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REVISITING ALLEN'S NITROGEN HYPHOTESIS FROM A CLIMATE PERSPECTIVE (1645-1740)

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Abstract

Building on Allen’s Nytrogen Hypothesis, this paper assesses the role of climate change in the English Agricultural Revolution. Our results show that, while Nitrogen-fixing plants, better cultivation and improved seeds explain half of the variation in yields, the changing climatic conditions characterizing the cooling period (1645-1715) and the subsequent warmer phase account for the remaining variation. Given that the colder and more humid climate existing during the second half of the 17th-century and early 18th-century negatively affected yields, farmers’ efforts during this period were even higher than what it is implied by the observed yields. Increasing temperatures in the next phase (starting c.1715), however, had a positive effect on agricultural productivity, so the role of the farmers in this stage has been previously over-rated.

Keywords: Agricultural Revolution, England, climate, Seventeenth century.

JEL CODES: N53, O13, Q10, Q54, Q55, Q57

Resumen

Partiendo de la hipótesis del nitrógeno de Allen, este documento evalúa el papel del cambio climático en la Revolución Agrícola Inglesa. Nuestros resultados muestran que las plantas fijadoras de nitrógeno, las mejoras en los cultivos y semillas explican la mitad de la variación en los rendimientos. Las condiciones climáticas cambiantes que caracterizaron el período de enfriamiento (1645-1715) y la fase más cálida posterior, explican la variación restante. Dado que el clima más frío y húmedo existente afectó negativamente a los rendimientos, los esfuerzos de los agricultores durante este período fueron aún mayores que los que implican los rendimientos observados. Sin embargo, el aumento de las temperaturas en la siguiente fase (a partir de 1715) tuvo un efecto positivo en la productividad agrícola, por lo que el papel de los agricultores en esta etapa ha sido sobrevalorado.

Palabras clave: Revolución Agrícola, Inglaterra, clima, siglo XVII.

INTRODUCTION[1]

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 18th and 19th centuries, other studies have stressed the importance of developments in earlier periods. E. L Jones (1965) argued that not only improvements were carried out between 1660-1750 but also that these improvements were applied both in open fields and enclosures. According to this author, tenants were the first to increase their investments, whose efforts were later replaced by those of the landowners[2]. 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, the latter 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' 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; Shaw-Taylor et al. 2018).

In this regard, Robert C. Allen has related the exceptional growth of agricultural productivity to the yeomen's revolution and the open fields[4]. 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 and, on the other hand, they also introduced legumes and convertible husbandry that led to an increase in the nitrogen stock. 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

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[2] The types of investment were also different: tenants invested in land management and cattle, whereas landowners invested in infrastructures and facilities (Jones, 1965).
[3] See also Thirsk, 1967, 1984, 1985, 1997.
[4] Allen 1992.

to the slow growth of the stock of nitrogen in the land, so nitrogen fixation was very slow and has a small impact in the short term[5],

The impact of climate on English agriculture history, however, has received little attention. During the 17th century the climate in England generally worsened. This phenomenon has been related to a long fall in the solar activity, the Maunder Minimum[6], but this solar minimum is likely to have coincided with other adverse climatic forces[7]. Average temperature fell but rainfall variability and humidity increased[8]. The production of dry materials from crops decreased further, in proportion to reduced solar radiation absorbed by plants[9]. 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.

Although some research explores how climate affects agricultural yields both in the short and long term[10], there is little research exploring how the coldest phase (1645-1715) interacted with the Agrarian Revolution and the possible adaptive response from farmers. By expanding on the Nitrogen model proposed by Allen and framing the agricultural revolution into the wider climate changes that occurred during the 17th and early 18th century, this paper re-asesses 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 with their efforts. Their role therefore was even higher than what it is implied by the observed yields. Increasing temperatures in the next phase (starting c.1715), however, had a positive effect on agricultural productivity, so the role of the farmers in this stage has been previously over-rated.

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 17th century. The "nitrogen hypothesis" suggested by Allen is based on the following model[11]:

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[5] Allen 2008.

[6] The astronomer Jack Eddy published in the magazine *Science* (1976, pp. 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.

