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Abstract

In this paper I analyze the ‘Nitrogen Paradox’ stated by Robert Allen in his interpretation of the English Agricultural Revolution as an adaptive response to the agro-climatic impacts of the last phase of the Little Ice Age. The colder and more humid climate during the second half of the 17th century negatively affected the yield of the land, but it also accelerated change in the agrarian sector. The first evidence suggests that the efforts from farmers could begin to be felt in the cold period from 1660-70. Although the results were not very visible at first, this increased effort prevented a greater fall in production. This can be seen in the wheat series, where production rose slightly. As wheat demand stagnated due to a slowdown in the rise of the population, wheat prices fell, determining the evolution of relative prices and a diversification in production. In others words, the crucial driving forces of the transition from the crisis to the agrarian revolution were climate, population and the capacity of adaptation. In order to prove this hypothesis, I developed new intermediate tools, opening an interesting research field in economic history.

JEL classification: N53, O13, Q10, Q24, Q54, Q55, Q57.

Keywords: Climate Change, Agrarian Revolution, Adaptation.

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BACKGROUND

So far, the impact of climate on English agriculture has been little studied. We have a few references on its dynamics in the short and long term, but there is little research linking the LIA (the Little Ice Age) or Maunder Minimum (1645-1715) to the Agrarian Revolution and the possible adaptive response from the farmers¹.

It is well known that during the 17th century the weather in England generally worsened. This phenomenon has been related to a long fall in the solar activity, the Maunder Minimum², but this solar minimum is likely to have coincided with other adverse climatic forces³. In any case, average temperature fell but rainfall variability and humidity increased⁴. Production of dry materials from crops decreased more, in proportion to reduced solar radiation absorbed by plants⁵. The energy balance between the heat latent in the soil and the evotranspiration levels of the plants, as well as photosynthesis processes and respiration became more unstable.

A past generation of agrarian historians has ably examined the issue of climate. In their pioneering works, W.G. Hoskins (1964, 1968), E. L. Jones (1964, 1965b: 155-156), Kerridge (1967) and Bowden (1967: 617-620-623) demonstrated the role of climatic anomalies during 1680-1730 in ‘breaking’ the cycles of good crops, spreading epizootics amongst livestock, and promoting changes in soil management. Since the decade of 1980, a second generation of historians has followed (Overton, 1989, 1996; Turner *et al*, 2001, 2003); and other authors have studied the relationship between climate and demography (Galloway, 1985, 1986; Appleby, 1979, 1980). Recently, a third group of studies have appeared, which have tried to measure the relationships between climate and agriculture using econometric methods during that period, including recent studies published by Michaelowa (2001), Brunt (2004, 2014) and Waldinger (2014).

The first and second generations of agrarian historians identified excess water in summer and frost in spring, not drought, as the main threats to crops. Moreover, they inferred some connection between certain agricultural techniques and the worsening of climatic conditions (Jones, 1965; Bowden, 1967). They related the spreading of water meadows and the enclosure of pastures to offer additional fodder in place of open

¹ Adam Smith (1778: 253, 256, 259), W.H. Beveridge (1921), G. Stanhill (1976:2), Kelly and O’Grada (2014a), L. Brunt (2004, 2014), W. G. Hoskins (1964, 1968), G. Utterström (1955), E. L. Jones (1964), A. B. Appleby (1978, 1979, 1980), P. Bowden (1967), M. Overton (1989), A. Michaelowa (2001), R. W. Hoyle (2013) and M. Waldinger (2014).

² The astronomer Jack Eddy published in the magazine *Science* (1976; 1189-1202) a famous article in which he provided scientific evidence of the existence of this solar minimum, named after the English astronomer who discovered it, E. W. Maunder (1851-1928). See also Parker, 2013.

³ Increase of clouds, volcanic dust and fluctuation in the North Atlantic. See Lean *et al* (1995), Luterbacher *et al* (2001, 2010), Guiot *et al* (2010), Yasuhiko *et al* (2010). Büntgen *et al* (2013).

⁴ Luterbacher *et al* (2001); Büntgen and Hellmann (2014); S. White (2014); G. Parker (2013).

⁵ According to the mechanism reasoned by Monteith, (1977:279).

fields⁶. Second, cold in spring and too much rain in summer damaged wheat more than cheaper cereals or pulses, which became an alternative to wheat. Not only could they be substitutes in case of a bad crop, but they also allowed greater cattle-raising which would also contribute to crop improvement increasing manure (Jones, 1965; Bowden, 1967; Overton, 1989; Turner *et al*, 2003; Hoyley, 2013). In fact, studies show evidence that farmers were aware that the spread of such agrarian techniques were aimed at overcoming climate disturbances (Jones, 1965b; Overton, 1989; Appleby, 1979, 1980; Hoyley, 2013).

The latest econometric studies started by A. Michaelowa (2001) have shown a clear relationship between climate trends and economic growth, proving that the climatic amelioration between 1700 and 1740 stimulated British population growth and agrarian production. Following Pfister's works in Switzerland (1988), he found a clear link between climate change (the Maunder minimum) and cereal prices⁷. The fall in prices during the second half of the 18th century encouraged investment and innovation, and since the prices of meat remained stable, a combination of cattle-raising and grain crops was favored. Therefore, the consumption of food helped the middle and lower classes grow, although the hotter summers kept mortality high. L. Brunt (2004) also proved that the main driving forces of British wheat production in 1770 were climatic and technological⁸. Waldinger (2014), by means of panel statistical techniques, connected rising temperatures with falling wheat prices in northern cities and rising prices in the south. This pattern of results suggests that temperature changes are related to changes in agrarian production (2013:3)⁹.

There are also complex issues of agrarian social change. The traditional historiography focused on enclosures, the size of the farms and the leadership of "learned pioneers" during the 18th and 19th centuries. However, the historiographical focus shifted to the study of open fields and to an earlier period, 1650 to 1750¹⁰. This started with E. L. Jones (1965a), who proposed some important ideas: first, improvements were carried out between 1660-1750; second, these improvements were applied both in open fields and enclosures (an integrated position, very close to the results in my research); third, the different types of soil (light or heavy) had an influence on these improvements; fourth, there is an apparent contradiction between the fall in the relative prices (fall in the prices of wheat and the rise or stability of cattle prices), and the low demand (caused by a population decrease or stagnation in spite of incipient urban growth). Jones's originality, not overcome yet, lies in his hypothesis claiming that agrarian investment had different speeds and its protagonists were changing, i.e. there were different waves of innovation, an idea which will be dealt with later on in this work. According to Jones,

⁶ E. L. Jones (1965b:155-156). Jones would deal with this issue in 1981, when he connected warm weather with advantages in agricultural techniques and innovations (Dell *et al*, 2013).

⁷ Michaelowa (2001:5).

⁸ L. Brunt, (2004:219).

⁹ In the same way, the changes generated by temperatures in small towns were bigger than those generated in big cities, and much more diversified.

¹⁰ Allen (1988, 1989, 1991, 1992, 2005); E. L. Jones (1964, 1965); J. Thirsk (1967, 1984, 1985, 1997).

tenants were the first to increase their investments when landowners were doing just the opposite, and later the efforts of landowners increased whereas those of the tenants fell. All this taking into account that the types of investment were different: tenants invested in land management and cattle, whereas landowners invested in infrastructures and facilities (Jones, 1965a).

This debate was revived in the works of Robert Allen (1992) and Mark Overton (1996) amongst others (Campbell and Overton, 1992). Whilst the former agreed with Jones's thesis emphasizing the leading role of the yeomen in the spread of agrarian innovations, especially during the period 1650-1750 (Thirsk, 1967, 1984, 1985, 1997), Overton followed the tradition that linked agrarian innovation and enclosure processes (Chambers and Mingay, 1966), placing the period of increase in yields in the second half of 18th century and giving more importance to the landowners' investment (Overton, 1996).

Robert Allen was one of the economic historians who related the exceptional growth of labour productivity between 1600 and 1800 to the rise in the yield of cereals and the merger of little fields into great capitalist country estates, reducing the employment rate per acre¹¹. In his search for the "Holy Grail" of yields he stated that the improvement of the yield of the land was due both to the increase of nitrogen stock (convertible agriculture, growing of pulses, sainfoin) and higher efficiency in its use, thanks to the changes in the way of growing and working the land (new tools and seeds, better labour). According to Allen, the word "revolution" needs qualifying: the process of change to higher yields was gradual, due to the slow growth of the stock of nitrogen in the land¹².

Allen suggested the Standard Model of Nitrogen as a starting point¹³. However, he did not take into account the temporal variability of the stock of nitrogen (**N**) or its mineralization rate (**r**). This variability can be explained, directly or indirectly by changes in temperature, rainfall, solar radiation and volcanic aerosols. For example, it is difficult to accept a constant **r** in long periods, since it decreases during climatic cooling¹⁴. *Ceteris paribus*, lower temperatures and shorter growing seasons lead to a lower mineralization rate and a slower loss of the stock of organic matter in the soil (OM) and humus¹⁵.

It is well known that after 1645-46 the climate of England became colder and wetter, a fact that reduced **r** and the decomposition speed of OM. There seems to be historical evidence that farmers struggled to avoid this. Farmers engaged in the following

¹¹ Allen (1988:62).

¹² Allen (2008). See also the argument of Mark Overton (1996), who considers the period after 1750 as the one showing the greatest changes.

¹³ Allen (2008:188).

¹⁴ Loomis *et al* (2002:190-191).

¹⁵ H. Jenny (1930). As Loomis *et al* stated, "the sensitivity of the balance level of humus to temperature and rainfall means that many changes may occur in the CC" (2002:191).

practices in order to maintain or increase OM: (1) including more pulse rotations in order to fix nitrogen in the soil; (2) slowing down the conversion of fallow land to crops¹⁶; (3) slowing down the increase of the cultivated area¹⁷; (4) maintaining permanent separation crop-pastures¹⁸ within a convertible system, the results of which were brief and which was used out of necessity or interest¹⁹; (5) replacing crops with pastures, in both uplands²⁰ and lowlands²¹; (6) opening new pastures; (7) with improvements of the techniques applied to pastures, such as the progressive reduction of common lands, enclosures and stone removal and finally use of water meadows. To Allen, one of the most impressive aspects of agrarian change was the increase of pasture and the reduction of communal tenure²². Besides the strong increase in surface (from 4 to 9 million acres between 1600 and 1700, and from 9 to 12 million between 1700 and 1750), two other relevant changes occurred; one related to communal pasture enclosures and the other related to the technological improvement. In the highlands of England and Wales enclosing pastures increased their productivity, since enclosures were made with the stones from the pastures and their removal from the surface improved yield. In short, Allen draws our attention to some key developments in English agriculture, such as changes in pastures management and the improvement of their yield. This could have begun an increase of the OM stock.

Another great qualitative advance was the better use of water meadows. During the period 1645-50 the “difficult” technique of floating started to become relevant, even giving rise to professional floaters. Although it was not new, this system was considered to be one of the great innovations in the management of English pastures by J. Thirsk and E.L. Jones²³. There were “water” pastures placed next to rivers or streams of water, driven to produce rich hay crops and stimulate grazing, with canalizations that allowed a continuous water flow at particular times. Through floating, mud rich in nutrients settled and a beneficial oxidation of the soil occurred. This technique also allowed a

¹⁶ This process became stagnant during the 1650-1700 period: 3.24 million acres in 1500, 2.16 in 1600, 1.88 in 1650, 1.91 in 1700, 1.59 in 1750, 1.28 in 1800 (Broadberry *et al*, 2011b:30, table 10).

¹⁷ The data show a decrease in the total cultivated land from 7.74 to 7.64 million acres between 1650 and 1700, in contrast to its long-term rise since 1450 (Broadberry *et al*, 2011b:30, table 10).

¹⁸ See Overton (1989: 291) or A.Smith (1778:286). Despite the generation of manure in barns (winter), the division system between pastures and crops was relatively inefficient (Shiel, 1989:666-67). On the contrary, it was a OM reserve: with the increase in the new rotation systems, the “night manure”, the new ploughs and the changes in agrarian constructions, this reserve allowed higher productivity.

