with the economy through subsistence wages and productivity. Egalitarian farms respond by maintaining population and increasing yields. Capitalist farms respond by reducing the number of workers per acre and improving incomes. This leads to involuntary and voluntary unemployment. Some communal farms have difficulty retaining some workers, given the relationship between the effort they must make and the income they earn. Women and children reallocate their energy consumption more efficiently by working in manufacturing. There is a liberation of labour in manufacturing and services. Non-agricultural wages began to differ from agricultural wages. The structural change of the second half of the 17th century marks the path of the origin of the British economic revolution.

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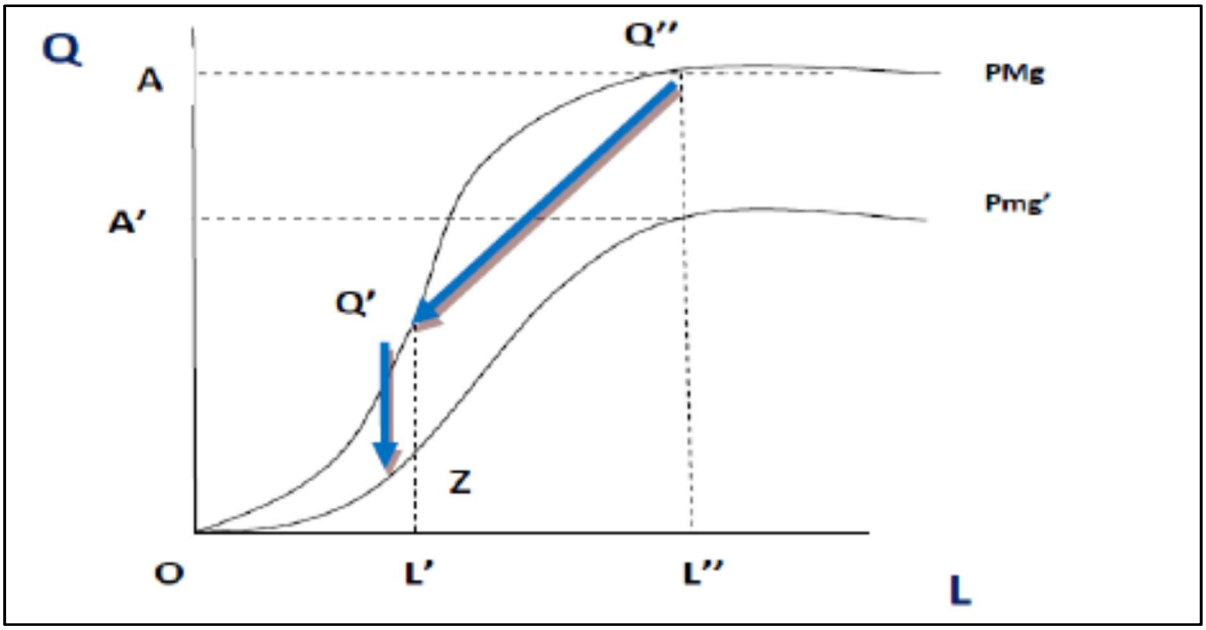
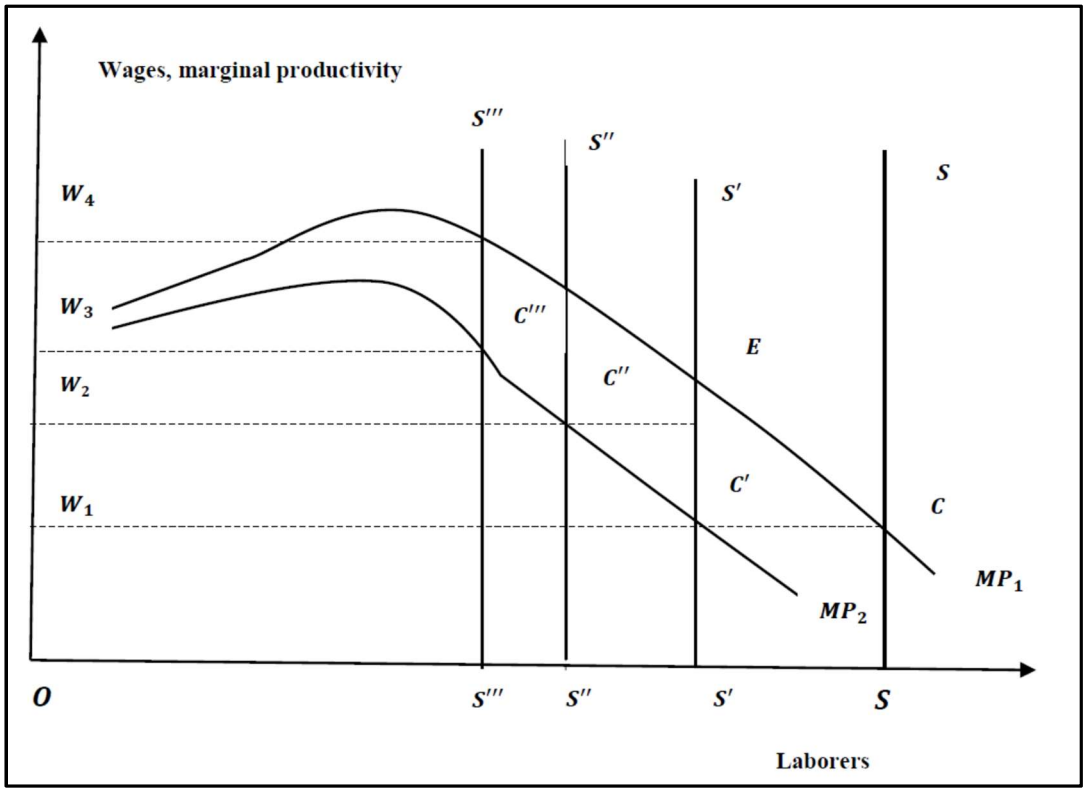
Annex 1