[7] Such as an increase in clouds, large tropical volcanic eruptions, emission of stratospheric sulfate aerosols and fluctuation in the North Atlantic. See, for instance, Lean *et al.* 1995; Luterbacher *et al.* 2001; Guiot *et al.* 2010; Yasuhiko *et al.* 2010; Büntgen *et al.* 2014, M. Sigl *et al.* 2015, Kevin J. Anchukaitis *et al.* 2017.

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

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

[10] See, for instance, Smith 1778; Beverigde 1921; Stanhill 1976; Brunt 2004, 2015; Hoskins 1964, 1968; Utterström 1955; Jones 1964; Appleby 1979, 1980; Bowden 1967; Overton 1989; Michaelowa 2001; Hoyle 2013, and Waldinger 2014.

[11] Allen 2008, p. 188.

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

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

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

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 medieval information. 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 takes into account the nitrogen loss from the previous year (rN_{t-1}) by considering the nitrogen mineralization rate (r), which Allen sets to 0.015. Lastly, equation 3 shows an equilibrium relation where, in order to prevent nitrogen stock losses, nitrogen mineralization must equal nitrogen additions. Allen seems to only study the keys in grain yield, but what is relevant here is that he does it from a more 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[12]. 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 Equation 1 is Equation 4, where K is the take-up ratio and F is the free nitrogen, which depends on the agricultural activity variables X_t.

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

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 it decreases during climatic cooling[13]. Ceteris paribus, lower temperatures and shorter growing seasons lead to a lower mineralization rate and a slower loss of the stock of organic matter (OM) in the soil and humus (Jenny 1930; Loomis et al. 2002).

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[12] Allen 2008, p. 187.

[13] Loomis *et al.* 2002, pp. 190-191. See also Tello *et al.* 2017.

Likewise, the quantity of mineralised nitrogen (*F* in Allen's model) 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, as well as other factors[14]. 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 the photosynthesis or the action of insects, diseases and plagues[15]. 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 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 also declines.

The model also fails to take into account that nitrogen (N) is only one of the main nutrients of the land, together with phosphorus (P) and potassium (K). According to Liebig's Law, yields are determined by the most limiting of these factors[16]. In this regard, apart from influencing nitrogen content, climate also shaped fertility in other ways, including the content of phosphorus, potassium, and acidity in the soil. In the case of phosphorus, although its function has been historically minimized[17], Edward I. Newman and Paul Dean A. Harvey pointed out that it could have been the main soil fertility factor until the 19th century[18]. 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 Little Ice Age.

Climate change also affected the development phases of plants (the germination and growth 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. Varieties of great resilience to climate such as *Lammas*, good performers and of excellent bread making quality, became very

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[14] 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, pp. 225 - 229).

[15] Bowden (1985, p. 47).

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

[17] Allen 2008.

[18] Newman and Harvey (1997, p. 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.

important to fight against the smut[19]. As for barley, early varieties 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 for two months or less, becoming very valuable in the wet and cold springs typical of the climatic downturn, and were very well-known in Cornwall and widely planted in Oxfordshire[20]. 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 suggests that climate was an influential factor in seed selection, an issue that still further research[21].

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*)[22]. 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 considerably[23].

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:

$$N_t\,(C_t) = N_{t-1} + A_t(C_t) - r(C_t) \cdot N_{t-1} \qquad (5)$$

Where $\mathrm{A_t}$ 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 $N_t\,(C_t)$, equation (1) becomes:

$$Y = m^* \cdot F(C_t) \qquad (6)$$

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[19] Plot 1676, p. 153; Mortimer 1712, pp. 94-96.

[20] Thirsk 1984, pp.168-169.

[21] Overton 1989b, p. 90.

[22] Loomis *et al.* 2002, p. 67.

[23] We 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 estimated the *N* cycle on an English farm of the 14th century where 16.1 kg/ha of *N* were yearly produced. Rainfalls, free *N*2 and fixing with peas was 8 kg/ha of *N*, higher than that of the seed (2.5 kg/ha), straw waste (2.5 kg/ha) or manure (3.1 kg/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).

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[24]. 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 consider now 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 and 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 before.