¹⁹ Although Kerridge focused the agrarian revolution on the up and down or convertible agriculture (rotation of pastures into crops and vice versa), E.L. Jones (1965a:156) and Shiel considered it of little importance during the 17th century (Overton, 1989:293-294). Despite the important release of nitrogen through the ploughing of these pastures, in a few years the situation became the same or even worse (soil acidification). Overton even pointed out that there was scarce written proof of its feasibility in the probate inventories. Neither did Kerridge provide enough proof, so this issue had to be further researched into.

²⁰ Broadberry *et al*, quoting Grove, 2004, and admitting the *LIA* (2011a:9).

²¹ Because of the long trend to turn crops from the heavy claylands in the centre of England into pastures (Bowden, 1985: 47-48, 55-56, 61-62). According to Broadberry *et al*, the importance of pastures in England was increasing, including permanent pastures. There was a process of elimination of forests in favor of crops and pastures with the change of the energy model from wood to coal. The increasing urban demand also stood in need of more permanent pastures to the detriment of permanent crops.

²² Allen (2005:6).

²³ J. Thirsk (1985, pp. 180-181, E.L. Jones (1965a, pp. 155-156).

reduction of the effect of frost in winter, promoting early grass growth and higher hay production in summer. Water meadows yielded up to four times the usual quantity and density of hay, which enable the year-round feeding and early breeding of livestock. Water meadows allowed one to struggle against climatic adversity by the management of canalization with chalk and covering to protect water against frost. This water was later drained and many essential nutrients for plants were collected. With all this the quantity of sheep and cattle could be kept and even increased in winter and summer as well, producing much more manure, OM, and nitrogen. If it were not for this system, the impact of the climate change on livestock would have been more intense.

But the quantity of mineral nitrogen (in Allen's model, F is the level of free nitrogen) does not only depend on **r** and **OM** variability. First, there is a direct input flow (rainfalls and free, non-symbiotic fixation) and output (denitrification, volatilization and leaching), which also depend on the climate, besides other factors²⁴. Allen assumed that this input and output were balanced, but in colder and wetter periods this balance could be uneven. We must remember that the microbiological processes of the soil depend on temperature, water and pH. Microbial activity slows down at low temperatures, affecting the speed of decomposition of OM. One of the processes of mineralization, ammonification, generated by microbial matter, is also very sensitive to temperature. The increase of humidity promotes denitrification, so that N returns to the atmosphere as gas in a greater quantity. On the other hand, there are some factors which affect the performance of pulses and the N quantities yearly fixed. The assimilation and fixing of N is proportional to biomass production, so that if biomass declines in colder weather, N fixing also declines²⁵.

Besides N content, climate influenced fertility in other ways, including the content of phosphorus, potassium, and acidity in the soil, and the germination and growth of plants. In the case of phosphorus, although its function has been historically minimized²⁶, Newman and Harvey pointed out that it could have been the main soil fertility factor until the 19th century²⁷. Phosphorus generation (from OM mineralization) is usually deficient during cold periods. That would mean that during the LIA (in the long term) its replacement management had to be improved. Climate change also affected the development phases of plants. The flowering period of the winter variety of wheat was critical and frost or a deep temperature fall could ruin the crops. The wet and cold springs, typical of the second half of the 17th century, would therefore affect agrarian production, forcing farmers to introduce new seeds such as Red-Stalked Wheat in 1670 (Oxfordshire), or White-Eared Red Wheat in 1650. As for barley, early varieties

²⁴ The increase in humidity and soil reflectiveness generates greater denitrification; the increase of urine in the soil generates greater ammonium volatilization and a greater humidity index together with higher nitrate levels from manure or urine cause higher lixiviation. (Loomis, 2002:225-229).

²⁵ Loomis *et al*, 2002, pp.209, 222, 230.

²⁶ Allen, 2008.

²⁷ Newman y Harvey (1997:136). On the other hand, pH seems to be affected by temperatures in the very long term. However, historiography indicates that farmers, in their struggle, increased their OM contributions, but they did it in a rather much wetter soil, which meant more acidification.

such as narrow-eared barley became predominant in the 17th century. These varieties were planted in May “better than in March” and stored in the barn in two months or less, becoming very valuable in wet and cold springs typical of the climatic downturn, and were very well-known in Cornwall and widely planted in Oxfordshire²⁸. Another variety which was widely spread was a spring barley, planted in Lincolnshire and typical northern species were successfully adopted in the south. All this makes me think that climate was an influential factor in seed selection, an issue still to be resolved²⁹.

Since this balance of factors was so weak, when crops grew in less than ideal conditions, slight variations in the environment could cause great variation in the yield and in the harvest index HI³⁰. This fact explains part of the nitrogen variation in wheat output between 1660 and 1740 ([graphic 1](#) in the appendix). For example, in the pre-industrial era, the nitrogen available to crops from rainfall and free nitrogen was as little as 6kg per ha per year. With a harvest index HI of 0.4 (at that time it must have been lower than today) and 0.02 kilograms of N/ha per kilogram of grain, it equalled about 120 kilograms of wheat on an average crop of 900 kilograms, that is 13.3 per cent of the total. With an elasticity of price for the demand of -0.4, this implied price variations of about 33 per cent. Consequently, slight variation of N caused by weather changes affected prices considerably³¹. This conclusion seems to be confirmed with the works by Liam Brunt (2014): not including climate in the calculation of yield distorts the agrarian historical series.

This revision of Allen’s model allows us to see in more detail how climate change could affect agriculture, and to gather historical information about some of the adaptive measures adopted by the rural world³². However, apart from climate, there was another driving force, population. The stagnation of English population has been pointed out as one of the causes of the depression in prices of wheat in late 17th-century England and Europe, favouring cattle-raising and the diversification of consumption (Slicher von Bath, 1959; W. Abel, 1978). It is also known that wheat supply was higher than demand between 1650 and 1750. So, why did it continue to increase?³³

²⁸ Thirsk, 1984:68-169.

²⁹ Mark Overton, 1989, p. 90.

³⁰ Loomis *et al*, 2002, p. 67.

³¹ I have supposed elasticity of 0.4 but some authors place to the figure as low as 0.1 (Fogel). This means that prices would be even more sensitive (133 per cent). A 900-1000 kg production of wheat was somewhat common in those times. R. S. Loomis (1978) estimated the N cycle on an English farm of the 14th century where 16.1 kilograms/ha of N were yearly produced. Rainfalls, free N₂ and fixing with peas was 8 kilograms/ha of N, higher than that of the seed (2.5 kilos/ha), straw waste (2.5 kilos/ha) or manure (3.1 kilos/ha). If the direct contribution of N was already relevant by then, it is reinforced by the indirect effect of climate, catalyzing changes in almost all the processes that affected the yield of the crops as the ones mentioned above (fixing, waste, manure).

³² For a critical review of Allen model, see E. Tello, J.L. Martínez, G. Jover, J. R. Olarieta, R. García-Ruiz, M. González de Molina, M. Badia-Miró, V. Winiwarter and Nikola Koepke (forthcoming).

³³ Already in 1965, Jones rightly observed that offer was ahead of demand. Production improved in spite of stagnant demand, innovation and price deflation. In his article, Jones deeply studied the different ways adopted according to the different types of soil or farm activity (E. L. Jones, 1965a).

MODELS AND METHODS

In an effort to explain these issues I consider three approaches: production, relative prices, and the Ricardian rent approach (R. Mendelsohn, D. W. Nordhaus, D. Shaw, 1992). First, we analyse the physical relationship climate-output in the short term. Then, we identify the driving forces of the agrarian market. Next, we infer the existence of adaptations. Finally, we try to understand the relationship between these driving forces and the different adaptive periods from a historical point of view. Since this is an analysis at the country level, econometrics is the main tool used, but also local research from primary sources would be necessary.

The starting point is a wheat production function (dependent variable) depending on land, labour and capital. In this research the main inputs are land and labour. A novelty, besides presenting the series of wheat, is including the “climatic box” as an explanatory variable. The objectives of this first approach are threefold: 1), since it seems obvious that the climate affects crops and land yield, if a relationship is detected, that means that the data are valid and we can continue to research; 2), this function includes climate as the main force in the short term, a fact that allows us to qualify Allen’s model of nitrogen and lets us correct slants in the traditional estimates of the yield of the land; 3), it opens new possibilities in the research for evidence of long-term effects and adaptive processes.

Next I try to integrate the supply and demand by inserting physical production into the market by means of the mechanism of relative prices. This way I try to determine the driving force of agrarian change. My proposal is to determine whether climate was a significant factor, together with population levels and agrarian improvements. The third step – and probably the most difficult one – goes into the relationship between climate and adaptations, by means of the production approach (analyzing separately the depressive and expansionary periods) and the Ricardian rent approach. Next, I try to consolidate my results from a double perspective, theoretical and historical. In order to do so, I analyze the combinations climate-population and I compare them to what really could have happened, i.e. what Economic History says.

DATA

Climatic Data

Although the pre-industrial figures are scarce, as far as climate is concerned we have temperatures, solar radiation, volcanic dust and rainfalls ([graphics 2, 3, 4, 5, 6, 7](#) in the appendix). We have a series of monthly records of temperatures which start in 1659, from several towns in the Midlands (G. Manley, 1974, series *TEMP*). Although there are other temperature series, they do not come from direct measurements of the soil, but

rather recent reconstructions³⁴. I have chosen Manley's series for various reasons: first, it offers monthly information; secondly, it is the only one coming from measurements on the ground, even when it is likely to contain biased calibration; the third reason is that they are temperatures from England; and the fourth is that, although I do not agree with it, it avoids the criticism by Kelly and O'Grada (2014) and McShane et al (2011) about the reliability of proxy reconstructions of temperatures. Manley's series presents some limitations: One is that it starts in 1659, that is, after the phase of accelerated cooling began (approximately in 1645), so many years of analysis are missing (when we combine this series with other containing data prior to 1659, these data cannot be used). Another one is that it does not represent the whole country but only a few specific points of it, which makes us remember that we must never lose our perspective.

As for solar radiation and volcanic activity, we have the series *SOLAR_IRRAD* and *DVI_VOLCANIC_INDEX*, both present in Mann et al (2000). According to Lean et al, irradiation explains 74 per cent of temperature variations in the pre-industrial phase³⁵. To J.L. Monteith and C.J. Moss, solar radiation falls on England in a nearly uniform way³⁶ and the different distribution of rainfalls determines the potential evaporation. The same Monteith established a positive relationship between dry material from the crops and the radiation intercepted. This could justify the use of radiation as an influencing datum. According to the author, most of the cultivated lands are in +/- 10% of 9MJ/m² daily average per year. This means that the regional differences would have been caused by other factors, such as rainfall.³⁷

Nevertheless, we do not have direct humidity, rainfall or weather instability records in the 17th century apart from the references written at the time by A. Smith (1778), Comber (1808) or T.Tooke (1838). However, some recent academic works are beginning to throw some light on this issue through May-August (summer) rainfall reconstruction in the south of England (Rinne et al, 2013, *RINN* series), rainfalls between March and July (spring-summer) in the east of England (Cooper et al, 2012, *RICH* series) and rainfalls between March and July (spring-summer) in the south and centre of England (Wilson et al, 2012, *WILS* series). I will use this series because I do not have any others. However, we must take into account that: a) they are reconstructions; b) measurements come from trees located in specific territories, when I am going to analyse the whole country; and c) it seems that rainfalls have a more local and diverse incidence than temperatures, depending upon many geographical factors³⁸.

³⁴ One of them corresponds to those of J. Luterbacher's et al (2006), which presents the average European temperatures organized by seasons. A second reconstruction is the one developed by Guiot et al (2010), with annual temperatures April-September organized by latitude and longitude of the earth every 50°, being the most suitable in the case of England *TAS_2_5W_52_5N* (west of England, near Birmingham) y *TAS_2_5E_52_5N* (east of England, but near the sea), and reconstructed from 117 different intermediate indicators (including tree rings, historical documents, pollen and ice records).

