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Assessing agricultural adaptation to changing climatic conditions during the English agricultural revolution (1645–1740)

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Abstract
This article examines the impact of climatic variability on the English Agricultural Revolution using Allen's Nitrogen Hypothesis. While half of the variation in yields can be attributed to nitrogen-fixing plants, better cultivation, and improved seeds, the remainder can be attributed to changing climatic conditions during the relatively cold period from c. 1645–1715 and the subsequent warmer phase. The study finds that farmers made even greater efforts than observed yields during the colder and more humid climate of the second half of the seventeenth century and the early eighteenth. Conversely, increasing temperatures in the following period had a positive effect on agricultural productivity, indicating that farmers' role during this phase have been overrated.

Keywords Agricultural revolution · England · Climate · Nitrogen · Seventeenth century

JEL Classification N53 · O13 · Q10 · Q54 · Q55 · Q57

1 The controversy over the English agricultural revolution: enclosures, investments by farmers, and climate impacts

This article highlights the importance of capturing historical adaptations to changes in climatic conditions that potentially could have an adverse impact on a region. If adaptations are successful, negative impacts may not occur, and social changes may appear to have been brought about by other dynamics. This point is essential to understand and challenge one of the main shortcomings of the integrated economic

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models (IAM) advocated by economists, as well as other predictions about the future impacts of climate change or economic growth that exclude adaptations.

Ultimately, it is crucial to reinforce the narrative around the value of resilience and human adaptive capacity, in this case, through economic history. Those countries and regions that have implemented effective policies and practices to address climate change and other challenges and are able to adapt more effectively will be more likely to prosper in the future. It is important to bear in mind that, in an increasingly interconnected world exposed to multiple risks, the ability to cope with exogenous and endogenous shocks becomes a key factor for survival and sustainable growth.

Mitigation actions seek to prevent an undesirable future. However, these actions may involve high costs and little short-term gain, which can make them challenging to implement. In contrast, adaptation actions can be more feasible in the short term for individuals and communities, as they can generate immediate benefits, and many of them are private and local (Tol 2005; Moser 2012; Landauer et al. 2015; Altieri and Nichols 2017; Thornton and Comberti 2017; Sharifi 2020). Looking back in time, we can see how English farmers reacted to worsening climatic conditions during the climax of the Little Ice Age in the late sixteenth and seventeenth centuries. Through trial and error, they increased the flow of energy and labor, accumulated nitrogen, and increased agricultural production, as well as using more coal and wood to meet their energy needs.

In this context, a growing and robust body of historical research is emphasizing the role of resilience and adaptations. The importance of interdisciplinary collaboration has been recognized as a way of understanding the causal relationships between climate and pre-modern societies. It is fully accepted that crises in a society are never monocausal or predetermined, and that the relationship between the environment and human societies is complex and shifting (Haldon et al. 2018). This literature criticizes the erroneous tendency to focus on crises and collapses, instead of considering the existing diversity of responses to climate change. There is no doubt that many societies manage to adapt. The complex human responses contributed to the resilience of societies, allowing them to thrive under the changing climatic conditions during the Little Ice Age. Such resilience was conditioned by a combination of factors, such as food diversification, integration into broader markets, and the presence of effective political and institutional responses (Degroot et al. 2021). It is important to understand that this resilience affected various groups and social sectors within each society differently. Often, its costs were externalized and distributed unevenly among different social classes (Izdebski et al. 2018; Haldon et al. 2018).

The complexity of the research and the disciplinary diversity have required important efforts to create a synthesis There have been considerable advances in historical climatology and palaeoclimatology, including in reconstructing and recording the impacts of extreme temperature and precipitation events. There have also been notable advances in the study of historical droughts, with multidisciplinary analyses of floods, storms, and hurricanes in many regions beyond Europe (White et al. 2023). An assessment of 165 studies published between 2000 and 2019 on the impacts of climate variability in medieval and modern European human history shows promising results, but also areas for improvement. Challenges include the use of inappropriate paleoclimatic and historical data, the need for a better understanding of causality, the promotion of interdisciplinary collaborations, quantification of the influence of different meteorological parameters on food production, and the need to pay more attention to cultural responses and the processes of adaptation and learning, among others (Ljungqvist et al. 2021).

Over the past two decades, various studies have reconstructed climate trends and anomalies in 16th-century Europe and their impacts on the natural and social worlds. It has been observed that winter temperatures generally remained below the 1901–1960 average, except during the 1520s and 1550s. Toward the end of the sixteenth century summer climates cooled, a process in which volcanic forcings played a significant role. The correlation between these climatic variations and prices for rye was significant throughout the century, particularly in the latter half, which was associated with a decline in production. Cereals, viticulture, and dairy production were equally affected during cold spring periods, as well as by weeks of intense rain in mid-summer. Between 1568 and 1630, significant impacts were identified, exacerbated by political, war-related, and cultural events (Pfister and Brázdil 1999; Pfister 2005). Overall, the growing body of research on historical climate change and food shows significant patterns, but the effects of climate on agriculture and food supply cannot be understood in isolation from the resilience of societies, states, and economies (White et al. 2018; Ljungqvist et al. 2024).

Over the last 25 years, there have also been significant advances in strengthening the relationship between historical climate science and natural climate science. This progress has been achieved through the use of new climate reconstructions based on biological and non-biological data, as well as documentary sources (Pfister and Wanner 2021). During the Little Ice Age, increased volcanic activity and reduced solar irradiance led to a series of extremely cold winters and cooler summers, although there were also some very warm summers in certain periods. During this period, four major solar minima occurred (Wolf, Spörer, Maunder, and Dalton).[1] These events were coupled with dynamic processes in the upper atmosphere and ocean (negative NAO), as well as cooling due to changes in land use (Wanner et al. 2022).

The profound transformation of the English agricultural landscape has proved to be a controversial field of study. Although the traditional historiography focused on enclosures, farm size and the leadership of learned pioneers during the eighteenth and nineteenth centuries, other studies have stressed the importance of developments in earlier periods. Jones (1965a, b) argued not only that improvements were carried out between 1660 and 1750, but also that these improvements were applied to both open fields and enclosures. According to this author, tenants were the first to increase their investments, their efforts later being replaced by those of

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[1] The Maunder Minimum period (c. 1645–1715), rather than initiating a cooling phase, actually continued an already established phase of significantly colder temperatures. This period followed on the heels of a preceding era of cooling, thereby extending a notably frigid climate both in Europe and globally. The late sixteenth century and early seventeenth century, therefore, were characterized by an extended period of lower temperatures, which persisted through the Maunder Minimum (Pfister and Wanner 2021; Wanner et al. 2022).

the landowners.[2] This debate was revived in the works of Allen (1992, 2008) and Overton (1996a, b), amongst others. 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, the latter followed the tradition that linked agrarian innovation with the process of enclosure (Chambers and Mingay 1966), placing the period of increase in yields in the second half of the eighteenth century and giving more importance to the landowners' investments.[3] Recent research reconstructing the occupational structure of the population confirms the precocity of the agricultural revolution by sustaining a growing number of people working outside the agricultural sector. By 1700, only around 48 per cent of the population was working in agriculture, thus making England a historical exception at that time (Wallis et al. 2018).

In this regard, Allen (1992, 2008) has related the exceptional growth of agricultural productivity to the yeomen's revolution and the open fields. This author argues that there were two main factors explaining the improvement in grain yields. On the one hand, farmers gradually adopted better cultivation techniques, seeds and improved drainage. On the other hand, they also introduced legumes and convertible husbandry that led to an increase in the nitrogen stock.[4] The latter mechanism would explain about half of the rise in yields. Likewise, Allen stressed that the word revolution needs qualifying: the process of change to higher yields was gradual, due to the slow growth in the stock of nitrogen in the soil, so nitrogen fixation was very slow and had only a limited impact in the short term (Allen 2008).