Consequently, we can reformulate m as follows:

$$m = f\ (HI, K) \qquad (7)$$

Where both the harvest index (HI) and the take-up ratio (K) depend on climate: $HI = f\ (C_t)$; $K = f\ (C_t)$. 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 period of 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 equation (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, the new units of nitrogen added would not increase production sufficiently, not even to replace 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 as 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. When Allen mentions the improvements in the take-up ("eliminating competing plants", "better plowing", "greater labor intensity", seed drills, ploughs, better plants varieties, water, lime), they are still unexplained. Allen has carried out an

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

extraordinary seminal work, as usual, but what were the causes of these improvements? Why did they speed up?

The climate of the 17th 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 of 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 $f(n)$ by the former expression, finding the stock of nitrogen per capita *n*, applying the Napierian logarithms and deriving respect time we obtain 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 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 technical change.

A simple arithmetical exercise confirms these theoretical conclusions, thus strengthening the need to make the model less rigid. As mentioned before, although the standard model 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[25]. 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[26]. As shown in Figure 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 intensified the agrarian improvements through the additions of organic nitrogen A_t, thus further evidencing the need to expand the standard model.

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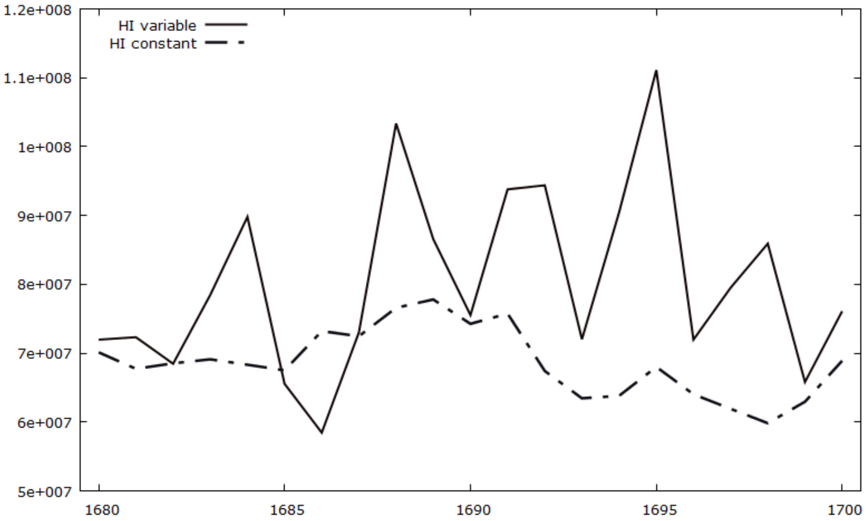
[25] Given a stock of mineral nitrogen, if the *HI* is higher, so are yields. Therefore, *m* is also higher.

[26] Calculating like Loomis *et al*. 2002, p. 67.

Figure 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.

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

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

Note: 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 9ºC and modifying the *HI* proportionally according to temperature deviations from 9ºC (Loomis 2002, p. 67).

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, are originated by the 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.

METHODOLOGY AND DATA

In order to analyse these issues further, this article first explores the physical relationship 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, climate (C_t) and agricultural (X_t) variables. Therefore, at the formal level, the impact equation can be rewritten as to make it amenable to econometric modelling:

$$Y = f\ (HI, K, F) = f\ [HI(C_t, X_t), K(C_t, X_t), F(C_t, X_t)] = g\ (C_t, X_t) \cong\ \alpha + \beta C_t + \gamma X_t \quad (8)$$

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:

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

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 qualifying the standard nitrogen model and correcting potential biases in the traditional estimates of land yields. On the other hand, it opens up the possibility of exploring long-term effects, as well as farmers' adaptive processes. This second step analyses the relationship between climate and adaptations relying on the dummy variables approach.

Production Data

Since there are no monthly/annual physical measures of output (in volume or weight), we use a robust estimation of production in bushels and kilograms (Martínez-González 2019)[27]. According to Davenant (1699), the grain warehouses had limited mitigating

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[27] Broadberry *et al.* only offer estimates every fifty years.

power, just five months and only in case of good harvests. Their influence on the interannual prices was therefore minimal (Hutchison 1988, pp. 51-52). On the other hand, the total surface cultivated with wheat between 1650 and 1750 remained stable in about 2 million acres (Broadberry *et al.* 2015). This allows us to use the wheat output as a measure of yield.