Figure 1. Climate effects on labor productivity



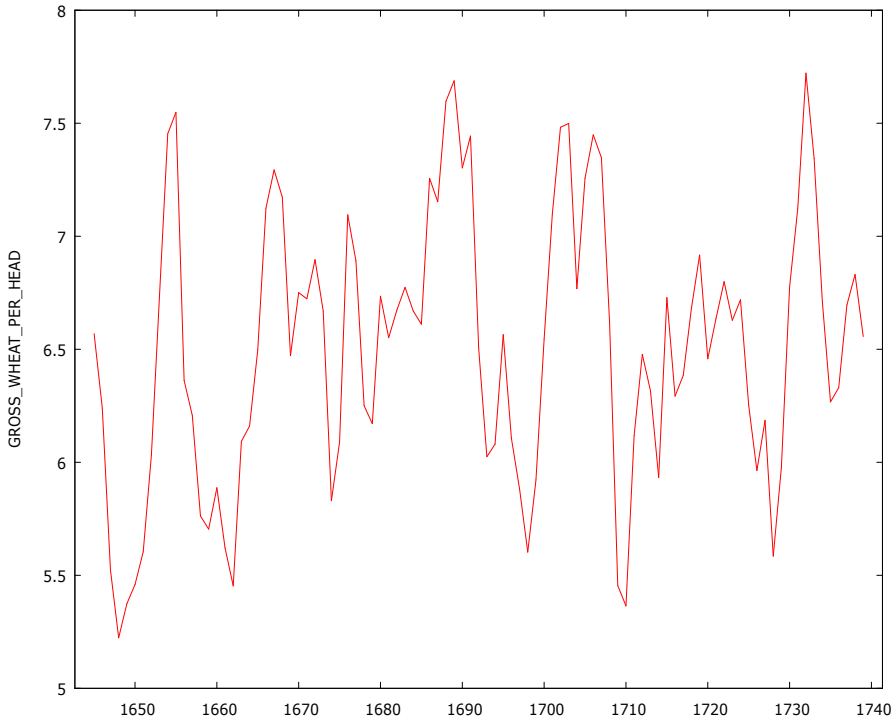
Own elaboration

Figure 2. Variations in energy consumption, productivity and wages



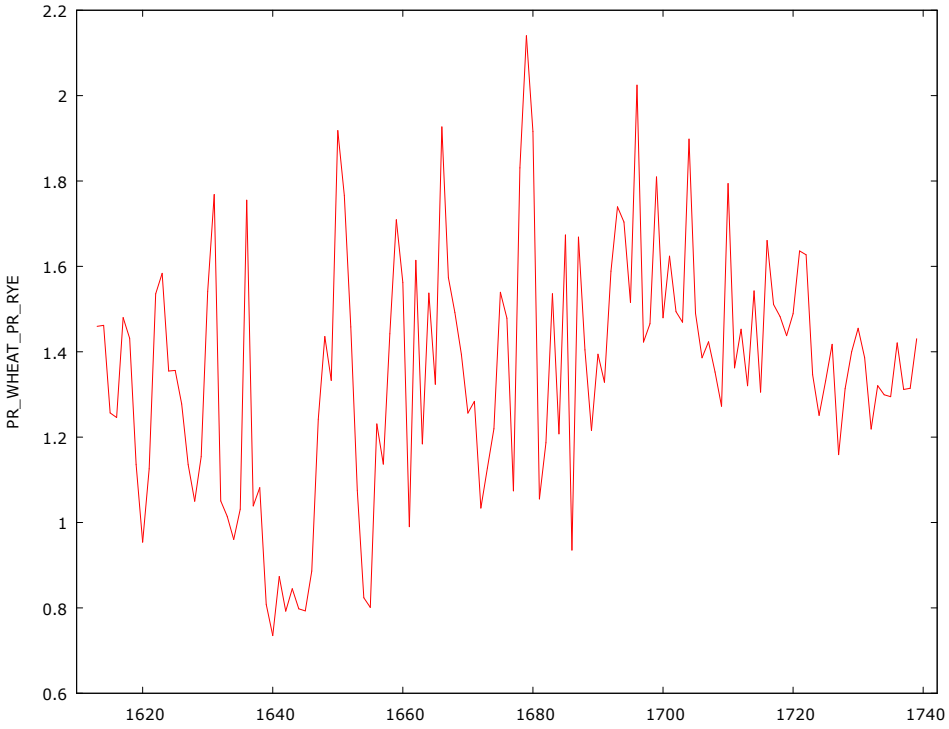
Own elaboration

Figures 3. Gross wheat per head in bushels. England and Wales, 1645-1740.



Own elaboration from Martínez-González et al- 2019 wheat estimates and Wrigley et al. 1981 population estimates.

Figure 4. Relative prices between wheat and rye. England and Wales, 1645-1740.



