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The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients  The period from 1645 to 1715 saw a series of extremely cold winters, with temperatures lower than average, even for the Little Ice Age (c.1300–c.1850), as well as a succession of weather extremes. According to some authors, the length of the growing season was shortened two to four weeks, and the ability of certain grains to withstand cold was severely tested, jeopardizing agricultural yields. Yet, this was exactly the time when the English Agricultural Revolution began, giving rise to one of the major improvements in traditional organic farm systems throughout preindustrial Europe. How can both facts be reconciled? Why did so many English farmers and


writers about agriculture start to look for new crops, seeds, rotations, and tillage methods during that period? How can climate history be harmonized with English economic history at this critical juncture?

This general question is related to another more specific one. Allen wondered what incentives English farmers might have had to strive for better fertilization when they introduced leguminous crops into their rotations. Given that the rewards through higher yields would have been long delayed due to a slow mineralization
of the nutrients caught into the soil organic matter, why did they adopt these new crops?  

Our hypothesis is that the English farmers acted to improve soil fertility by diversifying crops and experimenting with new methods of fertilization in response to cooling climatic conditions, as well as to prevailing price trends and public export bounties. Our tests below suggest that farmers were able to counteract, at least partially, the impact of climate change on wheat production when the temperature plummeted, and their efforts led to a long-term increase in yields when the temperature rose again. We acknowledge, however, that this interpretation has to be studied in detail by using more English series of physical outputs at the regional and local scale to permit an interpretation of their trends in the light of the nutrient balances attained in other times and places in Europe. Such a comparative analysis could help to explain why similar climatic challenges led to different responses, depending on prevailing institutional and socioeconomic conditions.

CHALLENGES AND OPTIONS DURING THE MAUNDER MINIMUM  In overview, diversification and new rotations in England and Wales helped farmers to endure the harsh temperatures—in contrast with other parts of Europe where the entire food system still relied on the success or failure of a single annual crop. This interpretation does not question the explanations based on the role played by

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the institutions and economic incentives that existed in England but not yet in most other parts of Europe at that time. On the contrary, placing the onset of the English Agricultural Revolution in its climatic and agro-ecological context allows us to look at the role of socioeconomic agency in a more realistic way. It also provides a solution to Allen’s conundrum about what induced farmers to search for new sources of organic N (nitrogen) to fertilize their soils despite the delay in obtaining higher yields.  

Might the initial aim of English farmers have been to maintain, rather than to increase, land fertility in the face of the harsh climatic conditions? This notion would be consistent with the economic history of the period only if we were to interpret the decrease in temperature as a specific context in which all of the socioeconomic variables played their own roles. From an economic standpoint, the century from 1640 to 1740 has been characterized as a long “agrarian depression,” mainly because of the decreasing trend in population and prices for grain. The very fact that lower wheat prices became a problem does not fit with a period that might have had to endure food scarcities. No doubt, bad harvests and high grain prices in England became more intense during certain years but not more frequent during the Maunder Minimum than in earlier or later times. What stands out is the

English farmers’ ability to overcome these climatic shocks in a much better way than their continental counterparts. 4

Indeed, English landowners found the persistent stagnation, or fall, in wheat prices so worrisome that an Act of 1663 promoted grain exports with public subsidies and imposed high duties on imports. Ceiling prices for cereal exports were abolished in 1670, and the bounties paid on overseas sales introduced in 1672 were suspended only in 1699, 1709, 1728, and 1740, when domestic grain prices temporarily rose. The drop in relative prices of wheat and rye, linked to population decreases among other things, was a general European trend. In the English case, the downturn in population went hand in hand with a significant increase in urbanization—the growth of London, in particular—following the rise of British colonial hegemony and trade. While grain prices stagnated or fell, those of other farm products like meat and dairy products, vegetables, fruits, beer, or industrial fibres (wool, hemp, and flax) remained steady or even increased, thanks to the growing urban demand. Thus, relative prices encouraged agricultural diversification and inaugurated a salient phase of alternative agriculture in England and Wales. 5


Maunder Minimum refers to the period from the mid-seventeenth century into the eighteenth century when sunspots were especially rare. It was named for the astronomers Edward and Annie Maunder, who studied the period.