³⁵ Global data, geographically speaking.

³⁶ J.L. Monteith and C.J. Moss (1977:277-278).

³⁷ Monteith (1977:280).

³⁸ Thanks to Teresa Rinne and Richard Cooper for having provided me with their series.

There is also another important issue. If we draw an individual graphic analysis, it is rather difficult to interpret trends as a whole. An innovative solution is to integrate the series in the same graph, standardizing them from their means and standard deviations, making them comparable. That makes me consider two ‘quantitative’ ways; the first is the one I use in this paper (by means of the original series); the second is an index that I call Climate Index of the Productivity of the Land (CIPL). Changing the weightings of each climatic input, several alternative CIPL series can be calculated ([graphics 8, 9, 10, 11, 12, 13](#)). In these series a climate worsening can be observed until the early 18th century. I have also tested how all the climatic indices have predictive capacity in the production of wheat ([chart 2](#)). However, it is essential to have the support of soil scientists and agrarian biologists available so as to be able to use these series.

Production Data; Wheat Annual Series in bushels

Since there are no monthly/annual physical measures of the output (volume and weight), I estimate the English production in bushels and kilograms³⁹. To do this, I will use the influential equation Davenant-Jevons-Bouniatian (Wrigley, 1992), adjusted by means of the most reliable trend indicator: population⁴⁰. [Graphics 14, 15 and 16](#) in the appendix show the resulting series (wheat supply, moving average wheat supply and wheat production). We must distinguish wheat supply from wheat production. After the harvest, one part of the cereal is used as seeds for the land or food for livestock (there is even a part kept for other uses such as personal consumption or as a means for payment/exchange in kind). The resulting offer faces demand and the farmers’ expectations, so new factors come into play⁴¹. Underlying all these considerations, I obtain series of gross production OUTPUT_BUS, the one I use in the econometric modelling. We can see how the wheat supply increases slowly and gradually, settling at

³⁹ As an example, among more than 1500 “farm inventories” in Hampshire only two country estates offered this type of information punctually, so yield had to be calculated by using indirect procedures and period grouping. (M. Overton, 1989; P. Glennie, 1989:27, 257). Undoubtedly, thanks to the works by economists and historians we are closer to obtaining series of physical production, but the data is still fragmented in time and among counties. These figures were obtained through indirect calculations (Clark, Broadberry *et al*) or through works carried out from primary sources, in country state records or probate inventories. (Allen, Overton, Glennie, Yelling, Turner *et al*, Theobald) and also in specific regions. G. Clark’s series (2002) offers decennial information about the real output based 100=1860 between 1550 and 1910. A series of Broadberry *et al* (2011b:31) presents an agrarian GDP based 100=1700 with annual information. The problem of this series is that, even with constant prices, the agrarian GDP in monetary units does not reflect the climate’s physical impacts properly. If adverse weather reduces crops 50 per cent but prices increase, let us say, about 100 per cent, the fall of the physical production is not visible in monetary values.

⁴⁰ The equation is $y = 0,757/(x - 0,13)^2$, (Wrigley, 1992:139), where y stands for the price of wheat (G. Clark (2004, 2005, 2007), and x represents the proportion between the real quantity and the usual quantity. As the usual quantity we take the one supplied by Broadberry *et al* (2011b, 31) in 1700. The price of 1700 takes the unity. We deflate prices according to the population growth rate (taking Broadberry’s POP_INDEX to use data in a harmonic way) because it is the most consistent trend variable in wheat demand. I dismiss the use of the GDP deflator and other price indexes because of their lack of independence from the price of wheat. As for the controversial issue of the role of silver in prices, in this first estimate I have assumed its influence as neutral. Its inclusion is left for the future.

⁴¹ Demographic pressure, urbanization, substitute product prices, imports, storage, inflation, production costs and social dynamics.

over 30 million bushels. That means a progressive, soft growth; and consequently, as Allen states, the Agrarian Revolution was a long and slow process where farmers were able to adapt to changes.

When I put the series to different tests, its strength is surprising. First, I combine the series with gross climate data, without adding any other factors, using multiple regression models. If any relationship were detected, it could mean that the route is correct. Secondly, I check the crops chronology to see if it matches my series. Third, I contrast the results of the series with the figures partially obtained by historians and economists. If my series stays within reasonable intervals, my approach could be right, although there is still much to do. In all the tests, the results are acceptable, which means a lot, taking into account the fragility of the figures and the initial assumptions.

As for the econometric test, an explanatory capacity of 41 per cent is obtained ([table 4](#) in the appendix), with only the temperature, rainfall, volcanic dust and radiation. Regarding the second test, the series proves what historiography says from price movements. Bowden suggested the existence of bad crops during the second half of the 17th century, from 1645-51, 1656-63, 1695-99, and good crops in 1664-72, 1685-91, 1714-24, and 1741-49⁴². Additionally, Hoskins qualified as deficient the crops from the years 1646, 1657, 1710, 1711, bad or very bad those from the years 1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728, 1729 (workhouses for the poor appeared in the last decade of the 17th century and the government blocked all kinds of exports during the most critical periods); “average” years were 1699, 1718, 1719, 1720; and good years 1652, 1653, 1654, 1655, 1665-72, together with the 80s, generally good, and the periods 1700-1707 or 1721-23⁴³. Finally, we have the sequence of the food riots, most of which occurred during the years of production fall⁴⁴. All these data match my series.

A third proof of the reliability of the calculated series is that it matches the physical data provided by Broadberry *et al* in the decades 1650 and 1750 ([table 3](#))⁴⁵: around 1650 they give a figure of 27.01 million bushels with respect to the 27.12 that I obtain. By the mid 18th century, this comparison is also reliable: 31.48 against 31.89 million bushels⁴⁶. Additionally, keeping the wheat surface constant (only as a first test), I obtain an average figure of 12.6 bushels/acre for the whole country in 1660, 14.8 in 1720 and 15.35 in 1730. Although it is difficult to compare with the research carried out using probate inventories or indirect estimates, given the regional differences, we find that Wrigley points out an average of 10 bushels of wheat per acre in the Davenant era, or from 13 bushels/acre in 1660 to 15 in the decades 1720 and 1730, according to

⁴² Bowden, 1984, p.56.

⁴³ Hoskins, 1968, pp. 20-22.

⁴⁴ B. Bohnstedt, 2010, pp. 33-54.

⁴⁵ Net output of seeds to grow or animal feeding.

⁴⁶ Broadberry *et al* (2011b:31)

Overton⁴⁷. All this suggests that, once again, the series seems to match. Overton himself provides the data of 14.5 in 1660-1679 [13.8-18.8], 15.9 in 1680-1709 [14.39-19.39] and 19.2 in 1710-1739 [14.86-19.86] for Norfolk and Suffolk (gross data)⁴⁸. As for Lincolnshire he gives a figure of 15.1 between 1650 and 1674 [13.85-18.85], 14.7 between 1675 and 1699 [13.88-18.88], 16.5 between 1700 and 1724 [14.88-19.88], and 18.7 between 1725 and 1749 [15.56-20.56]⁴⁹. In Woodland and High Suffolk Theobald estimated 15.5 in 1660 [12.6-17.6], 17.5 in 1690 [15.44-20.44], 19.60 in 1720 [14.80-19.80] and 20.1 in 1750 [16.26-21.26]⁵⁰. Bowden obtained 10 bushels/acre in St. Horsham in 1682 [13.86-18.86] and 17.4 in Arretton in 1732 [17.91-22.91]⁵¹. Finally, Allen provided the figure of 19 gross bushels/acre in England, in 1700 [13.97-18.97]. This last datum matches nearly completely my 18.97 bushels/acre⁵².

RESULTS AND DISCUSSION

Production approach and climate

In this first contrast ([chart 4](#)), the function of wheat production in bushels (endogenous variable) is well-explained by the climatic parameters. Model 1 only includes the average temperature of the year, volcanic activity, solar radiation from last year and rainfalls from the present year and last. It can be claimed, then, that the series used are reasonably valid, since they prove the obviousness that climate (and not other factors) influences the wheat crops (41 per cent). The variables show the expected signs: more temperature and radiation increase wheat production, more volcanic aerosols and summer rainfall generate worse crops. A decrease in temperature by 1°C and an increase of the summer rainfall by 50 per 100 (over the global average) resulted in a fall in wheat production of about two million bushels. If we add a reduction of 0.073 per 100 of solar radiation, which reduces production by another 1.4 million bushels, plus the increase of volcanic aerosols and the summer rainfall from the previous year, the effect accumulated on production is still larger. Besides being a solid result, it matches some works already mentioned (Brunt, Michaelowa) or those of Chmielewski and Potts, who proved the explanatory aspect of weather between 33 (grain) and 50 per cent (straw)⁵³. In model 2 I add the two production factors: the labour-energy factor⁵⁴ ([graphic 17](#) in

⁴⁷ Wrigley (1992:140-141).

⁴⁸ Between square brackets I include my estimates of the net and gross yields for that year.

⁴⁹ M. Overton (1989b:302-304).

⁵⁰ Theobald (2002:9).

⁵¹ Bowden (1967:882-883).

⁵² Allen (2005:32).

⁵³ Chmielewski & Potts (1995:43).

⁵⁴ This series is part of a second hypothesis which is not dealt with in this document. We know that the daily energy expenditure (DEE) depends on the basal metabolic rate BMR (the necessary energy to maintain the body inactive and without digesting) the physical activity level PAL. That makes $DEE = BMR \times PAL$ and in men $BMR = (14.7 \cdot M) - (5.6 \cdot TMEAN) + 735$, where M stands for the body mass index in kilograms and $TMEAN$ stands for the average annual temperature in grades centigrade (Froehle, A. W., Churchill, S. E., 2009, pp.96-116). According to the WHO, the PAL are between 1.55 and 1.77 (light activity), 1.78 y 2.09 (moderate activity) and 2.09-1.81 (heavy activity). Supposing a PAL of 1.71 and that M depends on the environment influence of the 13 previous years (TEMP), we obtain an

the appendix) and the land factor⁵⁵. The level of global significance of this model goes from 41 percent to 68.6 percent and the signs of the climatic parameters remain the same, especially those regarding temperatures and rainfalls. Labour supply is not a significant variable, and that means that abundance or scarcity of crops may determine labour demand. Previous agronomic practice (land factor) shows wheat production from a previous year with a positive sign, i.e. a good crop led to another good crop and a bad crop led to a bad one; confirming Hoskins's wheat-price series theory⁵⁶. Model 3 is a variation of model 2. The labour force variable has been removed and a fictitious variable has been included (EXP), which shows an institutional measure, the English mercantilist policy of protecting the national wheat market and exports incentives. This mercantilist policy is quite significant: the incentives helped increase wheat production but, globally, they don't carry much weight (about 3 percent), which leads one to think that excessive importance has been attached to it in literature⁵⁷.

One of the key forces in the relative prices, the climate

Models 4, 5, and 6 ([chart 5](#)) explore the statistical causes of the movements in the relative prices of wheat/cattle, wheat/pig production and wheat/milk production. Three main forces have been analyzed: climate (temperatures, rainfalls, volcanic activity and solar radiation), demography (annual population, annual birth rate, and annual death rate) and adaptation (mineral nitrogen of the current and previous years, experience and expectations)⁵⁸. The good news is that the group of climatic, demographic and adaptation variables seem to offer a good and reliable explanation about the relative prices, although we must be very careful about the results and continue to investigate. In

estimated series of the male individual's daily gross availability in kilocalories which was 2,569 kilocalories in 1700. Broadberry's calculations show 2,162 in 1705, Allen's were 3,255 kilocalories in 1700, and 3,579 kilocalories according to Muldrew (quoted in Kelly, M. and Ó Gráda, 2012). Taking next Clark's agrarian labour force weight (2001:40) on population (datum by Wrigley *et al*, 1983) we obtain a second series with the number of workers and if we combine the two series we obtain a first approximation to the total gross availability of daily work-energy in England, adjusted with the increase of the worked days.