Furthermore, there have been advances in the 'intersections' of various fields, such as the integration of historical climatology, paleoclimatology, economic, and agrarian history. These areas continue to make progress, alongside studies on climate and famines, and the influence of political, social, cultural, and meteorological factors (White et al. 2023). In Europe between 1500 and 1800, clear evidence of the impact of temperatures on grain prices comes from utilizing state-of-the-art paleoclimatic reconstructions and extensive meteorological data series (Ljungqvist et al. 2022). However, the impact of climate on English agricultural history has received little attention. During the sixteenth and seventeenth centuries, the climate in England generally became colder. This phenomenon has been related to an increase in volcanic activity followed by a long fall in solar activity, a period

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[2] The types of investment were also different: tenants invested in land management and cattle, whereas landowners invested in infrastructure and facilities (Jones 1965a, b).

[3] See also Thirsk (1967, 1984, 1997).

[4] Convertible husbandry is an agricultural practice that involves alternating between arable farming and pasture.

known as the Maunder Minimum,[5] but this solar minimum is likely to have coincided with other adverse climatic forces.[6] This period followed hard on the heels of a preceding era of cooling, thereby producing a notably cold climate both in Europe and globally (Pfister and Wanner 2021; Wanner et al. 2022).

Average temperatures fell, but rainfall variability and humidity increased.[7] The production of dry materials from crops decreased further, in proportion to reduced solar radiation absorbed by plants.[8] The energy balance between the heat latent in the soil and the evapotranspiration levels of the plants, as well as photosynthesis processes and respiration, became more unstable.

While some studies have examined the effects of climate on agricultural yields in both the short and long terms, research on how the cold phase between 1645 and 1715 interacted with the agrarian revolution and how farmers potentially adapted to these conditions remains limited.[9] Between 1659 and 1700, a combination of cold and wet weather was prevalent, with temperatures below early twentieth-century averages being observed for 38 of the 41 years during this time frame (Martínez-González et al. 2020, pp 239–240). Scott et al. (1998) demonstrated how wheat prices were correlated with climatic conditions. Brunt (2015) posits that yields were significantly reduced by unfavorable weather during the 1690 s, which Overton's data on yields cover, leading to an over-estimate of yield growth during the eighteenth century.

By expanding on the nitrogen model proposed by Allen and framing the agricultural revolution into the wider climate changes that occurred during the seventeenth and early eighteenth centuries, this article re-assesses the role of improved farming techniques on the evolution of agricultural productivity. In this regard, our contribution stresses that the cold phase would have reduced nitrogen levels and yields unless farmers compensated for this by their own efforts. Their role was therefore even greater than what the observed yields imply. However, increasing temperatures in the next phase (starting c. 1715), had a positive effect on agricultural productivity, suggesting that the role of the farmers in this stage has previously been over-rated.

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[5] The astronomer Eddy (1976, pp 1189–1202) published 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). On the increase in volcanic activity, see Stoffel et al. (2022).

[6] Such as an increase in clouds, large tropical volcanic eruptions, the emission of stratospheric sulfate aerosols and fluctuations in the North Atlantic. See, for instance, Lean et al. (1995), Pfister and Brázdil (1999), Luterbacher et al. (2001), Pfister (2005), Guiot et al. (2010), Yamaguchi et al. (2010), Büntgen and Hellmann (2014); Sigl et al. (2015), Anchukaitis et al. (2017), White et al. (2018), Ljungqvist et al. (2021), Wanner et al. (2022), Stoffel et al. (2022).

[7] Temperature variability also increased, as shown by decennial variation rates (Luterbacher et al. 2001; Büntgen and Hellmann 2014; White 2014; Parker 2013).

[8] According to the mechanism reasoned by Monteith and Moss (1977, p 279).

[9] See, for instance, Smith (1776), Beveridge (1921), Stanhill (1976), Brunt (2004), Hoskins (1964, 1968), Utterström (1955), Jones (1964), Appleby (1979, 1980), Bowden (1967), Overton (1989a), Michaelowa (2001), Hoyle (2013), and Waldinger (2014).

2 The standard nitrogen model: a theoretical review

The introduction of legumes and convertible husbandry increased the nitrogen stock and greatly contributed to the agricultural revolution that took place during the seventeenth century. The nitrogen hypothesis suggested by Allen is based on the following model[10]:

$$Y = m \cdot F \tag{1}$$

$$N_t = N_{t-1} + A_t - rN_{t-1} \tag{2}$$

$$rN_t^e = A_t \tag{3}$$

Equation (1) shows that the direct link between the level of mineralized nitrogen (F) and grain yields (Y) depends on m. Although m is a non-constant rate, Allen equals it to 8.349 based on information from the Middle Ages. Equation (2) relates the stock of organic nitrogen in year t (N_t) with the stock from the previous year (N_{t-1}) plus the potential additions of nitrogen resulting from natural deposition, manure, seeds, and nitrogen fixed by beans (A_t). The latter also take into account the nitrogen loss from the previous year (rN_{t-1}) by considering the nitrogen mineralization rate (r), which Allen sets at 0.015. Lastly, Eq. (3) shows an equilibrium relation where, in order to prevent nitrogen stock losses, nitrogen mineralization must equal nitrogen additions. Allen seems to take into account only the keys in grain yield, but what is relevant here is that he does by using an agronomic rather than an economic approach (from the soil point of view), and therefore does not include other direct variables such as labour or investment in horses. These elements are included in the take-up ratio, as we will see later.

This model allows Allen to divide the rise in yields into two mechanisms: those that increased nitrogen (mostly from natural deposition and nitrogen-fixing plants) and those that increased the efficiency with which nitrogen was used. In order to obtain the concept of efficiency, Allen states that m equals the harvest index (HI) multiplied by the ratio of dry matter to nitrogen assimilated by the plant and at the same time multiplied by the take-up ratio K (the fraction of the F in the soil absorbed by the plant). Allen assumes that the two first elements do not vary very much because the morphology and chemistry of grain is fairly stable, so the take-up ratio is equivalent to efficiency.[11] In this respect, new tools, new seeds and better working of the earth increased the take-up of nitrogen. This is where factors such as human work and horses are included or new techniques, for example. Therefore, an equivalent form of Eq. (1) is Eq. (4), where K is the take-up ratio and F is the free nitrogen, which depends on the agricultural activity variables X_t.

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[10] Allen (2008, p 188).

[11] Allen (2008, p 187). The harvest index is a ratio that represents the proportion of the harvested part of a crop (such as the grain, fruit or tuber) to the plant's total above-ground biomass. The harvest index has evolved historically along with changes in crop genetics, management practices, and technology. In general, the harvest index has tended to increase over time for many crops due to the selection of higher-yielding varieties, improved cultural practices, and advances in agricultural technology.

$$Y = f(K, F) = f\left[K(X_t), F(X_t)\right] = g(X_t) \tag{4}$$

However, Allen did not consider the temporal variability of the stock of nitrogen (N) or its mineralization rate (r). According to the soil-science literature, this variability can be explained, directly or indirectly, by changes in temperature, rainfall, solar radiation and volcanic aerosols. It is difficult, for example, to accept a constant $r = 0.015$ over long periods because r decreases with decreasing temperatures (Loomis and Connor 1992; Tello et al. 2017). *Ceteris paribus*, lower temperatures and shorter growing seasons lead to lower mineralization rates and a slower loss of the stock of organic matter (OM) in the soil and humus (Jenny 1930; Loomis and Connor 1992).

Likewise, the quantity of mineralised nitrogen (F in Allen's model) does not depend only on r and OM variability. First, there is a direct input flow (rainfall and free, non-symbiotic fixation) and output (denitrification, volatilization and leaching), which also depend on the climate, as well as other factors.[12] Allen assumes that these inputs and outputs were balanced but this is surely not the case in colder and wetter periods. We must bear in mind that the microbiological processes of the soil depend on temperature, humidity and acidity level (pH), as well as on the photosynthesis or the action of insects, diseases and plagues (Bowden 1985, p 47). Microbial activity slows down at low temperatures, affecting the speed of decomposition of OM. One of the processes of mineralization, namely ammonification, which is generated by microbial matter, is also very sensitive to temperature. The increase in humidity promotes denitrification and, consequently, nitrogen returns to the atmosphere as gas in greater quantities. In addition, there are some factors which affect the performance of legumes and the stock of nitrogen fixed yearly. The assimilation and fixing of nitrogen are proportional to biomass production, so if biomass declines in colder weather, nitrogen-fixing declines with it.