5 For English exports and policy, see Thirsk, Alternative Agriculture, 26; David Ormrod, English Grain Exports and the Structure of Agrarian Capitalism, 1700–1760 (Hull, 1985); Stephen Hipkin, “The Coastal Metropolitan Corn Trade in Later Seventeenth–Century England,” Economic History Review, LXV (2012), 220–255; for trends in relative prices, Abel, Agricultural Fluctuations; de Vries,
Unlike in France or Central Europe, spring-sown barley and oats became integral to a three-course crop rotation in England, helping to compensate for wheat harvest failures; beer production could be temporarily reduced in harsh times to absorb the shock, together with a reduction in grain exports. Thus, England could avoid severe grain shortages, even though consumption had to shift to cereals of lower quality during years of bad harvest. Fallow land underwent further innovations to ensure animal feeding. Given that grain intake by horses could impinge on human food supplies when crops failed, finding alternatives for animal feed became an issue. By cultivating leguminous forages in former fallows—sometimes even fodder swedes, mangel beets, or turnips—and by improving water meadows, farmers could sustain human food and animal feed alike in harsh weather conditions. These strategies paved the way to a tighter integration of livestock and cropland tillage during a time when the relative prices of cheese and meat were high. Although the scanty figures available do not show a countrywide increase in livestock densities throughout England and Wales, a tighter integration of animal husbandry with farming presumably provided more manure for the arable land. Shortening the crop-growing season and confining herds to barnyards for longer periods would have resulted in larger amounts of well-composted manure ready to be carted to cropland. This integration might not have been intentional at first. When the harsher temperatures from 1645 to 1700 became entrenched, farmers were far more interested in creating barnyards built of stone or brick to store grains, hay, and forage and to shelter livestock in winter.6

Hence, the combination of economic incentives and edapho-climatic challenges during the second half of the seventeenth century fostered different regional specializations, depending on local natural resource endowments and socio-institutional landowner-ship distributions and tenancy entitlements. In areas of light soils, farmers introduced legumes and sometimes swedes, fodder beets, or turnips in ever more complex rotations, fostering a higher land-use intensity that provided them with a wider set of marketable products and alleviated the weather risks. In areas with clay-heavy soils, however, colder conditions and market trends drove farmers and large estates toward more extensive land uses, such as livestock rearing. The adaptations undertaken in areas of light soils facilitated more complex mixed farming, which allowed for grass leys and water meadows to replace diminishing fallow pastures in livestock feeding. Besides providing more animal feed and sources of N to the soil, these farming innovations also helped to protect from frost.\(^7\)
Abundant evidence indicates that during the second half of the seventeenth century, farming, livestock husbandry, and gardening became highly fashionable among the English elites, intellectuals, and some politicians of the time, even while remaining the centerpieces of everyday life among tenants and laborers. Manure became a popular topic among agricultural writers and gardening activists searching for new crops and tighter integration between livestock feeding and cropland tillage. For example, John Worlidge (1640–1700), who wrote that the fertility problem had to be solved by “warming the soil,” considered manure—above all, horse dung—to be the fertilizer with the most “heat.” Old agricultural treatises describe how English and Scottish farmers managed different sources of manure—either human, animal, or vegetal—including the practice of burning sods in piles and scattering the ashes in the fields. As far away as in the Scottish Highlands, farmers increased their efforts to transfer nutrients from meadows to arable land via animal dung and collected seaweed from the shore to plough into the soil. They


employed all sorts of organic fertilizing methods to replenish the nutrients extracted by crops, an issue that needs to be addressed from the standpoint of an overall nitrogen (N), phosphorus (P), and potassium (K) balance sheet.\(^8\)

The discovery of crucial mixed-farming innovations based on the fertilizing role of legumes, grown to feed both humans and animals, relied on the traditional practical knowledge of peasants, yeomen, farmers, and the gentry. Horticulturists, first women and then men, tested the new methods before farmers took the risk of applying them on a larger scale. The English yeomanry led the first wave of agricultural change, which mainly addressed land produce rather than labor productivity, as Allen and Overton stressed.\(^9\)

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9 For gardening, see Jenny Uglow, *A Little History of British Gardening* (New York, 2004); Margaret Willes, *The Gardens of the British Working Class* (New Haven, 2014); for the widespread
However, knowing that grains thrive better when sown after legumes is not the same as implementing this information successfully; farmers had to identify the appropriate plants and varieties to introduce them into rotations amid the specific climatic and economic frame of the second half of the seventeenth century. This story involved the circulation of not only books and ideas but also germplasm, throughout Europe and as far south as the Mediterranean. French, Belgian, and Dutch refugees from the European religious wars connected England and the continent in this regard. The two fodder tubers first introduced in English rotations during the Maunder Minimum came from the colder territories of Sweden (hence the name swedes, called rutabaga in North America) and Germany (mangel-wurzel). British imports of a wide range of seeds of sainfoin and lucerne legumes from southern Europe soared when many English innovators attempted to acclimatize them before discovering that native clover was the best option for forage in the new rotations. These imported leguminous seeds could not be sown at a large scale at their point of origin, due to the lack of rainfall and soil moisture in the Mediterranean bioregion. A full understanding of the English Agricultural Revolution requires adopting a comparative perspective of the agro-ecological innovations of the time encompassing Europe as a whole.10


has to be placed in this context. During the second half of the seventeenth century, English farmers adopted alternative crops, changed land uses, and implemented new tillage methods stimulated by trends in relative market prices, as well as by the challenges and options that presented themselves during the colder temperatures of the Maunder Minimum. Climate change might have played a role as important as market incentives in this endeavor. Although economic historians have paid much attention to market incentives as an explanation for the English Agricultural Revolution, scholars have paid relatively less attention to the former until recently.¹¹