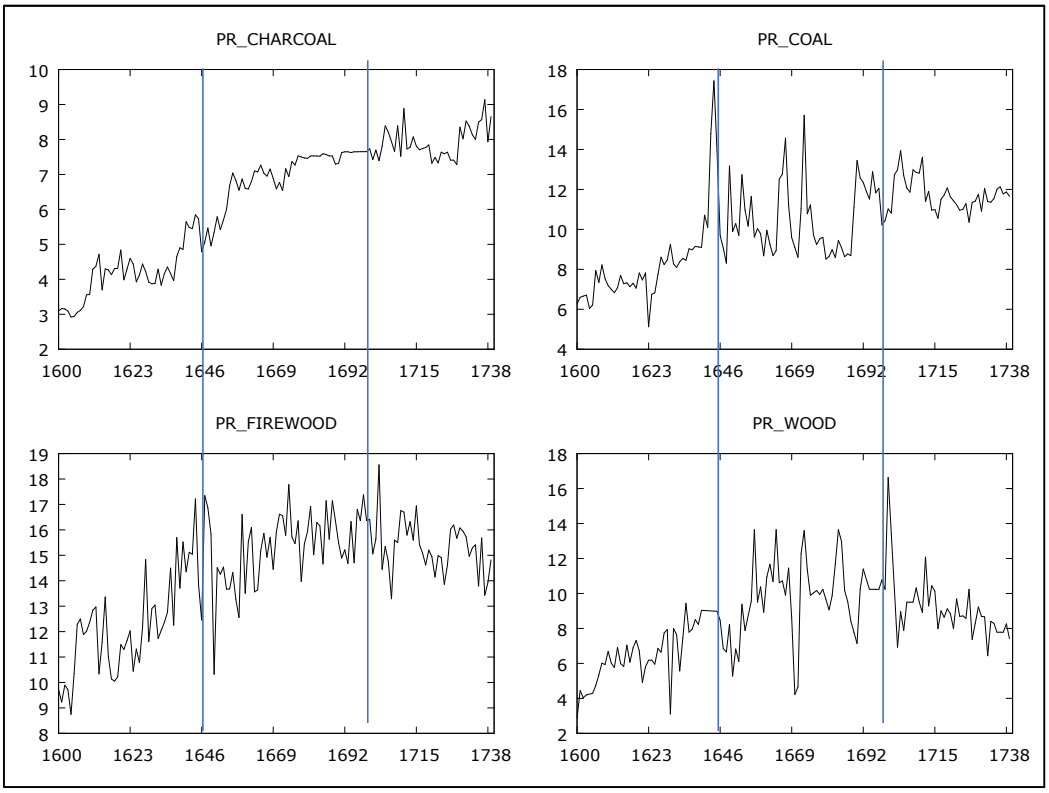
Own elaboration with Clark prices

Table 1. Testing the relationship between the demand for food energy and climate variables, in the short and long term. England and Wales.

Dependent variable	GROSS_WHEAT_ PER_HEAD 1645-1739	PR_RYE 1645-1739	PR_OATS 1645-1739	
Constant	6.12*** (0.0001)	5.60*** (0.0002)	2.44*** (0.0001)	
TEMP		−0.24*** (0.0060)		SHORT TERM
TEMP (-2)	0.14** (0.0184)			
TEMP (-3)	0.14** (0.0387)		−0.06** (0.0422)	
TEMP (-4)			−0.05* (0.0868)	
TEMP (-6)	-0.16** (0.0114)	0.20** (0.0329)		LONG TERM
TEMP (-7)	−0.019*** (0.0017)		0.06** (0.0374)	
TEMP (-10)		0.31*** (0.0014)		
SUMMER RAIN	−0.002*** (0.0027)			
SUMMER RAIN (-1)	−0.002*** (0.0013)			
SUMMER RAIN (-3)	0.001** (0.0451)	−0.002** (0.0476)		
SUMMER RAIN (-4)	0.001* (0.0700)	−0.004*** (<0.0001)		SHORT
SUMMER RAIN (-5)	0.002*** (0.0015)	−0.002* (0.0727)	−0.001*** (0.0024)	
SUMMER RAIN (-6)			−0.0006* (0.0541)	
SUMMER RAIN (-7)		−0.002** (0.0202)		LONG TERM
SUMMER RAIN (-8)		−0.004*** (0.0002)		
SUMMER RAIN (-9)			−0.0008** (0.0106)	
SUMMER RAIN (-10)	0.002*** (0.0010)		−0.0005* (0.0761)	
SPRING RAIN (-1)	−0.004*** (<0.0001)	0.004** (0.0201)		SHORT T.
SPRING RAIN (-2)			0.0014*** (0.0054)	
SPRING RAIN (-6)	0.003*** (0.0008)		−0.001** (0.0304)	
SPRING RAIN (-9)	0.003*** (0.0017)	−0.005*** (0.0024)		LONG TERM
SPRING RAIN (-10)		−0.006*** (0.0013)		
N	95	95	95	
adj R^2	0.54	0.48	0.28	
F	9.61	8.91	4.93	