Moreover, the model overlooks the fact that nitrogen (N) is just one of the primary nutrients in the soil, alongside phosphorus (P) and potassium (K). According to Liebig's Law, yields are determined by the most limiting of these factors.[13] In this regard, apart from influencing nitrogen content, climate also shaped fertility in other ways, including the quantities of phosphorus, potassium, and acidity in the soil. In the case of phosphorus, although its function has been minimized historically (Allen 2008), Newman and Harvey (1997, p 136) pointed out that it could have been the main soil fertility factor until the nineteenth century.[14] Phosphorus generation (from OM mineralization) is usually deficient during cold periods. Therefore, its replacement management had to be improved in order to maintain its levels during the period from 1645 to 1740.

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[12] The increase in the humidity and reflectiveness of the soil generates greater denitrification; the increase of urine in the soil generates greater ammonium volatilization and a greater humidity index, while higher nitrate levels from manure or urine cause higher lixiviation (Loomis and Connor 1992).

[13] For an excellent qualitative review of Allen's model, see the first part of the article by Tello et al. (2017).

[14] On the other hand, pH seems to be affected by temperatures in the very long term. However, historiography indicates that farmers struggled to increase their OM contributions, but did so in a rather much wetter soil, which meant more acidification.

Climate change also affected the development phases of plants (that is, their germination and growth). The flowering period of the winter variety of wheat was critical and frost or a steep fall in temperature could ruin the crops. The wet and cold springs that were typical of the second half of the seventeenth century would therefore affect agrarian production, forcing farmers to introduce new seeds such as Red-Stalked Wheat in 1670 (in Oxfordshire), or White-Eared Red Wheat in 1650. During the period under study, the importance of highly climate-resistant crop varieties, such as *Lammas*, cannot be overstated in the context of combating smut, a fungal disease that had a detrimental effect on cereal yields and was highly sensitive to environmental conditions. This sentiment is echoed in primary sources such as Plot (1676, p 153), Mortimer (1712, pp 94–96), and Tull (1751, pp 139–143), who emphasize the significance of Lammas for its good yields and excellent baking quality. As for barley, early varieties such as narrow-eared barley became predominant in the seventeenth century. These crop varieties, when planted in May rather than March, gave better yields and were stored in the barn for two months less than the other varieties. This short storage period made them particularly valuable during the wet and cold springs that were a common feature of the climatic downturn, and they were very well-known in Cornwall and were widely planted in Oxfordshire (Thirsk 1984, pp 168–169). Another variety in widespread use was a spring barley, planted in Lincolnshire, while typical northern species were successfully adopted in the south. All this suggests that climate was an influential factor in seed selection, an issue that still requires research (Overton 1989b, p 90).

Balancing all these factors was extremely challenging and, when crops grew in less-than-ideal conditions, slight variations in the environment could have caused great variation in yields and the harvest index (*HI*).[15] For example, in the pre-industrial era, the nitrogen available to crops from rainfall and free nitrogen was as little as 6 kg 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 kg of N/ha per kilogram of grain, it equalled about 120 kg of wheat on an average crop of 900 kg, or 13.3 per cent of the total. With a price elasticity of demand of -0.4, this implied price variations of about 33 per cent. Consequently, slight variations of N caused by weather changes affected prices considerably.[16]

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[15] Loomis and Connor (1992).

[16] I have assumed an elasticity of 0.4 but some authors place the figure as low as 0.1 (Fogel). This means that prices would be even more sensitive (133 per cent). Producing 900–1000 kg of wheat was quite common in those times. R. S. Loomis estimated the N cycle on an English farm of the fourteenth century where 16.1 kg/ha of N were yearly produced. Rainfall, free $N2$ and fixing with peas was 8 kg/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 must have been reinforced by the indirect effect of the climate, catalyzing changes in almost all the processes that affected the yield of the crops like those mentioned above (fixing, waste, manure).

3 Integrating climate into the standard nitrogen model

The previous discussion advises thus to expand Allen's model using climatic parameters. Equation (2) assumes the following form:

$$N_t\left(C_t\right) = N_{t-1} + A_t\left(C_t\right) - r\left(C_t\right) \cdot N_{t-1} \tag{5}$$

where A_t and r now also depend on climatic variables (C_t). Consequently, N_t is a function of C_t. Given that F originates from organic nitrogen $N_t\left(C_t\right)$, Eq. (1) becomes:

$$Y = m^* \cdot F(C_t) \tag{6}$$

An important point here is the descriptive character of the standard model: it does not explain why innovation occurred. If in (1), m were (nearly) constant in the short term, the marginal product of nitrogen would be m, as well as its average product. Undoubtedly, this is too rigid an assumption for innovation to happen.[17] However, if the level of free nitrogen F were conditioned by climate, the marginal product Y' would be $m^* \cdot F'(C_t)$. The marginal product could then be above or below the average product, according to weather variations, and in the short term $m \neq m^*$. Therefore, the exclusion of the weather factor overestimates or underestimates output, thus making it difficult to understand farmers' behaviour.

Let us now consider the long term, where m is an endogenous variable. Although Allen assumes that the first two components of m (the harvest index (HI) and the ratio of dry matter to nitrogen assimilated by the plant) are constant, the HI is closely influenced by the nitrogen level, while the latter has undergone historical variations and depends on temperature (Sinclair 1998; Wheeler et al. 1996). Moreover, the take-up ratio K depends on F, which at the same time depends on the weather, as explained earlier.

Consequently, we can reformulate m as follows:

$$m = f(HI, K) \tag{7}$$

where both the harvest index (HI) and the take-up ratio (K) depend on climate: $HI = f\left(C_t\right)$; $K = f\left(C_t\right)$. Changes in m are thus positive or negative according to weather variations. A fall in the average temperature, higher temperature variability and an increase in humidity and summer rainfalls, as happened during the Maunder Minimum, would decrease m. According to (5), to maintain Y, $F(C_t)$ must be increased but F has also fallen due to the decrease in the mineralization rate r. Therefore, in the face of this climate shock, to maintain the balanced in the Eq. (3), farmers must increase their contributions of organic nitrogen A_t.

In any case, if we still assume that the two first components of m are constant, we can assess the model in the long term. Given that the take-up is the efficiency ratio, if Y were only a capital-nitrogen function, production could not keep going indefinitely in a steady, constant way. Due to the law of diminishing returns, eventually,

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[17] Neither does Allen have into account the costs of nitrogen for the farmer or income by unit produced.

the new units of nitrogen added would not increase production sufficiently, not even to compensate for the existing depreciation. There would not be enough resources left to increase the nitrogen stock per capita, so there would be no more growth. Allen considers the take-up ratio to be an exogenous efficiency ratio. This way, production can grow positively in the long term. However, here efficiency grows without a clear cause, and therefore the mystery remains unsolved. Although Allen mentions improvements in the take-up (eliminating competing plants, better plowing, greater labor intensity, seed drills, ploughs, better plants varieties, water, lime), they remain unexplained. Allen has carried out an extraordinary seminal work, as usual, but what were the causes of these improvements? Why did they speed up?