⁵⁵ This second factor is quantified by means of the proxy "wheat production of the previous years in bushels", which collects the previous agrarian experiences globally: harvest indexes, seed management and their content in nitrogen as well as the farmers' expectations.

⁵⁶ Hoskins (1968:17-19).

⁵⁷ Observing the three models, we can see that summer temperatures and rainfalls are solid variables, but volcanic activity and radiation are not. In model 2 they stop being significant and in model 3 only volcanic activity is. When we complete model 1 with agrarian or institutional variables, as the model becomes more explanatory, these two variables lose strength. In model 3, the result is apparently surprising. Although the wheat production of the previous year has the same sign as the current year, the one from two years before has the opposite sign; that is, a higher production two years before affected production in the opposite way. All this suggests that there were alternating cycles in the crops of 2-3 years.

⁵⁸ As temperature indicators I use TEMP (average temperature of the year), TEMP_1 (average temperature of the previous year) and TEMP_SQUAR or TEMP_SQUAR_1 (average squared temperatures of the current and previous year). As rainfall indicators I use RAIN_RINN (summer rainfalls) and RAIN_WILS_1 (spring rainfalls of the previous year). DVI_VOLCANIC_INDEX_1 indicates the volcanic activity of the previous year and SOLAR_IRRAD indicates volcanic radiation. The use of squared terms is due to the possible non-linearity of the variables, and the lagged variables are used because this is economic history and the dynamic series contain relevant information in their past.

the case of PR_WHEAT_PR_BEEF, the climate variables TEMP, TEMP_SQUAR and TEMP_SQUAR_1, RAIN_WILS_1, DVI_VOLCANIC_INDEX_1 and SOLAR_IRRAD seem significant. However, even if the temperature and volcanic activity signs are the ones expected (higher temperatures/less volcanic activity caused a decrease in the relative prices in favour of cattle, since wheat crops improved and their prices went down), the signs of rainfalls and solar radiation required another type of reasoning. Rainfalls and solar radiation, even if they are usually good for wheat production, are likely to have been even better for hay production, which lowered the cost of livestock. As for demographic variables (population, birth and death rates), they are significant and with the expected signs (more population or higher birth rate the previous year means higher production during the year and lower prices indicating adaptive adjustments on the offer, whilst the pressure of the demand during the same year pushes up prices). The rate of the global model determination might be too high (nearly 90 per cent), inviting its adjustment. Even if all the conditions of the OLS estimate occurred, we must take into account that the nitrogen content series IC_VAR_N_0_02 has been calculated on the basis of harvest indexes conditioned by temperatures. Besides, the source-series for its calculation, wheat output, has been estimated from a population index of Broadberry *et al.* All this indicates a certain degree of colinearity. The subsequent question is: what other series can we choose as indicators of agrarian improvements? So far and as a conclusion, three relevant explanatory forces for the relative price variations have been identified: climate, demography and adaptation. However, the statistical work must be strengthened. More research on the relative strength of each force is needed to develop a simpler and stronger model.

Long term impacts and adaptation

We find causality in the long term between temperature and wheat production at about 14 percent ([chart 6](#))⁵⁹. This leads us to research the relationship between climate change and adaptation from two approaches: the production and the land rent approach (Ricardian). Through the production approach it is possible to find out whether there was an agrarian adaptation or not regarding the influence of climate by dividing the period 1645-1740 into two parts, the first being the cooling phase and the second the phase of climate recovery, *but accepting instability in the degree of influence of each weather variable*. In each of the two parts the best model is selected, even if the influential climatic variables are not always the same. Using this strategy, the first results ([chart 7](#)) confirm that in the first period the climatic variables have less effect on wheat production⁶⁰. That means that there were great efforts to lessen the climatic shock from 1640 to 1660, at the beginning of the Maunder Minimum⁶¹. This conclusion can

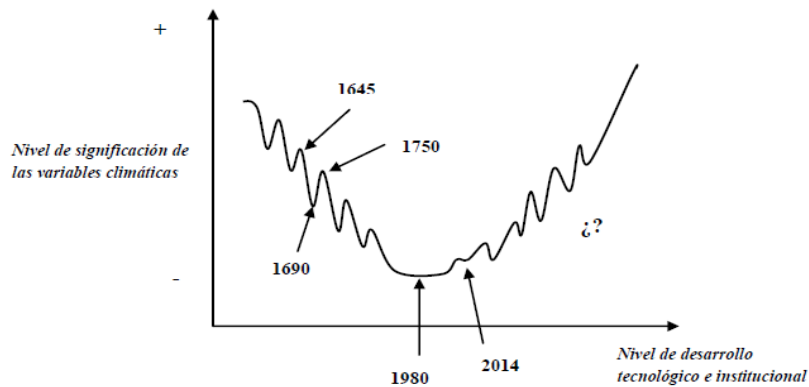
⁵⁹ Taking both series, we verify that they are stationary (augmented Dickey-Fuller test under a lagged variable and with a constant), as well as the cointegrated regression residuals.

⁶⁰ I chose three breakpoints: 1689, 1700 and 1715.

⁶¹ There are three aspects to be taken into account: first, that the climate impact is asymmetric. When it harms us we react more dramatically; when it benefits us we relax. This means that during the cold period farmers worked hard to overcome the difficulties, increasing the content of nitrogen, cushioning the environmental impact of the climatic variables. On the other hand, when the weather improved they did

be supported by means of direct contrast with dummy variables⁶² ([chart 6b](#)) or with the endogenous Bai-Perron test ([chart 6c](#)), avoiding the division of the series and the resulting reduction in the number of observations⁶³. The detected breakpoints are 1664, 1700 and 1730. From a far more general point of view, the British case shows us how, even if the long-term trend of the global significance of climate on the economic system is decreasing, during shorter periods the paradox of phases during which the climate recovers its explanatory capacity may occur ([graphic 22](#)).

Graphic 22. Level of influence of climate in the very long term



Source: compiled by the author

An alternative approach is that of the land rent (Ricardian Approach), developed by Robert Mendelsohn, William D. Nordhaus y Daigee Shaw (1992), frequently applied in current studies on climate impact on agriculture. It is based on the idea that the function of production does not measure agrarian adaptations correctly and overestimates damage (or at the most it equals it). On the other hand, the function-rent (or soil value) measures improvements and innovations in a better way. According to Clark's decennial rents (2001), there seems to be a long-term relationship between climate change and land rent, i.e. the existence of agrarian adaptation ([chart 8](#)). Higher temperatures and more abundant spring rainfalls seem to increase the rents in the long term. When the climate favoured cereal production, prices were brought down and so were the rents. Therefore, the fact that the rents increased (or remained the same) in the long term means that landowners were able to keep their income or increase it, either

not need to struggle so much, so *the explanatory capacity of the climatic variables was higher*. Secondly, the relationship climate-agrarian production is a reflection of human activity and must not be considered an input, on the same level as those supplied by the farmer. Therefore, the agrarian improvements boosted the positive effect of climate in the short term. Third, since 1700 the critical episodes were more isolated (although hard) as in 1709, 1714, 1727 and 1739, catching farmers off their guard. This leads to a major explanatory capacity of the climatic variables, since the previous phase, more changeable, cold and wet, allowed the farmer to be more prudent.

⁶² The influence of temperatures on wheat production becomes stronger by 18 per 100 from 1700, and the negative impact of summer rainfalls, comparing their rates, decreases by 41.3 per 100, also from 1700.

⁶³ J. Bai and P. Perron (2003).

innovating and diversifying their activity towards cattle production or pressing tenants further⁶⁴.

The last step is to compare what is expected to occur when the two main forces, climate and population, are combined (the theory, [Schema 2](#)), to what history says ([schema 1](#))⁶⁵. From this comparative analysis four phases appear: first, unfavourable climate and increasing population (1645-63); second, alternating climate and stagnant or decreasing population (1664-1691); third, unfavourable climate and initial stagnant population increasing later (1692-1700, 1708-14); fourth, favourable climate and increasing population (1715-1750, especially from 1730)⁶⁶. It is observed that, after the climate shock at the end of the 1640s, farmers managed to maintain wheat production and even increased it gradually when the temperatures or the rainfalls were more favourable (since 1664). This, together with a period of demographic stagnation and lower demand, led to a medium-term decrease in the price of wheat. Meanwhile, there was also a climate impact on cattle breeding, which stagnated, and so there was a process of diversification towards sheep. Since demand was depressed, livestock prices tended to remain relatively stable or increased (except mutton prices, which fell). Therefore, the balance of prices wheat/livestock products favoured the second. That makes me think that climate, population, and the agrarian capacity to adapt were key forces for relative prices, as long as the institutional environment was favourable, since it was a key element which made England different from the European continent. Finally, this first analysis allows us to understand better the consecutive innovative waves carried out by Yeomen and Landlords and also what the socioeconomic dynamics were ([Schema 2](#)). During the climatic shock (1645-1663), the mineralization rate of nitrogen and the harvest index fell. Wheat production decreased when the population was growing. All this led to a period of high prices, a stagnating demand for goods and agricultural labour, with a consequent decrease in real salaries, higher rural unemployment, a rise in land rents and more inequality. Neither did institutions help, given the existence of wage ceilings and migration controls in the counties. The number of landless would increase, the diets and life conditions of the tenants and workers would worsen, leading to social and political unrest. It is likely that the first wave of innovation came from yeomen and small farmers. It was necessary to maintain the prosperity of the community, expanding the areas of arable land and marginal plowing. The area of land devoted to cattle-raising had to be reduced. Farmers resorted to convertible agriculture. Seed management made a huge leap forward. According to E. L. Jones (1965), innovation was spread faster among light soils.

When climate conditions improved (1664-1691), it was the landowners' turn. The previous reaction by the farmers increased organic matter supply. On the other hand,

⁶⁴ However, although the model is valid, the sample is too small. It would be very interesting to have an annual rent series or to do future research using primary sources to guarantee these results.

⁶⁵ All this is proved by means of the econometric analysis of the structural break points detected with the production approach (charts 6b and 6c), specifically the years 1664, 1700, 1715 and 1730.

⁶⁶ It is important to point out that within the period 1664-1691, there is a period of bad crops, during the 70s.

milder weather made the flow of nitrogen into the soil easier. All this helped to improve production and the wheat harvest index. In the meantime, the human and animal population stagnated and even fell, leading to a decrease in cattle yield, although urban growth was unchanged. The prices of wheat and mutton fell, whereas the rest of cattle products rose or remained stable. This way, the well-known process of a descent in relative prices started. Real salaries rose or remained stable but the opposite happened to land rents. Institutions became more favorable, stimulating both new written works on agriculture and gardening and a new moral vision of labour, together with mercantilist policies which encouraged domestic production. The number of landless decreased and diets improved, as well as the situation of tenants and workers. During this period, then, the landowners acted: the area of arable land decreased and the area devoted to cattle-raising increased. Yeomen went back to permanent division in the open fields, but not the landlords, who increased pastures, the rotation of lands and water meadows. Forest areas were substituted by cattle-raising, increasing clovers and turnips. Investment in rural construction increased.⁶⁷

The third phase, again a climatic shock, was so intense that this time it affected the whole of the agrarian sector (1692-1700, 1708-1714). The rate of mineralization of nitrogen fell again and cold and humidity damaged the crops. Wheat production fell sharply, as did the harvest index. Population and demand remained depressed, although poised to recover. Prices started to rise, and consumption and demand for labour started to decline. Real wages fell and unemployment increased. Neither did the land rents escape the crisis (i.e., there was a global crisis in the agrarian sector). The government stopped restrictions on wheat imports. The arable area increased, but so did that of pastures or grasslands and marginal lands. The farmers resorted to convertible agriculture, intensified improvements of seeds, and converted production from wheat to barley or oats, avoiding new famines.