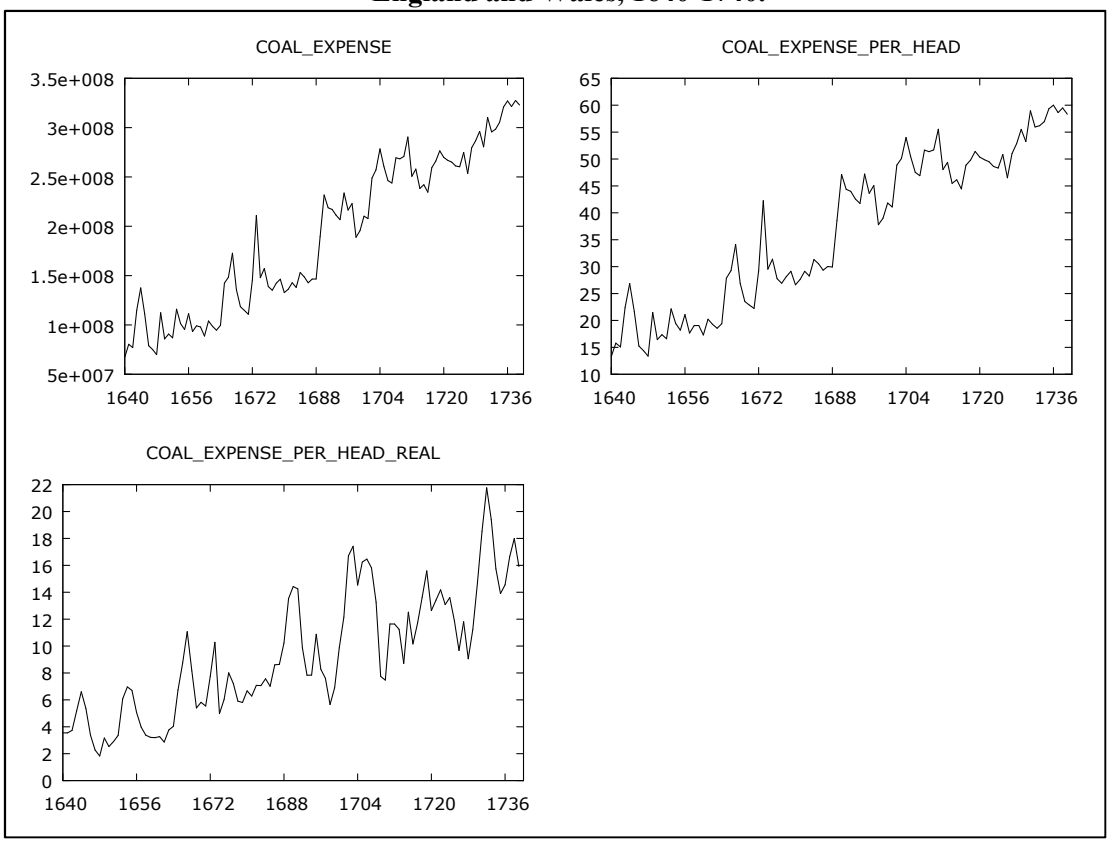
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Figures 5, 6, 7, 8. Prices of charcoal, coal, firewood and wood. England and Wales, 1600-1740.



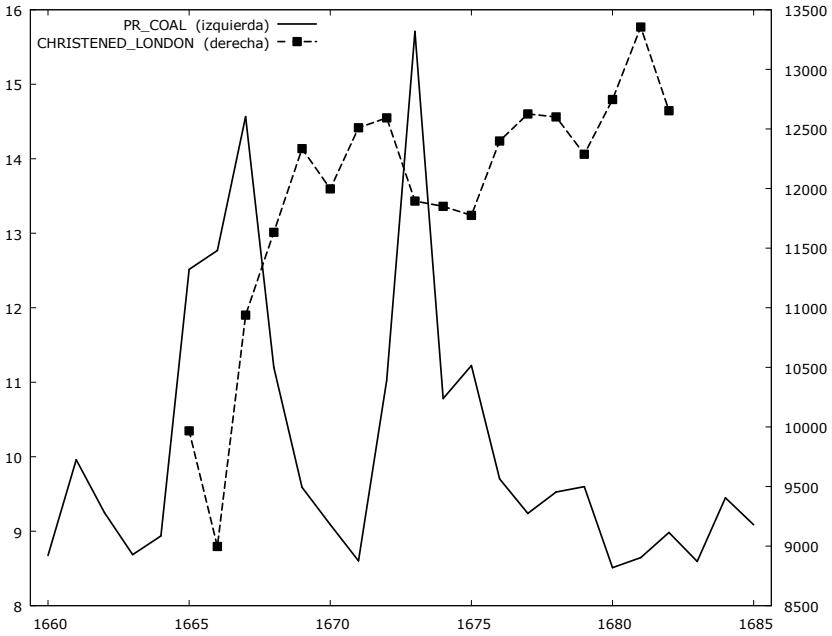
Own elaboration with Clark prices.