The climate of the seventeenth century is certainly exogenous. Let us take a model, where K is the take-up ratio and $\frac{\partial K(t)}{K(t)} = a > 0$. C stands for the climatic parameter. Let us add the take-up ratio and the climatic impact on the production function $Y = (KL)^{1-\propto}(CF)^{\propto}$. K stands for the number of units of labor efficiency, since only the take-up (that increases labor efficiency) allows the existence of equilibrium with constant growth rates through time. C would indicate a greater efficiency of nitrogen thanks to the improvement in the climate. The contribution of the stock of nitrogen in the output is $\propto$, and the condition $0 <\propto< 1$ is met. The function of the per capita production is $y = K^{1-\propto}(Cn)^{\propto}$, where y stands for per capita production and n is the stock of nitrogen per capita. The golden rule applied to a model where the capital is nitrogen is $s \cdot f(n) = (p + \delta) \cdot n$, where s stands for the savings rate, p stands for the population and δ is the depreciation of nitrogen. Substituting $f(n)$ for the former expression, finding the stock of nitrogen per capita n, applying the Napierian logarithms and deriving respect to time we find that the growth rate of the nitrogen per capita equals the take-up ratio plus the variation rate of the climatic parameter:

$$\frac{\delta n^*}{n^*} = \frac{\delta K}{K} + \frac{\propto}{1-\propto}$$

Therefore, growth occurs if the take-up ratio and climate improve, through their impact on the variation rate of the nitrogen stock per capita. If the second term is positive, this growth is even bigger than if we only observe a technical change.

A simple arithmetical exercise confirms these theoretical conclusions, thus strengthening the need to make the model less rigid. As mentioned earlier, although the standard model posits that the harvest index (*HI*) is fixed, temperature variations actually lead to changes in the *HI*. If the *HI* is higher, so is m and vice versa.[18] Let us consider now two hypotheses regarding N contributions in wheat output: a constant *HI* with of a value 0.3 and a flexible *HI varying* between 0.2 and 0.4 according to temperature.[19] As shown in Fig. 1, which reports the evolution of nitrogen in wheat production, variations in F are higher when the harvest indexes depend on temperatures. The mechanism behind this figure is reflected in Table 1, which shows how m fluctuates according to changes in temperatures. These examples stress how climate

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[18] Given a stock of mineral nitrogen, if the *HI* is higher, so are yields. Therefore, m is also higher.

[19] Calculating like Loomis and Connor (1992).

intensified the agrarian improvements by adding organic nitrogen A_t, thus providing further evidence of the need to expand the standard model.

Summing up, the Standard Nitrogen Model assumes that all the factors that affect the take up ratio (K) and the level of free nitrogen (F), and therefore agricultural productivity/production, originate in agricultural activity. However, given the interactions between climate and the processes described above, the model improves if it takes into account climate variables C_t that affect Y either in a direct way, or indirectly, through agricultural activity variables (X_t), thus making some of these variables endogenous.

4 Methodology and data

To investigate these issues further, this article begins by examining the physical relationships between climate, nitrogen, and output in the short term (production approach) and then infers the existence of potential adaptations. The starting point is a flexibilization of the standard Allen model, where agricultural output depends on the harvest index HI, the take-up K and the free nitrogen F, factors that depend on climate variables and agrarian practices. In other words, wheat production depends on two groups of supply factors, climatic (C_t) and agricultural (X_t) variables. Therefore, at the formal level, the impact equation can be rewritten so as to make it suitable for econometric modelling:

$$Y = f(HI, K, F) = f\left[HI\left(C_t, X_t\right), K(C_t, X_t), F(C_t, X_t)\right] = g(C_t, X_t) \cong \alpha + \beta C_t + \gamma X_t \tag{8}$$

where Y_t is the impact variable to be studied (physical output, yields), C_t is the set of climate variables (temperature, rain, solar radiation, volcanic dust) and X_t is the matrix of the variables proxying for agricultural practices. At the same time, direct and indirect impacts are explored, contemporary or lagged, following this specification:

$$Y_t = \propto + \sum_{i=0}^{n} \beta_i C_{t-i} + \sum_{i=0}^{n} \gamma_i X_{t-i} \tag{9}$$

In this regard, while C_t measures the weather impact in two principal ways: direct effects (e.g. storms, frosts or diseases) and indirect effects (through variations in the mineralization rate of nitrogen r in year t, in the rest of nutrients or through the mechanisms explained above), C_{t-i} captures the indirect impact of weather of the previous years $t - i$ (through r or on the rest of the nutrients). X_{t-i} refers to a set of agricultural practices taking place in previous years which also affect the harvest index, the take-up ratio, r and F indirectly.

The objectives of this approach are twofold. On the one hand, this model includes climate as a relevant dimension in the short term, a fact that allows the standard nitrogen model to be qualified and potential biases in the traditional estimates of land yields to be corrected. On the other hand, it opens up the possibility of exploring the long-term effects, as well as farmers' adaptive processes. This second step

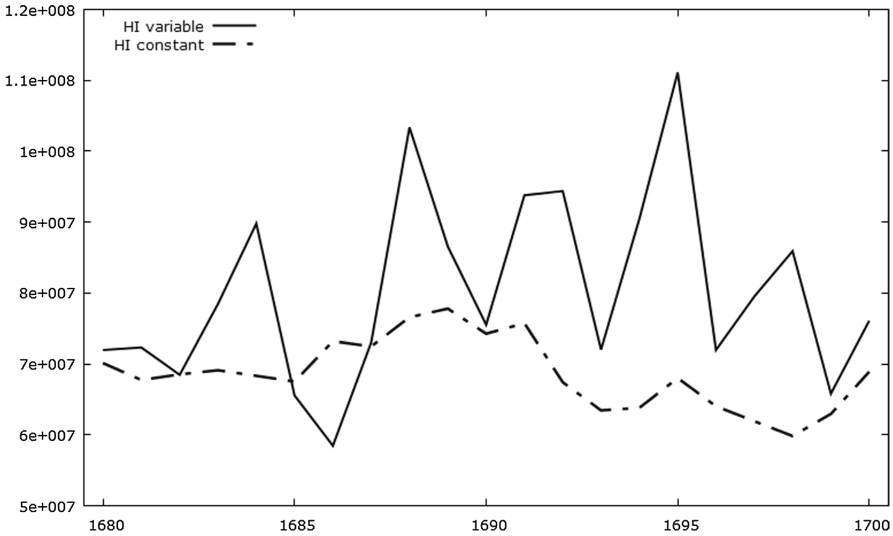

Fig. 1 Total nitrogen in wheat production (million kgs.). England and Wales, 1680–1700. *Note* The broken line shows total variations of *N* maintaining *HI* constant (0.3) and *N* content in the grain (0.02 kg of *N*/ha per kg of grain). The continuous line shows variations in N with a flexible *HI* (between 0.2 and 0.4) depending on temperature. An increase in *N* (*F*) is observed during the cooling phase (Maunder Minimum). The calculation of *N* variations (*F*) is explained in Table 1

analyses the relationship between climate and adaptations relying on the dummy variables approach.

4.1 Production data

Since there are no monthly or annual physical measures of output (in volume or weight), we use a robust estimate of production in bushels and kilograms, taking into account the yields obtained from probate inventories and farm accounts, that is, from the supply side (Martínez-González et al. 2019).[20] According to Davenant (1699), the grain warehouses had limited mitigating power, just five months and only in cases of good harvests. Their influence on the interannual prices was therefore minimal (Hutchison 1988, pp 51–52). On the other hand, the total surface area cultivating wheat between 1650 and 1750 remained stable at about two million acres (Broadberry et al. 2015). This allows us to use the wheat output as a measure of yield. Clark (2013, 2018) supports the Malthusian notion that the area under cultivation in England prior to 1700 was much larger. He argues that, if there were full employment and higher wages during the summer harvest season, the area under cultivation must have been much larger. However, the response of Broadberry et al. (2018) provides a convincing counterargument and is worth examining in detail. To supplement this response, there are additional arguments

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[20] Broadberry et al. only provide estimates for every fifty years.