The next phase was the warm period (1700-1707, 1715-1750). Temperatures and solar radiation increased, and rainfall became more favorable. As a result of the farmers' previous efforts, more organic matter and nitrogen were available (more TM) leading to an increase in cereal production. Population grew again. Sheep, animal work and the yield of livestock products also recovered. All this led to a growth in rural and urban demand together with the development of industrial demand. Agrarian prices fell, cattle prices remained stable or rose and the price of mutton fell. Labour force supply and demand both increased, whereas real wages remained higher than in the rest of

⁶⁷ The growing diversity of agrarian practice and climatic pressure modified some patterns in agrarian constructions. Different adaptations were carried out because of the heavy rains in the high lands of the west or because of the cold winds in the eastern counties in order to minimize the exposure of men and animals to the most extreme weather. The storage of grain and fodder was combined with the shelter and feeding of horses and cattle. In the Penine counties cold and wet winters determined cattle management originating a practice which became very popular since 1650: a barn, away from the house, which also sheltered the cattle. These barns with cowsheds also extended in pastoral areas, were used to store grain but also fodder and hay (M.W. Barley, 1985: 667-671). In some cases, the cattle sheltered from the elements produced higher quantities of manure and urine-containing straw than before, to be distributed on the land.

Europe.⁶⁸ Land rents remained stable. The use of the soil started to diversify in an environment of growing protection of property rights. Enclosures increased property fragmentation in some cases and concentration in others. The number of wage-earners grew, diet remained stable but the number of landless continued to grow.

I provisionally conclude that agrarian communities and great landowners innovated at different moments and using different methods (according to their resources), following these driving forces (environmental pressure, human and animal population, innovation, institutional framework). However, a deeper study is needed in this respect to totally or partially confirm or refute these conclusions.

PRELIMINARY CONCLUSIONS

The provisional results of this research suggest that the interactions between climate and population opened the door to a slow structural change during the second half of the 17th century, strengthening and promoting adaptations from the agrarian sector. Farmers invested part of their efforts in enriching the nutrient pool, succeeding in lessening the impact of climatic cooling. According to incentives, these adaptive measures were carried out by different social sectors, but in general there was an increase in the production of wheat in the long term and a decrease in relative prices, due to demographic stagnation during the second half of the 17th century. The union of climate recovery and agrarian efforts (the increase in nitrogen stock) and the increase in population within a favourable institutional framework led to a significant increase in production and yield during the first half of the 18th century. The final reading suggests that climate was a positive force in the long British Agrarian Revolution, answering the question of the missing link of nitrogen and solving the problem of the divergence between wheat supply and demand. In the framework of organic agriculture and little technology or resources, the rural sector was able to adapt to natural climate change. Now will current agriculture be able to adapt to the challenge of the global change to come?

⁶⁸ Despite the depressed cycle mentioned, between 1660 and 1740 the real agrarian and urban wages tended to increase in general (Clark, 2007; Overton, 1996). Also the incomes of wage-earners (wages and number of worked days) increased during that long period (De Vries, 2008).

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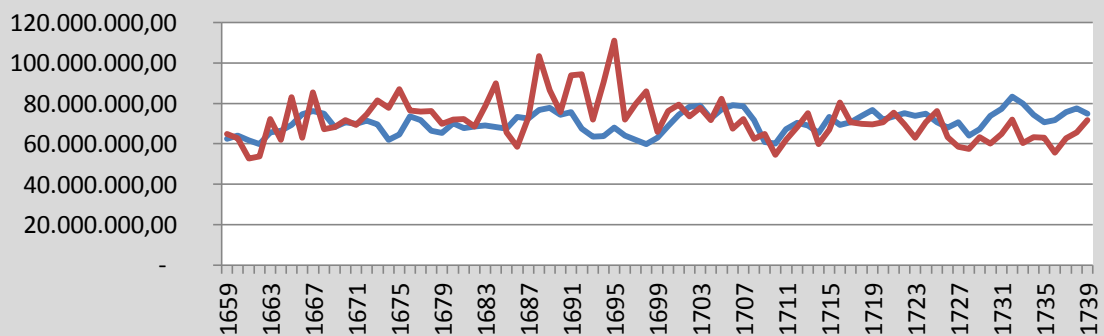
APPENDIX

**Chart 1. Average annual temperature versus non-constant m ratio ($m = \frac{Y}{F}$),
England, 1660-1739.**

Year	Temp averag	m
1660-1664	9,2	15,84
1665-1669	9,0	15,07
1670-1674	8,6	13,79
1675-1679	8,5	13,38
1680-1684	8,6	13,66
1685-1689	8,9	14,74
1690-1694	8,2	12,28
1695-1699	8,0	11,80
1700-1704	8,9	14,80
1705-1709	9,3	15,85
1710-1714	9,2	15,70
1715-1719	9,1	15,36
1720-1724	9,3	15,92
1725-1729	9,3	16,16
1730-1734	10,0	18,25
1735-1739	9,8	17,53

Source: Compiled by the author. In Allen's equation, Y is grain yield and F is the level of mineralized nitrogen. Taking Loomis's modified formula (total production variation * N content in the grain (0.02 kg of N/Kg of grain)/(Harvest Index HI)= total variation of N, we calculate a proxy of F . The grain production series is estimated as explained in the data section. The novelty is that here the HI depends on temperatures. This variability is calculated giving HI=0.03 for 9°C and modifying the HI proportionally according to temperature deviations from 9°C (Loomis, 2002:67).

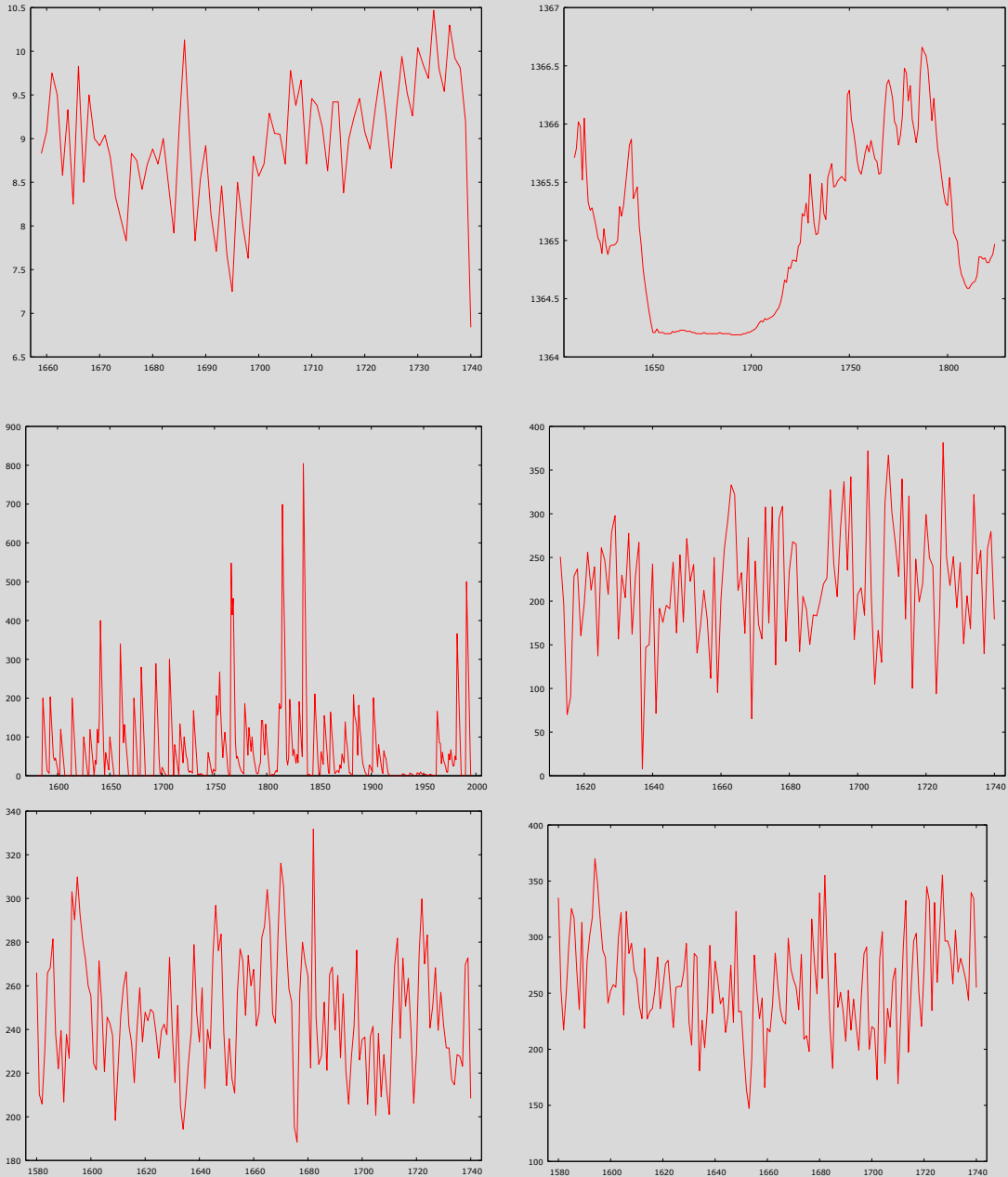
Graphic 1. Total nitrogen (kg) in wheat production. England, 1659-1740.



Source: Compiled by the author. The blue line shows total variations of N maintaining HI constant (0.3) and N content in the grain (0.02 kg of N/ha per kg of grain). The red line shows, with a variable HI (between 0.2 and 0.4) according to temperature. An increase in N is observed during the cooling phase (Maunder Minimum). The calculation of N variations (F) is explained in chart 1.

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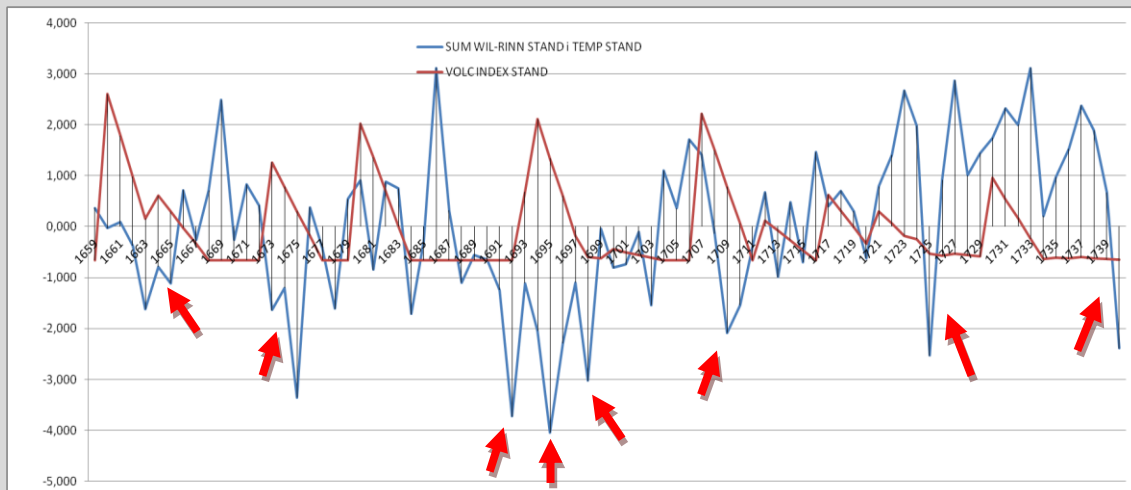
Climate graphics 2, 3, 4, 5, 6, 7: Temperature in degrees (TEMP); radiation in W/m2 (SOLAR_IRRAD); volcanic activity index (DVI_VOLCANIC_INDEX); rainfalls in mm. May-August (summer) in the south of England (RAIN_RINN); rainfalls en mm. between March and July (spring-summer) in the east of England (RAIN_RICH) and rainfalls in mm. between March and July (spring-summer) in the south and centre of England (RAIN_WILS).



Source: compiled by the author. Temperatures, series TEMP, G. Manley's data (1974); volcanic aerosols, DVI_VOLCANIC_INDEX series, data by Mann *et al*, (2000); solar radiation, SOLAR_IRRAD series, data by Lean *et al*, (1995); WILS series, rainfalls between March and July (spring-summer) in the south and centre of England, data by Wilson *et al* (2012); RICH series, rainfalls between March and July (spring-summer) in the east of England, data by Cooper *et al*, 2012; RINN series, rainfalls between May and August (summer) in the south of England, data by Rinne *et al*, 2013.