Figures 9, 10, 11. Coal expense, coal expense per head, real coal expense per head. England and Wales, 1640-1740.



Own elaboration with Clark prices.

Figure 12. Coal prices and baptisms, London, 1665-1682.



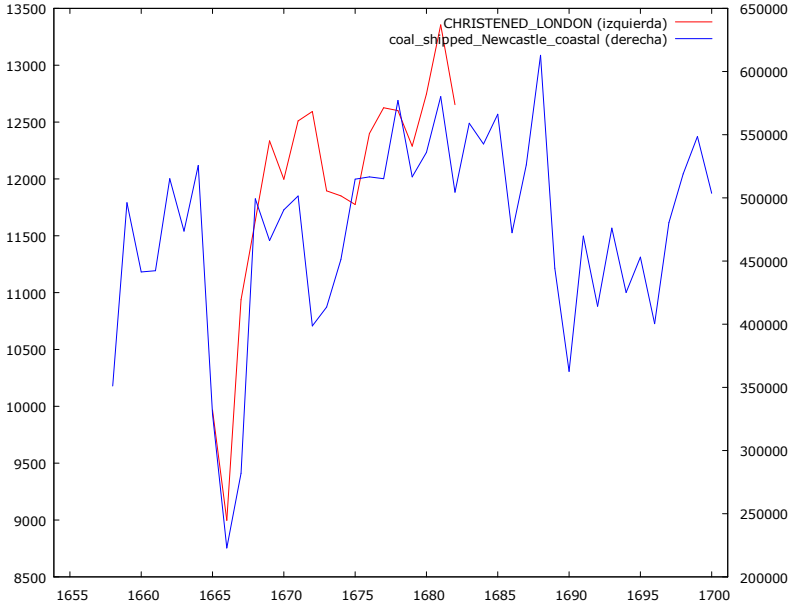
Own elaboration with Clark prices and Petty baptisms data.

Table 2. Testing the relationship between baptisms and coal prices, London, 1665-1682.

Dependent variable	CHRISTENED LONDON 1665-1682
Constant	15400.4*** (0.0001)
PR_COAL	−324.39*** (0.0042)
N	18
adj R^2	0.37
F	11.13

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

Figure 13. Coal shipments and baptisms, London, 1665-1682.



Own elaboration with Petty baptisms and Hatcher coal shipments data.

Table 3. Testing the relationship between baptisms, coal shipments from Newcastle plus seasonal temperatures. London.

Dependent variable	CHRISTENED_LONDON 1665-168
Constant	7639.47***
	(<0.001)
COAL_SHIPPED	0.00933767***
	(<0.001)
N	18
R^2	0.73
F	48.25

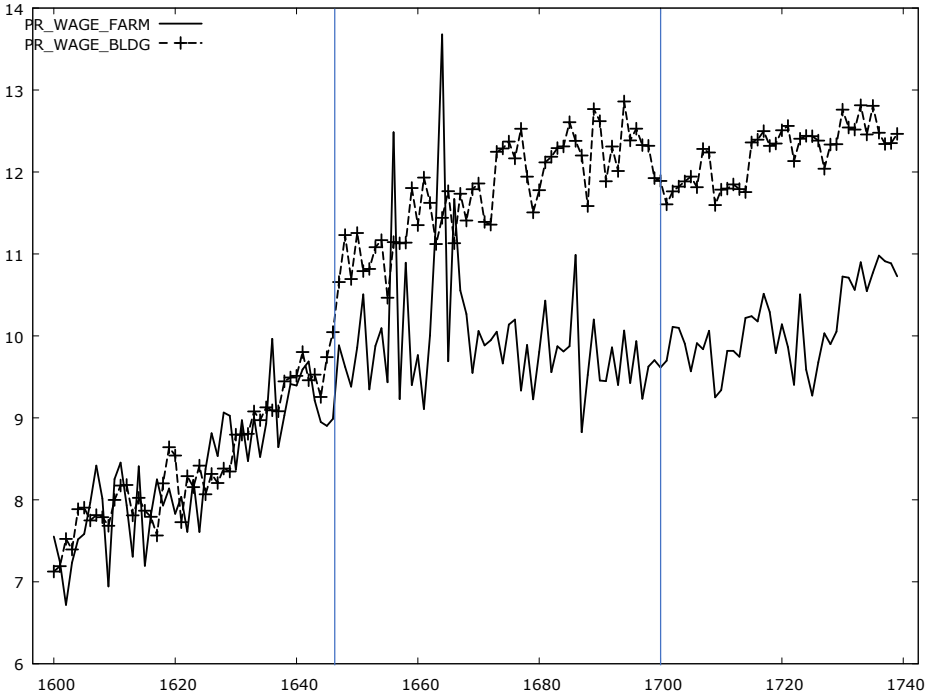
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