Table 1 Average annual temperature versus non-constant m ratio ($m=\frac{Y}{F}$)

Year	Temp average	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

England and Wales, 1660–1739

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 $HI=0.3$ for 9 °C and modifying the HI proportionally according to temperature deviations from 9 °C (Loomis 1992, p 67)

worth considering. Coleman (1956) describes seventeenth-century England as an underdeveloped nation with underemployment, work instability due to variable weather and the use of child labour. Hill (1975) observes that workforce mobility was limited and wage rates fixed. Bohstedt (2016, pp 33–54) highlights an increase in food riots during the period, while Bowden (1967) notes the difficulty of achieving full employment due to summer rains that depleted harvests. Bowden's argument is supported by scientific advances, such as estimated series of summer rains that illustrate the high levels of instability in this period (see Fig. 2). Therefore, in an environment marked by great instability, short life spans, and strong restrictions on labour mobility, full employment was unattainable. Consequently in this article, the emphasis on stability is more crucial than determining the greater or lesser area under cultivation, a point overlooked by Clark. Moreover, even though the basis of his argument is on working hours, it is apparent that between 1650 and 1750, these remained relatively stable, ranging between 276 and 286 (Clark and Van Der Werf 1998).

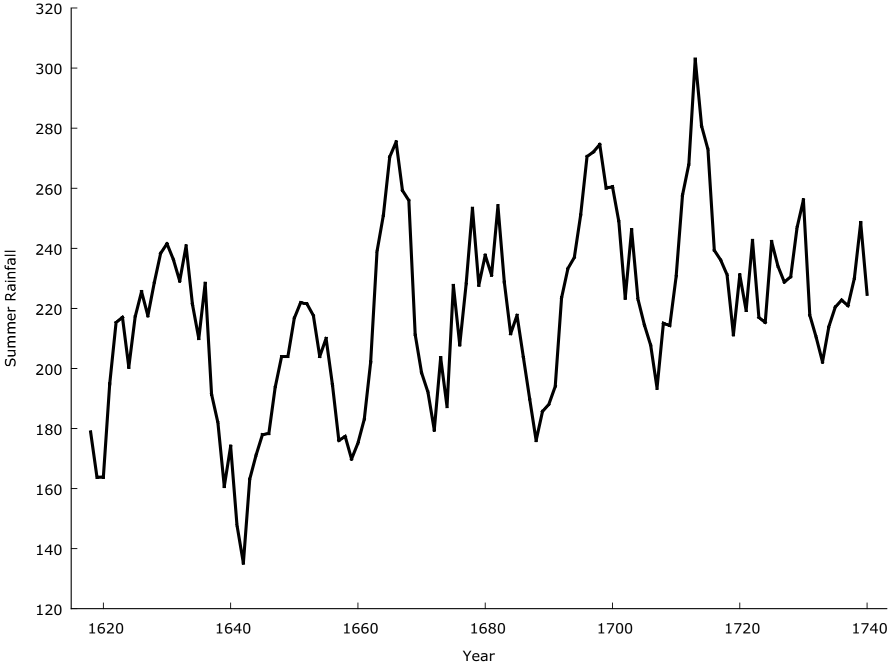

Fig. 2 Summer rains in mm, England, 1620–1740. Own elaboration based on Rinne et al. (2013). 5-year moving averages

4.2 Climatic data

Although information about climate from instrumental measurements is lacking prior to the mid-seventeenth century and rare prior to the eighteenth century, so that estimates prior to that must be derived from climate reconstructions based on documentary sources and/or natural palaeoclimate proxy archives, it is still possible to collect estimates of temperature, solar radiation, volcanic dust and rainfall.[21] The CET temperatures together constitute a series of monthly records of temperature from several towns in the Midlands starting in 1659 (Manley 1974). Although there are other temperature series,[22] this article primarily relies on Manley's series for various reasons: firstly, it offers monthly information; secondly, it is the only one resulting from direct measurements on the ground (instead of climate reconstructions); and thirdly, these temperatures are for England, which is the focus of this study. To test the results of this study further, we will also use the series by Van

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[21] It would be interesting to count on research on climate history in England from documentary resources in the future, e.g. taking the dates of salaries paid at the beginning of the harvests or keeping a record of the harvest dates.

[22] One of them corresponds to those of Luterbacher's et al. (2006), which presents the average European temperatures organized by seasons. A second reconstruction, which is also the most recent to date, is that developed by Luterbacher et al. (2004).

Engelen et al. (2001), which Kelly and Ó Gráda (2014) consider reliable. In fact, this second series provides empirical evidence supporting the validity of CET. More specifically, between 1645 and 1740, the correlation between the two series is statistically significant, with a Student's t of 11.562 and a correlation coefficient of 80%. Furthermore, as we shall demonstrate below, the econometric findings are consistent with this result.

As for solar radiation and volcanic activity, we have the series presented in Lean (2018). Moreover, solar radiation falls on England in a nearly uniform way,[23] and the different distributions of rainfall determine the potential evaporation (Monteith and Moss 1977). Monteith and Moss (1977) indeed established a positive relationship between dry material from the crops and the radiation intercepted. According to this author, most of the cultivated lands have ± 10% of 9 MJ/m^2 daily average per year. This means that the regional differences would have been caused by other factors, such as rainfall.[24] Unfortunately, there are no direct humidity, rainfall or weather instability records for the seventeenth century apart from the references written at the time by Smith (1776), Comber (1808) or Tooke (1838). However, recent studies, all tree ring-based, have reconstructed spring–summer rainfall for southern, eastern and south-central England (Rinne et al. 2013; Cooper et al. 2012; Wilson et al. 2012). These series will be used here, bearing in mind that: (a) they are reconstructions; (b) measurements come from trees located in specific territories, when the whole country should be analysed; and (c) rainfall has a more local and diverse incidence than temperatures, thus depending upon many geographical factors.[25]

Reassuringly, the climate variables employed here are shown to have a direct impact on yields (see Table 2). The variables show the expected signs: higher temperatures are associated with higher wheat production, and more rainfall in summer negatively affects harvests not only in that year but also the following year due to their effect on the nitrogen cycle (also because some of the organic matter generated in the previous year is used in the following years).[26] Relying on the series provided by Van Engelen et al. (model 2) yields similar results. Temperature and rainfall alone explain between 38 and 44 per cent of the variation in grain yields, thus supporting the adequacy of these series. Here we can put forward a quantitative assessment of what an adverse climate could bring. First, an excess of summer rains can damage crops (storms, floods, diseases), and falling temperatures also have a direct effect on plant growth. Second, there is another order of indirect impacts through changes in the amount of nitrogen and other nutrients, by varying the mineralization rate of nitrogen (r) and other mechanisms, thus affecting crop yields. But there are also delayed effects in that temperatures and rains from previous years can also influence the levels of nitrogen and those of the other nutrients and affect future crops. This is summarized in model 1. While year t captures the direct and indirect effects, year $t-i$ reflects the indirect effects of previous years. A 1 °C decrease in temperature and

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[23] Monteith and Moss (1977, pp 277–278).

[24] Monteith and Moss (1977, p 280).

[25] Thanks to Teresa Rinne and Richard Cooper for having provided me with their series.

[26] These results match those by Brunt (2004), Michaelowa (2001) and Chmielewski and Potts (1995), which find that climate explains around 33–50 per cent of yields (grain, straw).

a 50 mm increase in summer rainfall resulted in a fall of about 2.6 million bushels in gross wheat production.[27] In model 2, with van Engelen et al. temperatures, wheat output falls even further, by about 3.2 million bushels.

4.3 Agricultural inputs data

Given that there are no statistical series of Allen variables capable of directly capturing how nitrogen is added from manure, feeding beans or spring grains, we employ a set of proxies for the importance of different agricultural practices such as the use of spring grain, hay, legumes and wheat. We therefore use variations in the price of bean, barley and hay as a proxy for biomass variations associated to those agricultural practices, as well as wheat production in the previous year. Table 5 in the Appendix reflects the equivalence between Allen variables and the variables used here. Although the available information does not allow the take-up ratio to be measured with any precision, it should be stressed that this article is not intended to build a model that fully explains grain yields, but rather to make the Allen model more flexible by stressing the interactions between climate, agricultural productivity and farmers' responses.