Climatic Data

Although information on pre-industrial climate is scarce, it is possible to gather estimates of temperature, solar radiation, volcanic dust and rainfall[28]. The CET temperatures assembles together a series of monthly records of temperature from several towns in the Midlands starting in 1659 (Manley, 1974). Although there are other temperature series[29], 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), even when it is likely to contain biased calibration (Kelly & Ó'Gráda 2014); thirdly, these temperatures are from England which is the focus of this study. We should however bear in mind that Manley's series presents some limitations. In this regard, the series starts in 1659, that is, a bit after the phase of accelerated cooling began (approximately in 1645), so many years of analysis are missing. It also does not represent the whole country but only a few specific locations. In this regard, it's important to note that CET exaggerates interannual variability, because there is more short-term temperature variability in any one region of the country than in the country as a whole, and understates low-frequency variability, due to the way that early instrumental temperature series are homogenized to remove artificial breaks and trends (D. E. Parker 2010). Lastly, it also seems that, before 1700, the temperature drop was more intense (Macadam 2012). Therefore, to further test the results of this study, we will also use the series by van Engelen, Buisman and Ijnsen (2001), suggested by its reliability by Kelly and O'Grada (2014).

As for solar radiation and volcanic activity, we have the series presented in Mann et *al.* (2000). Capturing solar irradiation is especially useful because irradiation explains 74 per cent of temperature variations in the pre-industrial phase (Lean *et al.* 1995)[30]. Moreover, solar radiation falls on England in a nearly uniform way[31] and the different distribution of rainfalls determines the potential evaporation (Monteith 1977). Monteith (1977) indeed established a positive relationship between dry material from the crops

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[28] It would be interesting to count on research about 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 taking a record of the harvest dates.

[29] 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 50º. The most suitable are the case of England TAS_2_5W_52_5N (west of England, near Birmingham) and TAS_2_5E_52_5N (east of England, but near the sea), reconstructed from 117 different intermediate indicators (including tree rings, historical documents, pollen and ice records).

[30] Global data, geographically speaking.

[31] J.L. Monteith and C.J. Moss 1977, pp. 277-278.

and the radiation intercepted. According to this 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[32]. Unfortunately, there are no direct humidity, rainfall or weather instability records for the 17th century apart from the references written at the time by Adam Smith (1778), W. T. Comber (1808) or Thomas Tooke (1838). However, recent research has reconstructed spring-summer rainfall in the southern, eastern and south-central England (Rinne *et al.* 2013; Cooper *et al.* 2013; Wilson *et al.* 2012). These series will be used 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[33].

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 not only negatively affects harvests 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)[34]. Relying on the series of 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. We can advance here a quantitative assessment of what an adverse climate could bring. First, an excess of summer rains can damage crops (storms, floods, diseases), dropping 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 direct and indirect effects, year t-i reflects the indirect effects of previous years. A 1°C-decrease in temperature and a 50mm-increase in summer rainfall resulted in a fall of about 2.6 million bushels in gross wheat production[35]. In model 2, with van Engelen *et al.* temperatures, wheat output falls even further, about 3.2 million bushels.

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[32] Monteith 1977, p. 280.

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

[34] 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).

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

Table 2. Testing the Response of Gross Wheat Production to temperature and rainfall. England and Wales, 1645-1740.

	(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

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

Agricultural Inputs Data

Given that there are no statistical series of "Allen variables" able to directly capture how nitrogen is added from manure, feeding beans or spring grains, we employ a set of proxies that attempt to proxy for the importance of different agricultural practices such as the use of spring grain, hay, legumes and gross wheat. We therefore use variations in the price of bean, barley and hay to proxy for biomass variations associated to those agricultural practices, as well as wheat production in the previous year. Table A1 in the Appendix reflects the equivalence between "Allen variables" and the variables used here. Although the available information does not allow to measure the take-up ratio with precision, it should be stressed that this working paper is not intended to build a model that fully explains grain yield, but rather to make the Allen model more flexible by stressing the interactions between climate, agricultural productivity and farmers' responses.