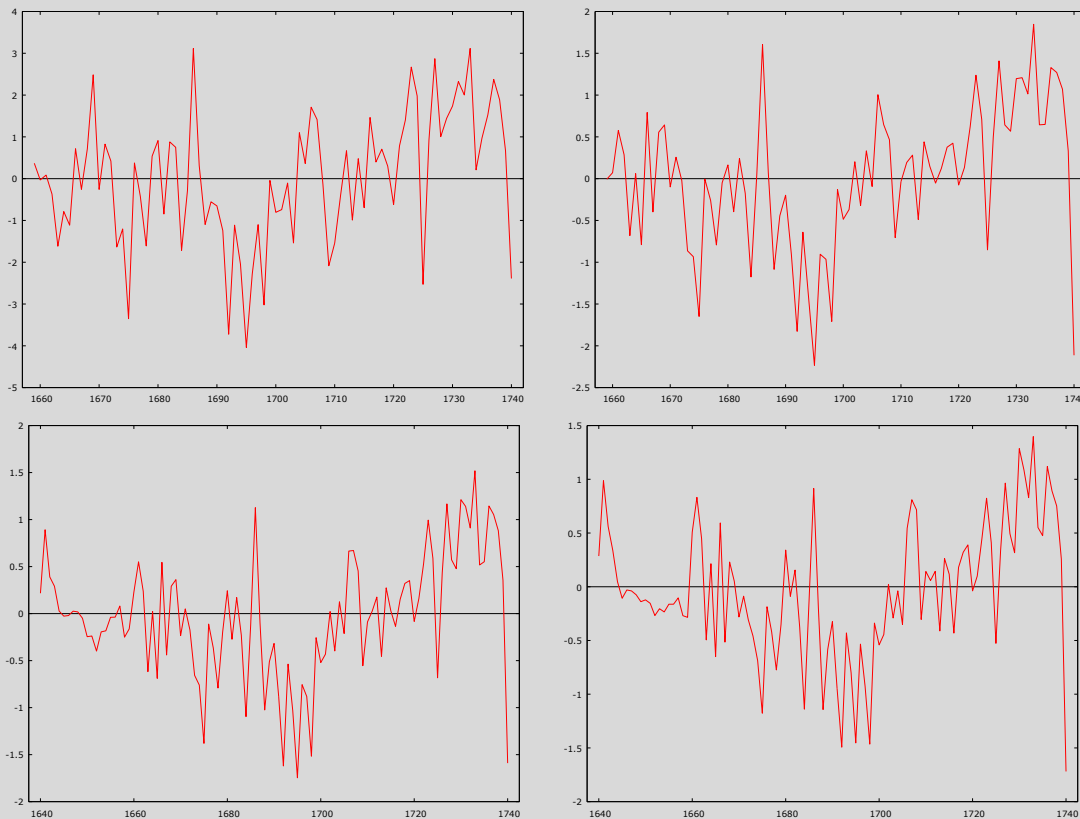
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Graphic 8. Net Index of Rainfalls and Temperatures (CIPL-1), England, 1659-1740 compared to the volcanic aerosols index DVI_VOLCAN_ESTAND. Standardized data.



Source: Compiled by the author. In red, the moments of highest social unrest and food raising, detailed by B. Bohstedt (2010:33-54). The correlation with the main aerosol movements until the 18th century is observable.

Graphics 9, 10, 11, 12 and 13. Climatic Indices of the Productivity of the Land (CIPL-1, CIPL-2, CIPL-3, CIPL-4).



Source: Compiled by the author. CIPL-1: balance 50% temperatures, 50% net rainfalls (the difference between spring rainfalls WILS and summer RINN); CIPL-2: 75% temperatures and 25% net rainfalls; CIPL-3: 60% temperatures, 20% net rainfalls, 10% volcanic dust, 10% solar radiation; CIPL-4: 60% temperatures, 10% net rainfalls, 20% volcanic dust, 10% solar radiation.

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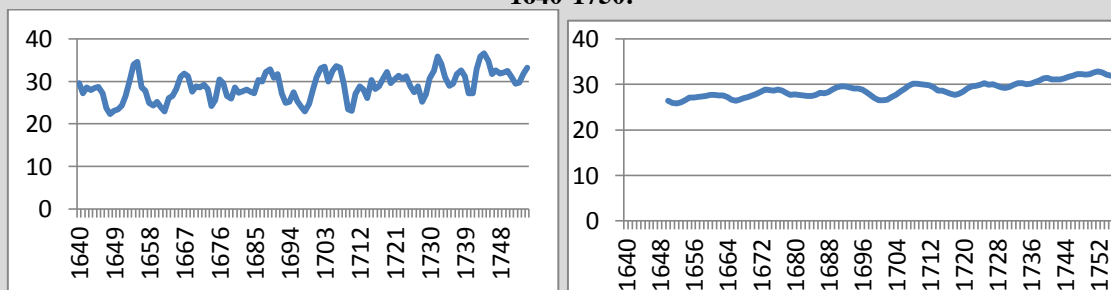
Chart 2. Contrast tests with productivity climatic indices, England.

Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS) (2)	Wheat production in bushels (OUTPUT_BUS) (3)	Wheat production in bushels (OUTPUT_BUS) (4)
Sample size	1659-1740 (T= 82)	1659-1740 (T= 82)	1642-1740 (T= 99)	1642-1740 (T= 99)
Constant	1.93298e+07*** (<0.00001)	1.94513e+07*** (<0.00001)	1.61218e+07*** (<0.00001)	1.54837e+07*** (<0.00001)
DVI_VOLCANIC_INDEX_1	-4850.62* (0.06289)	-5746.41** (0.02512)		
CIPL-1	447345*** (0.00232)			
CIPL-2		822610*** (0.00194)		
CIPL-3			942067*** (0.00334)	
CIPL-4				865060*** (0.00956)
OUTPUT_BUS_1 (value p)	0.8129*** (<0.00001)	0.814352*** (<0.00001)	0.916804*** (<0.00001)	0.931651*** (<0.00001)
OUTPUT_BUS_2	-0.30331*** (0.00326)	-0.306404*** (0.00288)	-0.334388*** (0.00053)	-0.332628*** (0.00064)
R-square adjusted	0.609662	0.611318	0.604776	0.596777
F	32.62818	32.84920	50.98680	49.34731

Source: compiled by the author, *=level of significance at 10%, **= level of significance at 5%, ***=level of significance at 1%. P-value between brackets. DVI_VOLCANIC_INDEX_1 is the index of volcanic activity from the previous year. OUTPUT_BUS is wheat production in bushels, the calculation of which is explained in the production data section. OUTPUT_BUS_1 belongs to the previous year, and OUTPUT_BUS_2 belongs to the year before the previous one.

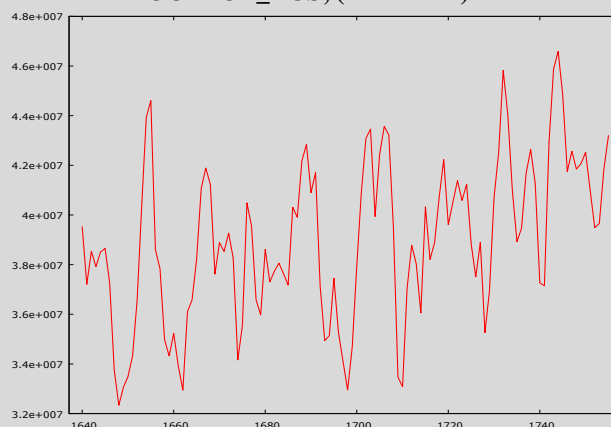
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Graphics 14 and 15. Wheat supply, England, in million bushels and in 11-year moving average, 1640-1750.



Source: compiled by the author. Short-term movements are well adjusted to Hoskin's calendars (1968:20-22): bad crops in 1646, 1657, 1710, 1711; bad or very bad in 1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728, 1729; "average" years in 1699, 1718, 1719, 1720; and good years in 1652, 1653, 1654, 1655, 1665-72, 1680s in general, between 1700-1707 and 1721-23.

Graphic 16. Wheat production series in bushels. OUTPUT_BUS, (1640-1755).



Source: compiled by the author. Short-term movements are well adjusted to Hoskin's calendars (see previous chart). The difference between this and the previous series is explained in this paper.

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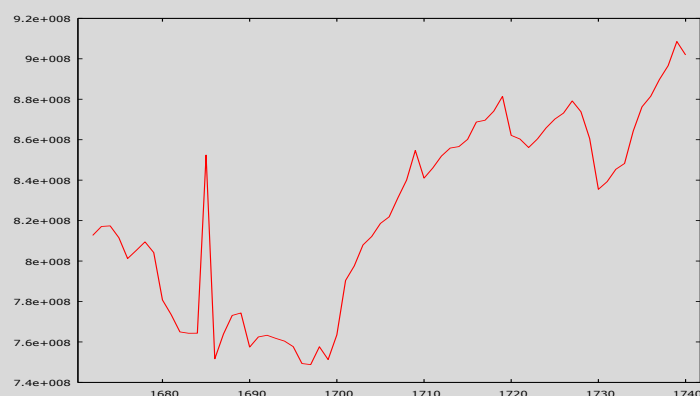
Chart 3. Comparison of my estimates to those of Broadberry's et al (2011b:31). In million bushels.

Period	MY AVERAGE	BROADBERRY'S AVERAGE	
Average 1645-1655	27.12	27.01	1650s
Average 1695-1705	28.39	27.94	1700s
Average 1745-1755	31.89	31.48	1750s

Source: compiled by the author.

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Graphic 17. Male agrarian labour-energy series (1672-1740).



Source: compiled by the author. See calculation in footnote 54. Data in KCAL.

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Chart 4. Statistic contrasts of climate impact in wheat production. England, 1659-1740.

Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS) (2)	Wheat production in bushels (OUTPUT_BUS) (3)
Sample size	1659-1740 (T = 82)	1672-1740 (T = 69).	1659-1740 (T = 82)
Constant	1.83485e+09* (0.05444)	6.54596e+08 (0.50047)	3.99448e+07 (0.95890)
TEMP	907586** (0.02743)	964089 *** (0.00452)	612634** (0.04511)
DVI_VOLCANIC_INDEX	-7712.18** (0.01415)	-1985.03 (0.44356)	-3948.96* (0.09519)
SOLAR_IRRAD_1	1.37213e+06* (0.05019)	496084 (0.48792)	45169.1 (0.93675)
RAIN_RINN	-8570.58** (0.02062)	-9951.3*** (0.00149)	-7888.01*** (0.00460)
RAIN_RINN_1	-18696*** (<0.00001)	-13987.8*** (0.00005)	-12107.6*** (0.00006)
FTM_KCAL_TOT		-0.00399085 (0.55655)	
OUTPUT_BUS_1		0.59191*** (<0.00001)	0.640781*** (<0.00001)
OUTPUT_BUS_2		-0.156753 (0.12219)	-0.233072** (0.01315)
EXP			1.09556e+06** (0.01644)
R-square adjusted	0.410784	0.686599	0.680281
F	12.29417	19.62184	22.54341

Source: compiled by the author

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%.

p-value between brackets. TEMP, temperatures; DVI... volcanic activity index; SOLAR...solar radiation RAIN_RINN, summer rainfalls...; FTM...labour-energy supply; OUTPUT_BUS, wheat production in bushels. The fictitious variable EXP took value 1 when incentives were active and value 0 when they were interrupted.

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Chart 5. Relative prices, climate, agrarian adaptation and population.