5 Results and discussion

5.1 The impact of agricultural practices and climate on wheat yields: a comprehensive analysis

Table 3 present the results of estimating Eq. (9) relying on the variables explained above.[28] Table 6 in the appendix presents summary statistics for the variables under consideration. Notably, all the series are stationary, as confirmed by correlograms and the Augmented Dickey–Fuller (ADF) test. Additionally, the linear functional form is accepted based on the Ramsey Reset test, and all the series are homoscedastic, as confirmed by both the White and Breusch–Pagan tests. Furthermore, there is no evidence of multicollinearity [verified using the variance inflation factor (VIF)]. The error series follows a normal distribution according to the Normal test, and there are no issues related to outliers. The regression is free from autocorrelation problems, as indicated by the h-Durbin test, LM test, and Ljung–Box test, with no evidence of the ARCH effects. Moreover, there are no changes in the parameters, as shown by the CUSUM and Harvey-Collier tests. These findings indicate that the series used are free from some of the potential problems associated with the use of estimates, as all the basic hypotheses of multiple regression are met, making the results robust.

The regressions presented here are a simplified and flexible version of Allen's model. Column (1) introduces the proxy variables legumes_use, spring grains_use,

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[27] Note that the average gross production of the period was 33.5 million bushels and the minimum was 27.3 million bushels in 1648.

[28] Employing summer or winter temperatures does not change the results reported here (see Annex I).

Table 2 Testing the response of gross wheat production to temperature and rainfall

	(1) 1659–1740	(2) 1645–1740
CET TEMPERATURE	0.959** (0.0129)	–
ENGELEN TEMPERATURE	–	1.255*** ($<$0.0001)
ENGELEN TEMPERATURE (– 1)	–	1.274*** ($<$0.001)
SUMMER RAINFALL	– 0.014*** ($<$0.001)	– 0.006* (0.0984)
SUMMER RAINFALL (– 1)	– 0.019*** ($<$0.001)	– 0.013*** (0.0008)
N	82	96
adj R^2	0.44	0.38
F	16.24	15.80

England and Wales, 1645–1740

Standard errors in parentheses; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$. For simplicity, the intercept is not reported

gross wheat_use and hay_use and confirms Allen's standard model. *Ceteris paribus,* the increase of the price of the spring grains between the years t and $t-1$ involves a fall in the size of the crops and consequently a decrease of the quantity of N from the manure from feeding spring grain, the free nitrogen on the spring grain field, the nitrogen mineralized or the stock of nitrogen.[29] The partial impact is a decrease of 4.1 million bushels in the wheat produced. If a similar fall in spring grains also occurs between the periods $t-1$ and $t-2$, the total impact multiplier is a reduction of 7.46 million bushels, as it is necessary to add the effect of the fall in spring grain production to the wheat production for the year $t-1$, which at the same time has impact on the wheat output of the year t through a fall of the addition of N from wheat chaff, wheat seed sown, free nitrogen on the wheat field, the nitrogen mineralized and the stock of nitrogen in year t.

Allen indicates that the short-term effect of the nitrogen supplied by the legumes is irrelevant. This assumption seems to be confirmed in model 2. A variation of the nitrogen derived from the production of legumes of the year $t-1$ or $t-2$ has no noticeable effect on the production of wheat. However, a decrease in the bean crops between $t-2$ and $t-3$ involves a slight fall in the wheat output of -0.47 million bushels from the nitrogen supplied by manure from feeding beans, the nitrogen stock from legume residues, the nitrogen mineralized and the stock of nitrogen.[30]

On the other hand, low *HI* is associated with low r and low wheat yields. The contribution of N through the seeds, as well as the straw waste and the handling of the seeds, depends on the grain harvested in previous years. That is, past production captures the nitrogen associated with the harvest index and influences the practice of sowing. For example, the use of older seeds in the new crops, especially if these seeds are from a low-quality and unproductive previous crop, can make yields worse

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[29] A variation of 6d is related to an important fall in production, since it approaches the maximum price reached during that period.

[30] In model 3, which includes van Engelen et al.'s temperatures, the results are not significant, suggesting that the contribution of nitrogen through legumes was a slow process, as Allen predicted.

Table 3 Testing the response of gross wheat production (models 1, 2, 3) to climate and soil management

	(1) 1661–1740	(2) 1661–1740	(3) 1647–1740
SPRING_GRAIN_USE	−4.094*** (<0.0001)	−3.607*** (<0.0001)	−3.398*** (<0.0001)
SPRING_GRAIN_USE (−1)	−1.374** (0.0281)	−1.158*** (0.0129)	−0.948** (0.0420)
SPRING_GRAIN_USE (−2)	–	–	−0.857* (0.0867)
LEGUMES_USE (−2)	−1.335** (0.0103)	−1.284*** (0.0011)	–
GROSS_WHEAT_USE (−1)	0.719*** (<0.0001)	0.641*** (<0.0001)	0.710*** (<0.0001)
CET TEMPERATURE	–	0.606*** (0.0032)	
ENGELEN TEMPERATURE	–	–	0.550*** (0.0021)
SUMMER RAINFALL	–	−0.009*** (<0.0001)	−0.008*** (<0.001)
SUMMER RAINFALL (−1)	–	−0.009*** (<0.0001)	−0.007*** (<0.001)
SUMMER RAINFALL (−2)	–	0.006*** (0.0092)	0.006*** (0.0054)
SPRING RAINFALL (−1)	–	−0.015*** (0.0036)	−0.015*** (0.0035)
N	80	80	94
Adj. *R*-squared	0.69	0.83	0.82
F	44.70	44.57	48.28

England and Wales, 1645–1740

Source: See text. p-value between brackets. * = level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%. For simplicity, the intercept is not reported

from a comparative point of view. In addition, previous agronomic practices, proxied by wheat production from a previous year, had a positive sign (i.e., a good crop led to another good crop, but a bad crop led to a bad one), thus confirming Hoskins's wheat-price series theory (1968, pp 17–19).

Including the climate variables described above greatly improves the explanatory power of the model. Taking into account this dimension also reduces the role played by Allen's variables (around 12–15 per cent for the use of spring grains and around 4 per cent for the use of legumes), thus stressing the importance of taking

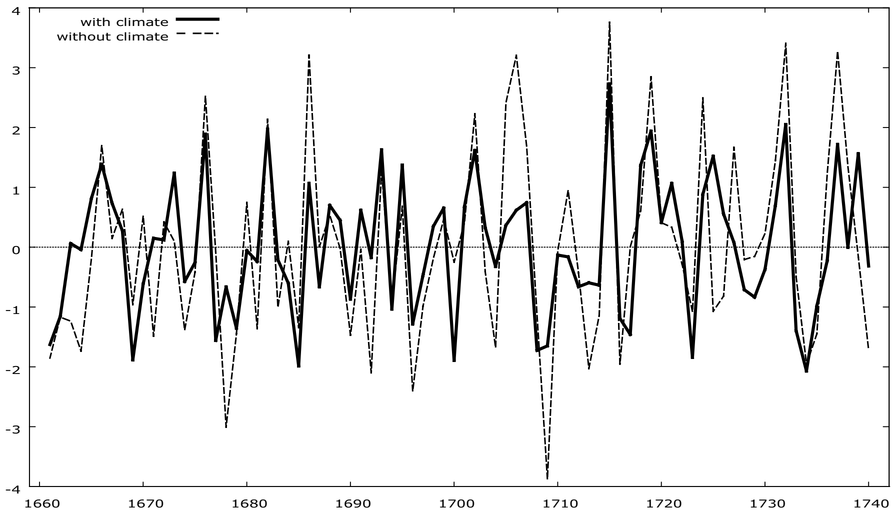

Fig. 3 Residual plot of the model with and without climate variables

climate into account when assessing the role of agricultural practices on yields.[31] An ANOVA analysis and the residual plot (Fig. 3) shows over- or under-estimates of the residuals in relation to model 2 and a biased estimate of the coefficients which affect the exogenous variables.[32]

Combining all the effects together,[33] namely climate (a 1 °C—decrease in temperatures plus a 50 mm—increase in rainfall) and agricultural practices (a 6d—decrease in nitrogen inputs: the seeds of previous wheat harvests and spring grains harvests, as well as nitrogen from legumes), results in a fall of the harvest of approximately 13.7 million bushels. Obviously, this disastrous combination never occurred, but it allows us to illustrate the importance of each factor: 51.6 per cent of this impact comes from the direct and indirect effects of the weather on *N* and the remaining nutrients (with lags included), and 48.3 per cent comes from the lagged indirect effects from agricultural practices, which in turn affect *r*. The hay biomass from previous years shows no effects; for this reason, we do not include this variable in the equation. This calculation serves to illustrate the importance of each factor because a combination of adverse weather was always accompanied by an increase in the efforts of farmers to add nitrogen. Therefore, the total climate impacts accounted for about half of the variations in yields, the rest coming from nitrogen-fixing plants and better cultivation, seeds and other factors. On the one hand, when we simulate a temperature drop of just 1 degree (−11% below average) and an increase in summer rainfall of 50 mm (+22% above average), the total impact is a decline in production of −3.38 million bushels, equivalent to a 10% reduction in the period

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[31] The coefficients are also reduced if we rely on van Engelen et al.'s temperatures (column 3) thus confirming the robustness of our results (the fall is even bigger in this model).