Table 4. Testing the relationship between Clark's London coal prices, and coal shipments from Newcastle plus seasonal temperatures, 1661-1700.

Dependent variable	PR_COAL_LOND 1661-1700 (1)
Constant	47.4083***
	(<0.001)
WINTER_TEMPERAT	−0.400246*
	(0.0517)
WINTER_TEMPERAT (-1)	−0.454780**
	(0.0281)
AUTUMN_TEMPERAT	−1.28203***
	(<0.001)
COAL_SHIPPED	-2.4983***
	(<0.001)
COAL_SHIPPED (-1)	-1.4555***
	(0.0016)
N	40
R^2	0.72
F	21.26

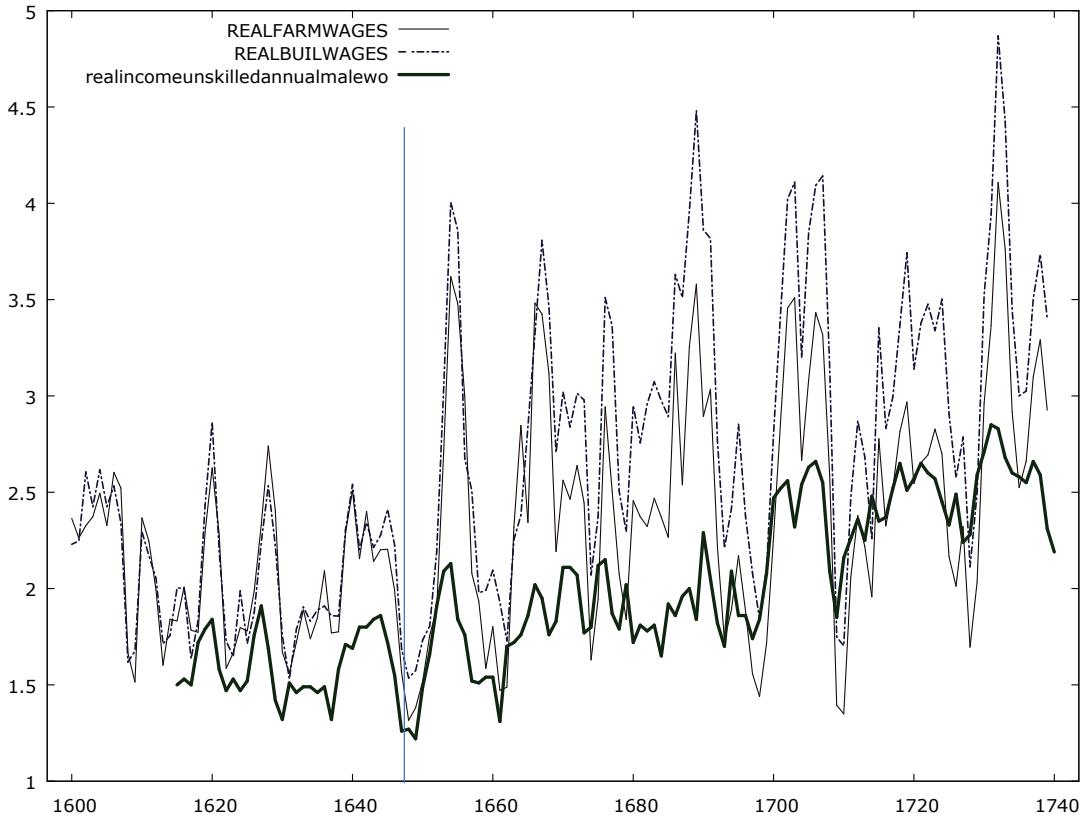
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

Figure 14. The divergence between the two wage sectors originated by climate crisis. England and Wales, 1600-1740.