Dependent variable	PR_WHEAT_PR_BEEF (4)	PR_WHEAT_PR_PORK (5)	PR_WHEAT_PR_MILK (6)
Sample size	1660-1739 (T = 80)	1660-1739 (T = 80)	1660-1739 (T = 80)
Constant	-231.934** (0.04839)	-226.408* (0.05351)	7.13008*** (0.00633)
TEMP	-2.77787*** (<0.00001)	-2.8593*** (<0.00001)	-3.11101*** (<0.00001)
TEMP_1			1.71263*** (0.00039)
TEMP_SQUAR	0.12045*** (<0.00001)	0.12277*** (<0.00001)	0.144524*** (<0.00001)
TEMP_SQUAR_1	0.0102894*** (0.00215)	0.0102289*** (0.00243)	-0.0767059*** (0.00160)
RAIN_RINN		-0.000295632* (0.08628)	
RAIN_WILS_1	0.000766007*** (0.00671)	0.000623145** (0.03414)	-0.000649942** (0.01379)
DVI_VOLCANIC_INDEX_1	0.000255158* (0.06421)	0.000332575** (0.02383)	
SOLAR_IRRAD	0.184703** (0.03247)	0.180931** (0.03586)	
POPULATION		1.4876e-06** (0.01175)	2.23781e-07** (0.01826)
POPULATION_1	-3.76751e-07** (0.02207)	-1.78246e-06*** (0.00876)	
BIRTH_RATE	-0.0172331** (0.02241)	-0.0262394*** (0.00719)	
DEATH_RATE_1	-0.00905939*** (0.00640)		
IC_VAR_N_0_02	-3.70916e-08*** (<0.00001)	-3.85272e-08*** (<0.00001)	-3.12431e-08*** (<0.00001)
IC_VAR_N_0_02_1	8.47861e-09** (0.01027)	8.25456e-09** (0.01321)	2.0434e-08*** (<0.00001)
PR_WHEAT_PR_BEEF_1	0.203118*** (0.00997)		
PR_WHEAT_PR_BEEF_2	-0.152468*** (0.00322)		
PR_WHEAT_PR_PORK_1		0.184421** (0.01923)	
PR_WHEAT_PR_PORK_2		-0.152104*** (0.00377)	
PR_WHEAT_PR_MILK_1			0.764702*** (<0.00001)
PR_WHEAT_PR_MILK_2			-0.141199** (0.03704)
R-square adjusted	0.870378	0.869148	0.848339
F	41.80499	38.48114	45.18998
Durbin-h	-0.487693	0.289082	-0.993105

Source: compiled by the author.

*=level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets. TEMP=annual average temperature; TEMP_1, idem previous year; TEMP_SQUAR, annual average temperature squared; TEMP_SQUAR_1, idem previous year; RAINN_RINN, annual summer rainfalls in mm.; RAIN_WILS_1, annual spring rainfalls from previous year in mm.; DVI_VOLCANIC_INDEX_1, volcanic activity index from previous year; SOLAR_IRRAD, annual solar radiation in W/m²; POPULATION, number of inhabitants of the year; POPULATION_1, inhabitants from previous year; BIRTH_DATE, English annual birth rate; DEATH_RATE_1, English annual death rate from previous year. Demographic data by Wrigley *et al*, 1981; IC_VAR_N_0_02 is F proxy explained in chart 1 and graphic 1; IC_VAR_N_0_02_1, idem from previous year. PR_WHEAT_PR_BEEF is the quotient between the prices of wheat and cattle of the year; PR_WHEAT_PR_BEEF_1 idem from previous year; PR_WHEAT_PR_PORK is the quotient between the prices of wheat and pigs; PR_WHEAT_PR_PORK_1 idem from previous year; PR_WHEAT_PR_MILK is the quotient between the prices of wheat and milk production; PR_WHEAT_PR_MILK_1 idem from previous year. All prices by G. Clark (2004, 2005, 2007).

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Chart 6. Output and temperatures in long -term growth, England.

Etapa 1: contrastando la existencia de una raíz unitaria en OUTPUT_BUS
 Contraste aumentado de Dickey-Fuller para OUTPUT_BUS incluyendo un retardo de (1-L) OUTPUT_BUS tamaño muestral 80, hipótesis nula de raíz unitaria: $a = 1$, contraste con constante, modelo: $(1-L)y = b_0 + (a-1)*y(-1) + \dots + e$
 -Coef. de autocorrelación de primer orden de e: 0.010
 -valor estimado de $(a - 1)$: -0.39793
 -Estadístico de contraste: $\tau_c(1) = -4.75903$
 -valor p asintótico 6.188e-005

Etapa 2: contrastando la existencia de una raíz unitaria en TEMP
 Contraste aumentado de Dickey-Fuller para TEMP incluyendo un retardo de (1-L)TEMP, tamaño muestral 80, hipótesis nula de raíz unitaria: $a = 1$, contraste con constante
 modelo: $(1-L)y = b_0 + (a-1)*y(-1) + \dots + e$
 -Coef. de autocorrelación de primer orden de e: -0.040 valor estimado de $(a - 1)$: -0.423927
 -Estadístico de contraste: $\tau_c(1) = -3.52182$
 -valor p asintótico 0.007475

Etapa 3: regresión cointegrante
 Regresión cointegrante - MCO, usando las observaciones 1659-1740 (T = 82), Variable dependiente: OUTPUT_BUS

	Coeficiente	Desv. Típica	Estadístico t	Valor p
const	2.42726e+07	3.90329e+06	6.219	2.15e-08 ***
TEMP	1.61659e+06	433879	3.726	0.0004 ***

Media de la vble. dep. 38772036 D.T. de la vble. dep. 2953043
 Suma de cuad. residuos 6.02e+14 D.T. de la regresión 2742966
 R-cuadrado 0.147869 R-cuadrado corregido 0.137218
 Log-verosimilitud -1330.954 Criterio de Akaike 2665.907
 Criterio de Schwarz 2670.721 Crit. de Hannan-Quinn 2667.840
 rho 0.634246 Durbin-Watson 0.703550

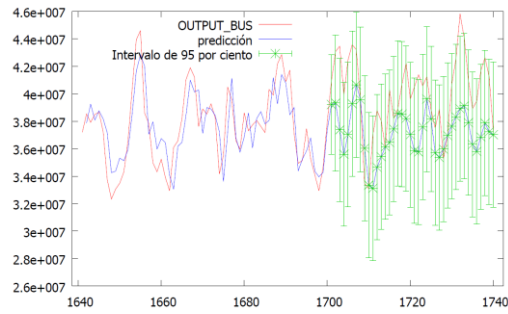
Etapa 4: contrastando la existencia de una raíz unitaria en uhat
 Contraste aumentado de Dickey-Fuller para uhat incluyendo un retardo de (1-L)uhat, tamaño muestral 80 hipótesis nula de raíz unitaria: $a = 1$, modelo: $(1-L)y = (a-1)*y(-1) + \dots + e$
 -Coef. de autocorrelación de primer orden de e: -0.024
 -valor estimado de $(a - 1)$: -0.441626
 -Estadístico de contraste: $\tau_c(2) = -4.7146$
 -valor p asintótico 0.0004988

Hay evidencia de una relación cointegrante si:
 (a) La hipótesis de existencia de raíz unitaria no se rechaza para las variables individuales.
 (b) La hipótesis de existencia de raíz unitaria se rechaza para los residuos (uhat) de la regresión cointegrante.

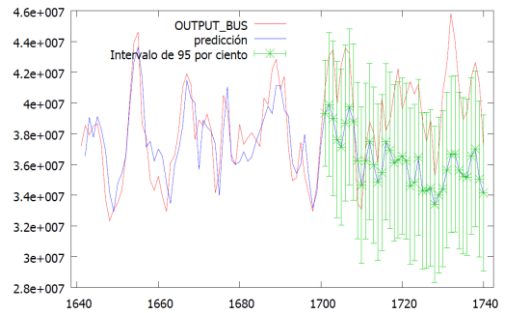
Source: compiled by the author

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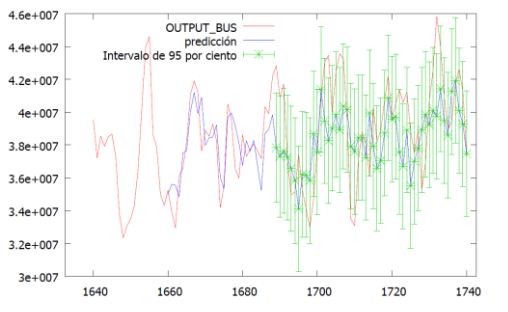
Graphics 17, 18, 19, 20 and 21. The increase of agrarian innovation could explain the gap between forecast and real wheat production.



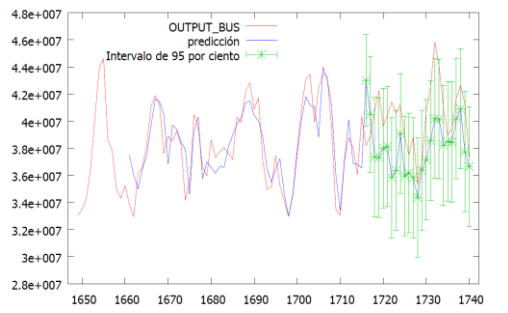
Dependent variable: OUTPUT_BUS
 1642-1700 (T = 59)
 RAIN_RINN
 RAIN_RINN_1
 OUTPUT_BUS_1
 OUTPUT_BUS_2
 R-square adjusted 0.613692
 Durbin-h 0.455419



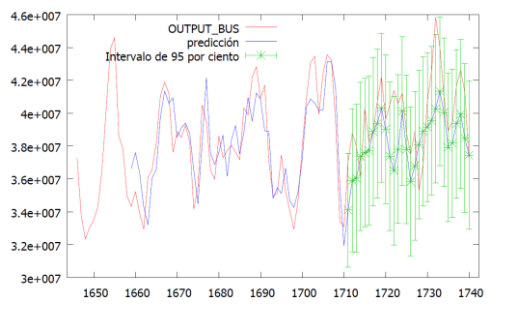
Dependent variable: OUTPUT_BUS
 1642-1700 (T = 59)
 RAIN_RINN
 RAIN_WILS_1
 OUTPUT_BUS_1
 OUTPUT_BUS_2
 R-square adjusted 0.650254
 Durbin-h 0.903482



Dependent variable: OUTPUT_BUS
 1660-1688 (T = 29)
 TEMP_MAX
 GRAD_SHORT
 GRAD_LONG
 OUTPUT_BUS_1
 R-square adjusted 0.533641
 Durbin-h 0.548846



Dependent variable: OUTPUT_BUS
 1661-1715 (T = 55)
 RAIN_RINN
 RAIN_WILS_1
 TEMP_2
 OUTPUT_BUS_1
 OUTPUT_BUS_2
 R-square adjusted 0.679316
 Durbin-h -0.291423



Dependent variable: OUTPUT_BUS
 1659-1710 (T = 52)
 RAIN_RINN
 RAIN_RINN_1
 TEMP_MAX
 OUTPUT_BUS_1
 OUTPUT_BUS_2
 R-square adjusted 0.689520
 Durbin-h 1.280392

Source: compiled by the author.

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Chart 6b. Statistic contrasts with dummy variables to value the existence of agrarian adaptation. England, 1640-1740.

Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS) (2)	Wheat production in bushels (OUTPUT_BUS) (3)	Wheat production in bushels (OUTPUT_BUS) (4)
Sample size	1659-1739 (T = 81)	1659-1739 (T = 81)	1659-1739 (T = 81)	1640-1739 (T = 100)
Constant	2.89512e+07*** (<0.00001)	4.51652e+07*** (<0.00001)	4.4234e+07*** (<0.00001)	4.49616e+07*** (<0.00001)
F2TEMP	181315** (0.02135)			
TEMP	1.00072e+06* (0.07144)			
F2RINN		11294.4*** (<0.00001)		15804.2*** (<0.00001)
RAIN_RINN		-16888.8*** (0.00004)	-11892.7*** (0.00281)	--20898.3*** (<0.00001)
RAIN_RINN_1		-17652.8*** (<0.00001)	-16302.7*** (0.00005)	-17319.9*** (<0.00001)
F1RINN			10133.9*** (0.00019)	
D1RINN				10101.1*** (0.00033)
R-square adjusted	0.186932	0.328716	0.260381	0.408052
F	10.19641	17.15954	12.73494	18.06107

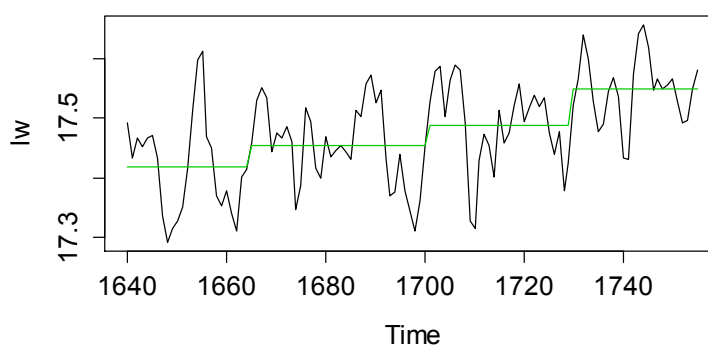
Source: compiled by the author

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%.

p-value between brackets. TEMP, temperatures; RAIN_RINN, summer rainfalls; OUTPUT_BUS, wheat production in bushels. The dummy variable F2 took value 1 from 1700 and value 0 before 1700. The dummy variable F1 took value 1 since 1715 and value 0 before 1715. The dummy variable D1 took value 1 between 1664 and 1691 and 0 in the rest. These results suggest structural changes in 1664, 1700 and 1715. There could be more break points, since this analysis has not been carried out with all the "candidate" years.

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Chart 6c. Bai-Perron Test to value the existence of agrarian adaptation. England, 1640-1740.



Source: compiled by the invaluable assistance of Professor Marc Badia Miró. Lw is the wheat production logarithm in bushels. The detected breakpoints are 1664, 1700 and 1730.

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Chart 7.1. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1640-1700 y 1701-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1640-1700 (T = 61)	1701-1739 (T = 39)
Constant (p-value)	4.67232e+07*** (<0.00001)	4.84412e+07*** (<0.00001)
RAIN_RINN	-10550.5** (0.04120)	-13955.8*** (0.00459)
RAIN_RINN_1	-12509** (0.02016)	-22260.3*** (0.00003)
RAIN_WILS_1	-14828.1*	
DVI_VOLCANIC_INDEX	-7264.74** (0.03115)	
R-square adjusted	0.226245	0.434050
F	5.385975	15.57189

Source: compiled by the author.

*=level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets. No more variables have been included in order to isolate climate effects.

Chart 7.2. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1640-1716 y 1717-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1640-1716 (T = 77)	1717-1739 (T = 23)
Constant	4.45009e+07*** (<0.00001)	3.09034e+07*** (<0.00001)
TEMP_SQUAR (valor p)		91519.1* (0.05682)
RAIN_RINN	-9130.15** (0.03786)	
RAIN_RINN_1	-17782.6*** (0.00012)	
DVI_VOLCANIC_INDEX	-7927.47** (0.01460)	
DVI_VOLCANIC_INDEX_1		25428.5*** (0.00394)
R-square adjusted	0.237144	0.373675
F	8.875212	7.562764

Source: compiled by the author.

*= level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets. No more variables have been included in order to isolate climate effects.

Tabla 7.3. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1660-1689 y 1690-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1660-1689 (T = 30)	1690-1739 (T = 50)
Constant	9.23392e+010* (0.07915)	3.32712e+07*** (<0.00001)
TEMP		1.5587e+06*** (0.00130)
TEMP_1	3.44379e+07* (0.06819)	
TEMP_SQUAR_1	1.86754e+06* (0.07570)	
RAIN_RINN	-12722.1** (0.04533)	-11943.5*** (0.00978)
RAIN_RINN_1	-12632.2** (0.01884)	-22678.4*** (<0.00001)
RAIN_WILS	30698.4** (0.01166)	
DVI_VOLCANIC_INDEX	-8578.56** (0.04220)	
SOLAR_IRRAD_1 (valor p)	6.78296e+07* (0.07866)	
R-square adjusted	0.440917	0.535566
F	4.267240	19.83489

Source: compiled by the author.

*= level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets. No more variables have been included in order to isolate climate effects.

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Chart 8. Statistic contrasts in the climate long-term impact: agrarian adaptation. Approaches of the land rent (Ricardian) and production. England, 1640-1740.

Dependent variable	Decennial rent, in m. of £. (1)	Decennial rent, in m. of £. (3)
Sample size	1640-1740 (T = 10)	1660-1740 (T = 8)
Constant	5.92199** (0.01683)	1.9334 (0.60923)
RAIN_WILS_DEC	0.029106*** (0.00541)	
TEMP_DEC		1.29526** (0.01737)
R-square adjusted	0.595794	0.578072
F	14.26588	10.59050
Durbin-Watson	1.565345	2.358401

Source: compiled by the author.

In DW, for T=10 and k=2, between ds (1,320) and 4-ds (2,68) absence autocorrelation. For T=8 and k=2, between ds (1,332) and 4-ds (2,67) absence autocorrelation. Total land rents and local taxes in m. £. by Clark (2001).

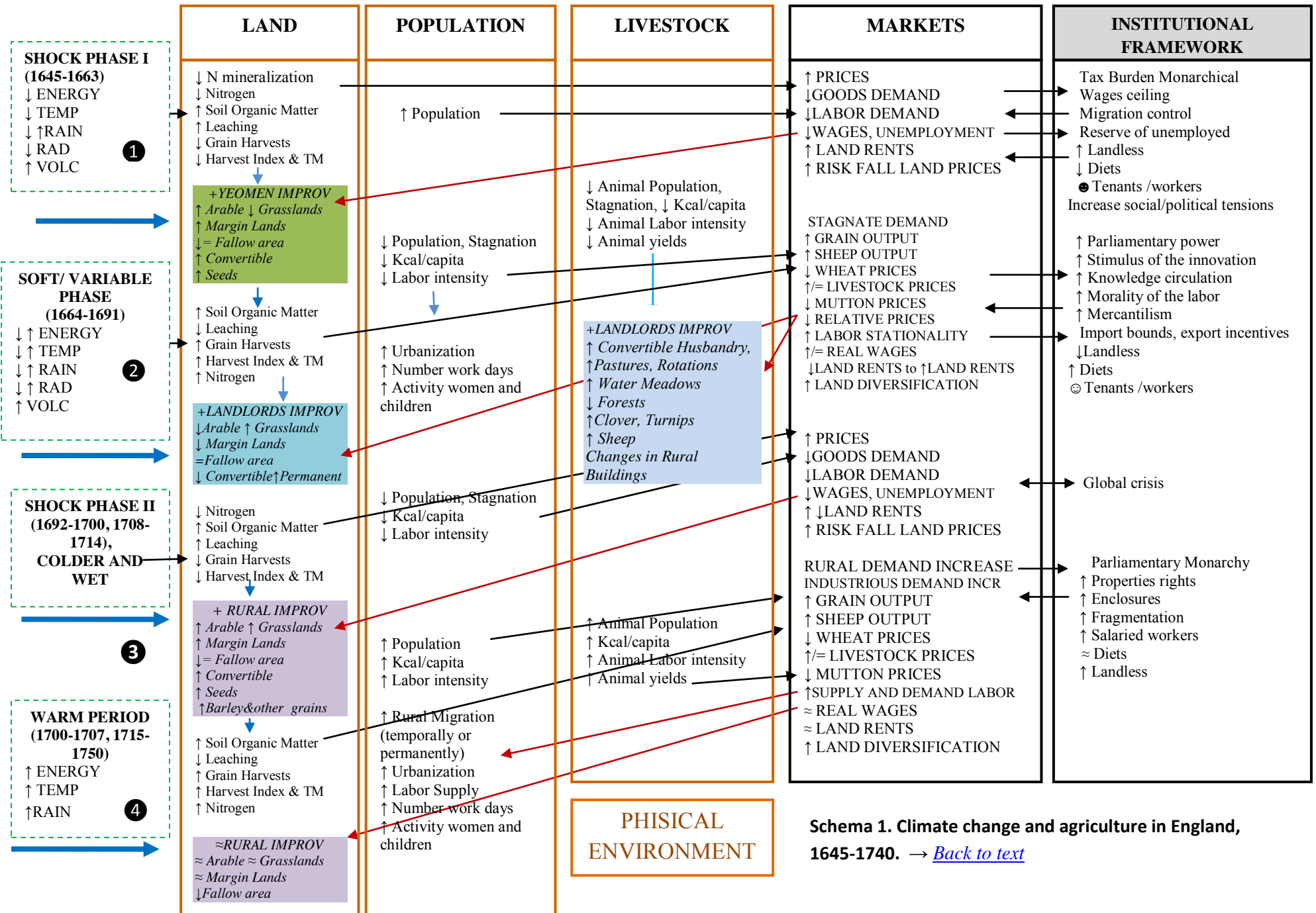
*= level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%.

p-values between brackets.

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ENVIRONMENT AND CLIMATE

THE CYCLE OF CLIMATE CHANGE IN AGRICULTURE: ENGLAND: 1645-1740



Schema 1. Climate change and agriculture in England, 1645-1740. → [Back to text](#)

Schema 2. The economic theory between climate and population.

	GROWING POPULATION (GP)	DECREASING POPULATION (DP)
FAVORABLE CLIMATE (FC)	<ul style="list-style-type: none"> • Δ Subdivision farms • Δ Fragmentation farms • Δ/∇ prices if $GP>FC$ / $GP<FC$ • Δ/∇ land values if $GP>FC$ / $GP<FC$ • Δ/∇ landless if $GP>FC$ / $GP<FC$ • ∇/Δ employment if $GP>FC$ / $GP<FC$ • ∇/Δ real wages if $GP>FC$ / $GP<FC$ • ∇/Δ diets if $GP>FC$ / $GP<FC$ • ∇/Δ landlords improvements if $GP>FC$ / $GP<FC$ • Δ/∇ yeomen improvements if $GP>FC$ / $GP<FC$ • Δ/∇ arable land if $GP>FC$ / $GP<FC$ • ∇/Δ grasslands, grazing if $GP>FC$ / $GP<FC$ • Δ/∇ use marginal land if $GP>FC$ / $GP<FC$ <p align="center"><i>Analysis applicable to 1700-1707 and 1716-1740</i></p>	<ul style="list-style-type: none"> • ∇ Subdivision farms • ∇ Fragmentation farms • ∇ prices • ∇ land values • ∇ landless • Δ employment • Δ real wages • Δ diets • Δ landlords improvements • ∇ yeomen improvements • ∇ arable land • Δ grasslands, grazing • ∇ use marginal land <p align="center"><i>Analysis applicable to 1664-1691</i></p>
UNFAVORABLE CLIMATE (UC)	<ul style="list-style-type: none"> • Uncertain subdivision farms • Uncertain fragmentation farms • Δ prices • Δ land values • Δ landless • ∇ employment • ∇ real wages • ∇ diets • ∇ landlords improvements • Δ yeomen improvements • Δ arable land • ∇ grasslands, grazing • Δ use marginal land <p align="center"><i>Analysis applicable to 1645-1663</i></p>	<ul style="list-style-type: none"> • Uncertain subdivision farms • Uncertain fragmentation farms • Δ/∇ prices if $UC>DP$ / $UC<DP$ • Δ/∇ land values if $UC>DP$ / $UC<DP$ • Uncertain landless • ∇/Δ employment if $UC>DP$ / $UC<DP$ • ∇/Δ real wages if $UC>DP$ / $UC<DP$ • ∇/Δ diets if $UC>DP$ / $UC<DP$ • ∇/Δ landlords improvements if $UC>DP$ / $UC<DP$ • Δ/∇ yeomen improvements if $UC>DP$ / $UC<DP$ • Δ/∇ arable land if $UC>DP$ / $UC<DP$ • ∇/Δ grasslands, grazing if $UC>DP$ / $UC<DP$ • Δ/∇ use marginal land if $UC>DP$ / $UC<DP$ <p align="center"><i>Analysis applicable to 1692-1700 (probably $UC>DP$)</i></p>

Source: compiled by the author.

Analysis of the demographic impact on agriculture by D. Griggs, 1982:27-31.

Rest of analyses by the author. This schema may also be developed according to the types of soil.

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