[32] Results in Appendix Table A3

[33] Direct and indirect, through *r* and *N*, including lagged effects.

average. Temperature and rainfall contribute equally, with each accounting for 50% of the impact. To mitigate this effect, farmers must increase nitrogen inputs in spring cereals by a minimum of 5% and in legumes by a minimum of 4.4%. By maintaining these practices, productivity can improve progressively if climatic conditions improve.

However, it is important to note that we are conducting a social experiment rather than a natural science experiment. In this context, last year's yields and prices can influence this year's planting and cropping decisions, as well as the amount of grain in storage. Therefore, yields may be linked temporally for reasons unrelated to nitrogen mineralization. Nonetheless, it is worth noting that yield estimates are based on supply, not demand, and that econometric tests indicate no autocorrelation or endogeneity issues.

Moreover, if we examine strictly natural experiments that are free from socio-economic contamination, we arrive at similar conclusions. For instance, Chmielewski and Potts (1995) analysed grain and straw yields from the Broadbalk winter wheat experiment at Rothamsted, UK, one of the oldest agricultural field experiments globally, from 1854 to 1967. Their findings indicate that long-term changes in crop yields at Rothamsted are partially related to climatic variations such as temperature and rainfall. In a similar vein, Addy et al. (2020) analysed yield data from long-term experiments with Broadbalk wheat and Hoosfield spring barley at Rothamsted Research and found that inter-annual variability in rainfall and temperature influenced crop responses to *N*, hence impacting on grain yields for both crops. As such, these contrasting experiments provide strong evidence that weather impacts cannot be attributed to changes in prices or management practices from one year to the next, by construction, thereby lending robustness to our findings.

5.2 Adapting to climate change: a production approach for analysing agrarian adaptation and management techniques in England

The relationship between climate change and adaptation is now analysed using a production approach. Wheat crops were directly conditioned by exogenous causes (environment and climate) as well as human action. *Ceteris paribus,* if, during an adverse climate period, production was less affected by the weather, there is only one explanation: farmers were improving the management of the soil. Through this approach it is possible to find out whether there was any agrarian adaptation or not regarding the influence of climate by dividing the period 1645–1740 into two periods to account for the cooling phase and the second phase of climate recovery.

Table 4 reports the result of estimating the effect of temperature and rainfall on wheat production but allowing this effect to change between periods. In this regard, the dummy variables *D*1 takes value 1 from 1700 and value 0 before 1700 (we have also tested the robustness of this approach by constructing the dummy variable *D*2 with a value 1 from 1715 onwards). The dummy variable *D*3 took value 1 between 1664 and 1691 and 0 in the rest. These results suggest structural changes in 1664, 1700 and 1715. These findings confirm that in the first period the climatic variables had less effect on wheat production. That means that there were great efforts

Table 4 Testing adaptive response of wheat net output, England and Wales, 1640–1740

Dependent variable Wheat net production in million bushels	1659–1739	1659–1739	1659–1739	1640–1739
TEMPERATURE	1.0007 (0.071)			
D1*TEMPERATURE	0.1813** (0.021)			
D1*SUMMER_RAIN		0.0113*** (< 0.00001)		0.0158*** (< 0.00001)
SUMMER_RAIN		− 0.0169*** (0.00004)	− 0.0119*** (0.002)	− 0.0209*** (< 0.00001)
SUMMER_RAIN (− 1)		− 0.0176*** (< 0.00001)	− 0.0163*** (0.00005)	− 0.0173*** (< 0.00001)
D2*SUMMER_RAIN			0.0101*** (0.00019)	
D3*SUMMER_RAIN				0.0101*** (0.00033)
N	81	81	81	100
$Adj.R^2$	0.19	0.33	0.26	0.41
F	10.19	17.1	12.73	18.06

Source: compiled by the author. p-value between brackets. *TEMPERATURE*, temperatures; *SUMMER_RAIN*, summer rainfalls. The dummy variable *D*1 took value 1 from 1700 and value 0 before 1700. The dummy variable *D*2 took value 1 since 1715 and value 0 before 1715. The dummy variable *D3* 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. For simplicity, the intercept is not reported

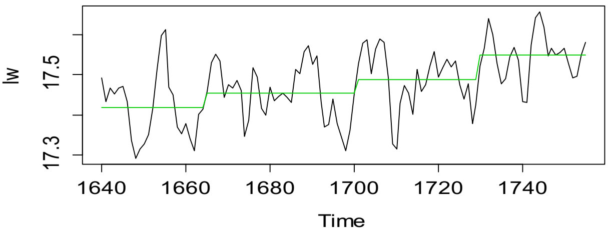

Fig. 4 Bai-Perron Test to value the existence of agrarian adaptation. England, 1640–1740. Source: Lw is the wheat production logarithm in bushels. The detected breakpoints are 1664, 1700 and 1730

to lessen the climatic shock from 1640 to 1660, at the beginning of the Maunder Minimum.[34]

The adaptive efforts carried out by the farmers can also be ascertained using an endogenous Bai–Perron test, thus avoiding the division of the series and the resulting reduction in the number of observations (Bai and Perron 2003). The detected breakpoints are 1664, 1689–90, 1700, 1715 and 1730 (see Fig. 4).

The primary objective of this study is to identify adaptations to climate variability using a methodology similar to the Ricardian approach proposed by Mendelsohn et al. (1994), as outlined in Dell et al. (2014). The aim of this approach is to detect evidence of adaptation to weather and climate change rather than to explain it, which is a complex task in its own right. Therefore, this study does not seek to explore the nature of these adaptations, which is a separate research question going beyond the scope of this article.

However, we can suggest potential avenues for future investigation regarding the adaptations made by farmers to climate variability. One possible approach is to examine the practices used by farmers to increase nitrogen additions and take-up ratios during the cooling phase. These practices may include incorporating more legume (clover) rotations to fix nitrogen in the soil, slowing down the conversion of fallow land to crops in order to maintain or increase organic matter (fallows that grow weeds or part cultivated as summerleys),[35] reducing the increase in the

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[34] There are four aspects to be take 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, and cushioning the environmental impact of the climatic variables. On the other hand, when the weather improved they did not need to struggle so much, so *the explanatory capacity of the climatic variables was higher*. Secondly, the relationship between climate and agrarian production is a reflection of human activity and must not be considered an input, at 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, which was more changeable, colder and wetter, allowed the farmer to be more prudent. Fourth, it is necessary to consider both the potential nonlinear effects of climate and the impacts of fertilization. Historically, it has been observed that increased levels of fertilization could mitigate some of the adverse effects associated with drought or excessively cold growing seasons.

[35] 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. 2015, p 89).

cultivated area to preserve organic matter reserves in the soil,[36] using the convertible system as a resilience tool,[37] replacing crops with pastures in both uplands and lowlands,[38] opening up new pastures,[39] and improving techniques for pastures, such as reducing common land, enclosing land and stone removal, as well as using water meadows to transfer nitrogen to arable land.