Own Elaboration with Clark wages

Figure 15. The divergence between the two wage sectors and annual incomes. England and Wales, 1600-1740.



Own elaboration with Clark wages and Humphries & Weisdorff estimates of unskilled real incomes

Table 5. Testing the relationship between temperature and wages. England and Wales, 1645-1700.

Dependent variable	REALFARMWAGES (1645-1700)	WAGE_CRAFT (1645-1700)	WAGE_BLDG (1645-1700)
Constant	1.26742 0.5582	18.9480*** <0.0001	10.8484*** <0.0001
TEMP	0.210329** 0.0197		
TEMP (-1)	0.231077** 0.0112	−0.281945** 0.0104	−0.141323** 0.0196
TEMP (-2)	0.303928*** 0.0013	−0.182646* 0.0998	−0.173806*** 0.0049
TEMP (-5)		−0.220804* 0.0616	
TEMP (-7)	−0.210621** 0.0452		
TEMP (-8)	−0.206879** 0.0486		
TEMP (-9)	−0.198464** 0.0639*		
HOUSING_PRICES (-1)		0.207280*** (<0.0001)	0.165621*** <0.0001
N	56	56	56
R^2	0.36	0.60	0.73
F	4.66	19.41	46.6

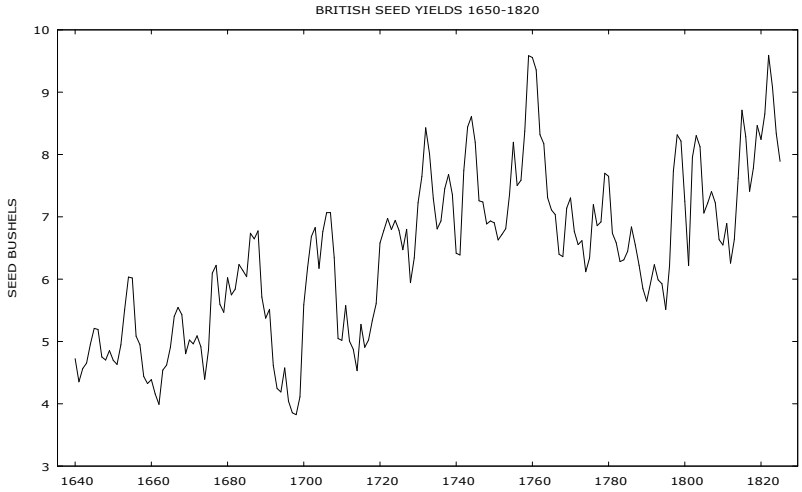
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Table 6. Testing the relationship between animal work and temperature. England and Wales, 1645-1700.

Dependent variable	HORSES 1645-1700	PIGS 1645-1700	COWS 1645-1700	BULLOCKS 1645-1700
Constant	694.556*** <0.0001	34.3079*** <0.0001	140.235*** <0.0001	−47.6391 0.1963
TEMP	−12.5748** 0.0478		−2.08483** 0.0105	5.88391*** 0.0093
TEMP (-1)	−17.0555*** 0.0089	−0.936031* 0.0767	−2.60439*** 0.0019	6.26005*** 0.0064
TEMP (-2)	−14.8932** 0.0208	−1.37797** 0.0108	−2.32712*** 0.0048	4.79468** 0.0333
N	56	56	56	56
R^2	0.21	0.15	0.29	0.24
F	4.74	4.5	7.31	5.58

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Figure 16. British seed yields, 1650-1820.



Own elaboration with estimates of wheat production by Martínez-González et al 2019

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