RESULTS AND DISCUSSION

Production approach and climate

Table 3 present the results of estimating equation (9) relying on the variables explained above[36]. The regressions presented are a simplified and flexible version of Allen's model. Column (1) introduces the proxy variables "legumes_use", "spring grains_use", "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 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[37]. The partial impact is a decrease of 4.1

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

[37] A variation of 0.5 shillings is related to an important fall of production, since it approaches the maximum price reached during that period.

million bushels of the wheat production. If a similar fall of 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 of spring grain production to the wheat production of 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 coming from the production of legumes of the year $t-1$ or $t-2$ has no noticeable effect in the production of wheat. However, decrease in the bean crops between $t-2$ and $t-3$ involves a slight decrease of 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[38].

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, depend 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 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 and a bad crop led to a bad one as well), 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 considering climate when assessing the role agricultural practices on yields[39]. An ANOVA analysis and the residual plot (figure 2) shows an over or under estimation of the residuals in relation to model 2 and a biased estimate of the coefficients which affect the exogenous variables [40].

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

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

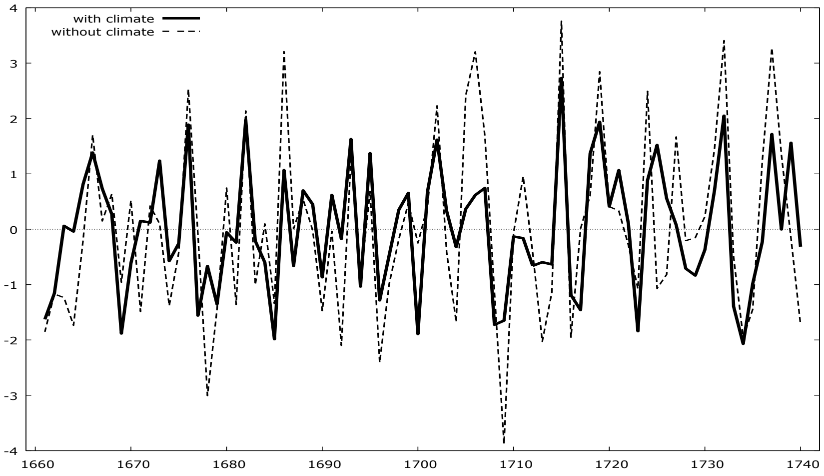
[40] Results available upon request.

Table 3. Testing the Response of Gross Wheat Production (models 1, 2,3) to climate and soil management. England and Wales, 1645-1740.

	(1)	(2)	(3)
	1661-1740	1661-1740	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
R-squared	0.69	0.83	0.82
F	44.70	44.76	48.28

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. All the series are stationary (correlograms and ADF Test). The lineal functional form is accepted (Reset Test). All the series are homocedastitic (White and Breusch-Pagan Tests) and free of multicollinearity (VIF). The error series follows a normal distribution (Normal Test) and there are no outlier problems. The regression is free of autocorrelation problems (h-Durbin Test, LM and Ljung-Box Tests, no ARCH effects). No changes in parameters are detected (CUSUM and Harvey-Collier Tests) The fact that all series are stationery and they do not violate any of the basic hypotheses of a multiple regression make the results robust

Figure 2. Residual plot of the model with and without climate variables.



Combining all the effects together[41], climate (a 1ºC-decrese in temperatures plus a 50mm-increase in rainfall) and agricultural practices (a 0.5 shilling-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 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 rest of 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 show 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 effort of farmers in nitrogen additions. Therefore, total climate impacts accounted for about half of the variations in yields, the rest came from nitrogen-fixing plants and better cultivation, seeds and other factors.

Long-term impacts and adaptation

The relationship between climate change and adaptation is now analysed from 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 an 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

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

dummy variables *D1* takes value 1 from 1700 and value 0 before 1700 (we have also tested the robustness of this approach by constructing the dummy variable *D2* 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 to lessen the climatic shock from 1640 to 1660, at the beginning of the Maunder Minimum[42].

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 authors. p-value between brackets. *TEMPERATURE*, temperatures; *SUMMER_RAIN*, summer rainfalls. The dummy variable *D1* took value 1 from 1700 and value 0 before 1700. The dummy variable *D2* took value 1 since 1715 and value 0 before 1715. 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. 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.

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[43]. The detected breakpoints are 1664, 1689-90, 1700, 1715 and 1730 (see figure 3).