According to Allen, one of the most impressive aspects of agrarian change was the increase in pasture and the reduction in communal tenures (Allen 2005, p 6). Besides the strong increase in surface area (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, the other to technological improvements. 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 yields. In short, Allen draws our attention to some key developments in English agriculture, such as changes in pastures management and improvements to their yields. The preceding factors could have contributed to an increase in the OM stock. However, it is crucial to acknowledge the significant advances made in developing more resilient seeds, which were discussed earlier in this article.

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 not new, this system was considered to be one of the great innovations in the management of English pastures by Thirsk (1984, pp 180–181) and Jones (1965a, pp 155–156). So-called water pastures were placed next to rivers or streams of water in order to produce rich hay crops and stimulate grazing, with canalizations that allowed a continuous water flow at certain times. Through floating, mud rich in nutrients settled and a beneficial oxidation of the soil occurred. This technique also allowed the impact of frost in winter to be reduced, promoting early grass growth and higher hay production in summer. Water meadows yielded up to four times the usual quantities and densities of hay, which enabled all the year-round feeding and the early breeding of livestock. Water meadows also allowed climatic adversity to be prevented by managing canalization with chalk and covering to protect water from frost. This water was later drained and many essential nutrients for plants were collected. As a result, the quantity of sheep

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[36] 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. 2015, p 89).

[37] See Overton (1989b, p 291) or Smith (1776). The generation of manure in barns (winter) was an 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.

[38] Broadberry et al., quoting Grove 2004, and admitting the Little Ice Age (2015, p 55). Note that permanent pasture may give rise to more organic matter, but this could not be utilised by arable crops if it were under permanent pasture. However, more permanent pasture meant more food for the animals and therefore more manure. On the long trend to turn crops from the heavy claylands in the centre of England into pastures, see Bowden (1985, pp 47–48, pp 55–56, pp 61–62).

[39] According to Broadberry et al., the importance of pastures in England was increasing, including permanent pastures. There was a process of eliminating of forests in favour 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.

and cattle could be maintained 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.

6 Climate and nitrogen: the dance of yields and farmer's resilient achievements

The evidence presented here confirms the validity of Allen's standard nitrogen standard model. The nitrogen additions arising from cultivating springs grains, wheat and legumes had a significant impact on yields. Also, as Allen predicts, the effect from legumes is slow. However, this article stresses that climate factors should also be considered in the model. This enables us to gain a deeper understanding of causality relationships, quantify the direct and indirect influence of meteorological variables, and examine the adaptive responses of farmers, as demanded by the most recent scientific literature. Climatic variations affect yields both directly and through their effects on nitrogen levels. The colder and more humid climate that characterised the period 1645–1715 negatively affected yields, thus forcing farmers to compensate by increasing their investments in nitrogen-fixing plants, better cultivation and improved seeds. By contrast, the milder climate that started circa 1715 improved yields regardless of farmers' efforts. Our results therefore highlight the fact that observed yields under- and over-estimate agricultural practices during those two periods respectively, thus providing further support to the precocity of the English Agricultural Revolution and given the harsher climatic conditions, the resilient achievements of the yeomen farmers.

Appendix

See Tables 5, 6 and 7.

Table 5 Equivalence between our proxy variables and Allen's variables

X_t Variables	Equivalence to Allen variables	Data
LEGUMES_USE	Addition to nitrogen from manure from feeding beans	Variations in Clark's bean prices as a proxy for variations in bean biomass
	Addition to the nitrogen stock from legume residues	
	Nitrogen mineralized per year in year t	
	Stock of nitrogen in year t	
	Bean yield	
SPRING_GRAIN_USE	Addition to nitrogen from manure from feeding spring grain	Variations in Clark's barley prices as a proxy for variations in spring grain biomass
	Free nitrogen on the spring grain field at year's end	
	Spring grain yield	
	Nitrogen mineralized per year in year t	
	Stock of nitrogen in year t	
GROSS_WHEAT_USE	Addition to nitrogen from wheat chaff	Gross wheat output as a proxy for wheat biomass
	Addition to the nitrogen stock from seed sown	
	Free nitrogen on the wheat field at year's end	
	Wheat yield	
	Nitrogen mineralized per year in year t	
	Stock of nitrogen in year t	
HAY_USE	No variables found in Allen	Variations in Clark's hay prices as a proxy for variations in hay biomass
C_t VARIABLES	Direct effects: storms, frost, diseases	Dynamic climate data as a proxy because of the lack of annual variables of r, N_t of F
	Indirect effects on r, F, rest of soil nutrients	
	Allen assumes that $r=0.015$, $m=8.345$, and assumes certain values of N and F per Ha (non-dynamic variables)	
C_{t-i} VARIABLES	Indirect effects between r, F, rest of soil nutrients	Dynamic climate data as a proxy because of the lack of non-annual variables of r, N_t of F
	Allen assumes that $r=0.015$, $m=8.345$, and assumes certain values of N and F per Ha	

Own elaboration. We assume that if prices variation > 0, the output falls, the Allen variables also fall. And vice-versa if prices variation < 0, the output rises, ergo Allen variables rise as well. For example, high wheat output can imply one or more of these items: more wheat chaff, more seed sown, more free nitrogen, more and better labour, new tools and wheat seeds. However, here we cannot discriminate the relevance of each component, we only obtain a general assessment. It is evident that during the modern age, the quantity harvested is the most influential variable in price. On the other hand, the part reserved for sowing, feeding livestock and other uses was very stable, between 2 and 2.5 bu/acre (Overton 1984; Wrigley 1987). Allen's variables in 2008, p 204

Table 6 Summary statistics

	Average	Median	Minimum	Maximum	SD	CV	Skewness	Kurtosis Exc	Perc. 5%	Perc. 95%	IQ Rank
GROSS WHEAT PRUDCTION	33.80	33.85	27.90	40.80	2.96	0.09	−0.08	−0.69	28.60	38.43	4.15
CET TEMPERATURE	8.97	9.00	6.80	10.47	0.70	0.08	−0.48	0.29	7.68	10.03	0.90
ENGELEN TEMPERATURE	8.99	9.10	6.40	11.20	0.80	0.09	−0.37	0.37	7.59	10.20	1.10
SUMMER RAINFALL	228.95	227.33	65.34	381.34	70.77	0.31	0.03	−0.53	100.86	341.00	101.57
SPRING RAINFALL	258.62	257.60	166.01	355.31	45.57	0.18	0.16	−0.57	183.39	339.77	68.87
SPRING_GRAIN_USE	0.00	−0.01	−0.78	0.80	0.32	459.38	0.20	−0.05	−0.46	0.44	0.44
LEGUMES_USE	0.00	0.03	−0.99	0.81	0.37	307.73	−0.25	−0.07	−0.72	0.63	0.53
GROSS_WHEAT_USE	0.08	0.40	−6.00	5.00	2.24	28.76	−0.23	−0.29	−3.69	3.75	2.95
HAY_USE	0.31	0.76	−13.54	23.51	6.87	22.15	0.41	0.66	−11.35	13.36	8.06

Table 7 Summary statistics

Source	Sum of squares	*df*	Mean square	*R* squared	*F*
First ANOVA Analysis (*Model 2*)					
Regression	572.122	9	63.5692		
Residual	99.8371	70	1.42624		
Total	671.959	79	8.50582	0.851424	44.571 ($p = 1.64e{-}025$)
Second ANOVA Analysis (*Model 1*)					
Regression	473.389	4	118.347		
Residual	198.571	75	2.64761		
Total	671.959	79	8.50582	0.704490	44.6997 ($p = 3.84e{-}019$)

Model 1 has fewer degrees of freedom (4 vs. 9), suggesting a simpler model. However, its R2 is lower (70.45% vs. 85.14%), indicating that it explains less variance in the dependent variable than model 2. Both models are statistically significant, but model 2 has a slightly lower *p*-value, indicating stronger evidence against the null hypothesis. Model 2 has a higher R2, suggesting a better fit with the data

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