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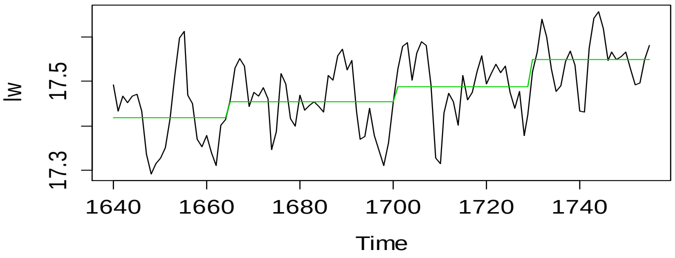
[42] There are three aspects to be taken into account: first, that the climate impact is asymmetric. When it harms the farmer, it reacts more dramatically; when it benefits him, it relaxes. This means that during the cold period farmers worked hard to overcome the difficulties, increasing the content of nitrogen, cushioning the environmental impact of the climatic variables. On the other hand, when the weather improved, they did 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, 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, more changeable, cold and wet, allowed the farmer to be more prudent.

[43] J. Bai and P. Perron 2003.

Figure 3. 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.

In this regard, the farmers were able to increase nitrogen additions and the take-up ratio during the cooling phase. Probably, they engaged in the following practices in order to maintain or increase the OM. First, including more pulse rotations in order to fix nitrogen in the soil. Second, slowing down the conversion of fallow land to crops[44]. Third, slowing down the increase of the cultivated area[45]. Fourth, maintaining permanent separation between crop and pastures within a convertible system[46]. Fifth, replacing crops with pastures, in both uplands and lowlands[47]. Sixth, opening new pastures. Seventh, 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. According to Allen, one of the most impressive aspects of agrarian change was the increase of pasture and the reduction of communal tenure[48]. 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

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[44] 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).

[45] 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).

[46] See Overton (1989, p. 291) or A. Smith (1778, p. 286). Despite the generation of manure in barns (winter), the division system between pastures and crops was relatively inefficient (Shiel 1989, pp. 666-67). On the contrary, it 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. 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, p. 156) and Shiel considered it of little importance during the 17th century (Overton 1989, pp. 293-294). Despite the important release of nitrogen through the ploughing of these pastures, the situation became the same or even worse after a few years (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 more research in needed on this issue.

[47] Broadberry *et al.*, quoting Grove 2004, and admitting the Little Ice Age or LIA (2015, p. 55). On the long trend to turn crops from the heavy claylands in the center of England into pastures, see Bowden (1985, pp. 47-48, pp. 55-56, pp. 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 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.

[48] Allen 2005, pp. 6.

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 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. Jones[49]. 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 certain times. Through floating, mud rich in nutrients settled and a beneficial oxidation of the soil occurred. This technique also allowed a 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 enabled all the year-round feeding and the early breeding of livestock. Water meadows also allowed preventing 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. As a result, 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.

CONCLUSIONS

The evidence presented here confirms the validity of Allen’s 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. Climatic variations affect yields both directly and through its effect on nitrogen levels. The colder and more humid climate that characterised the period 1645-1715 negatively affected yields, thus forcing farmers to compensate via increased investments in Nitrogen-fixing plants, better cultivation and improved seed. By contrast, the milder climate that started circa 1715 improved yields regardless of farmers’ efforts. Our results therefore highlight 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 heroic accomplishments of the yeomen.

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[49] Thirsk 1985, pp. 180-181; Jones 1965a, pp. 155-156.

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APPENDIX

Table A2. 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 -Addition to the nitrogen stock from legume residues -Nitrogen mineralized per year in year *t* -Stock of nitrogen in year *t* -Bean yield	Variations of Clark's bean prices as a proxy of bean biomass variations
SPRING_GRAIN_USE	-Addition to nitrogen from manure from feeding spring grain -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*	Variations of Clark's barley prices as a proxy of spring grain biomass variations
GROSS_WHEAT_USE	-Addition to nitrogen from wheat chaff -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*	Gross wheat output as a proxy of wheat biomass
HAY_USE	No variables found in Allen	Variations of Clark's hay prices as a proxy of hay biomass variations
C_t VARIABLES	Direct effects: storms, frost, diseases 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)	Dynamic climate data as a proxy because of the lack of annual variables of r, N_t of *F*
C_{t-i} VARIABLES	Indirect effects between 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	Dynamic Climate data as a proxy because of the lack of non-annual variables of r, N_t of *F*.

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.