**STRENGTHS AND WEAKNESSES OF ALLEN’S NITROGEN MODEL.** Allen’s pivotal question, which we reiterated above, opens a research agenda about the capacity, as well as the motivations, of traditional organic farming in different agro-climatic contexts to make improvements. The answer requires an interdisciplinary approach, jointly developed by historians, economists, agronomists, biologists, soil scientists, and climatologists. It requires deep research into the N flows that attended the changes in farming procedure during the Maunder Minimum and a thorough analysis of Allen’s pioneering attempt to link soil biophysical processes with economic incentives.¹²

Allen’s model highlights the slow pace at which the mineral nitrogen (N) is released from the stock of organic N compounds through the decay of humus. Underlying this outcome is microbial growth and decay in the soil, which is an N-limited biological process also influenced by the stock of soil’s organic carbon (C), acidity, moisture, soil composition, and temperature. Allen correctly points out that yields due to the investment of greater flows of organic matter into cropland may involve a delay. But how long this delay lasts depends on factors not taken into account in his model—for instance, the simultaneous supply of phosphorus

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¹² Allen, “Nitrogen Hypothesis.”
(P) through manure or the N immobilization during the decomposition of organic matter with a high C-to-N ratio.\textsuperscript{13}

Allen’s model simplifies the issue at crucial points, and its assumptions become too rigid to account for the range of actual processes that occur in agricultural soils at different spatiotemporal scales. This is not to say that Allen’s attempt is wrong. On the contrary, his seminal proposal invites economic and environmental historians to explore a new research issue in close collaboration with soil scientists. We criticize some aspects of Allen’s N-model only because we deem it to be foundational.

Mineralization of soil organic N is a site-specific process that depends on highly variable spatiotemporal factors that support the activity of soil microorganisms—that is, the entire biomass of decomposers integrated by the microfauna, bacteria, and fungi that turn the molecules of organically bound N into simple chemical compounds like ammonia and nitrate made available to plants. Bacterial activity uses carbon to release simple N compounds, provided that the C-to-N ratio of organic matter being decomposed is equal to or lower than 30. If the proportion of C relative to N is higher, microbial growth begins to incorporate available soil N into their bodies where it remains until their death, when available C is scarce. The result is some degree of N immobilization that sets a difference between gross and net N mineralization, which varies according to the composition of the organic matter involved. The process also depends on other environmental factors affecting the amount of bacterial biomass and its action, such as soil composition and texture, moisture, acidity, enzyme activity, and temperature. Farm management can modify some of these factors. Thus, soil N mineralization is a site-specific and variable process, for which it is difficult to establish reliable average values of decay rates. It also speaks to the extent of farmers’ local knowledge, obtained by trial and error.

After having reviewed nearly 250 models of soil N mineralization published in the last eighty years, Manzoni and Porporato

concluded that complexity and nonlinearity have increased in recent years, although they decrease as the spatial and temporal scale of observation grows larger. Keeping in mind their warning against transferring decay rates assessed in certain site-specific studies to other spatiotemporal scales, the figures reported a range from an increase in the annual net N mineralized of 9.5 kg/ha for any increase of 1° centigrade in mean annual temperature (as found by Reich et al. in various types of forest soils in 1997), to an increase of 0.25–0.32 kg/ha (as obtained by Burke et al. in grassland soils in 1997), and to a 7 percent increase of mineralized N for each temperature increase of 1° centigrade—corresponding to a temperature quotient, \( Q_{10} \), for N mineralization of 1.7 (according to figures proposed by Huang et al. and Koch et al. for organic alpine soils). To give a single example within these orders of magnitude, if total soil N in the top 50 cm of a hectare would have been 3,000 kg, about 2 percent of which was yearly mineralized, 60 kg N per hectare would become available each year. Under these circumstances, a decrease of 1° centigrade in the average annual temperature would lead to a reduction of 4.5 kg N/ha/year mineralized; during a span of fifty years, it would cause a reduction of 225 kg N mineralized per hectare. Most of this accumulated amount would become available when the temperature rose again.\(^{14}\)

Hence, N mineralization increases with soil temperature, although the exact relationship varies considerably by soil and climate conditions, and farm management can change the impact of temperature variation on soil microbial N mineralization to some extent. Again, to give an example, manure application, or some other organic amendment, can buffer the changes of soil temperature by warming soil in winter and cooling it in summer. In this regard, we consider four main assumptions in Allen’s N-model to be unrealistic: (1) his fixed N mineralization rate; (2) his fixed

lixiviation rate of N; (3) the linear relationship that he posits between the mineral N content of soil and the N uptake by all sorts of crops, grains, and legumes; and (4) the linear relationship that he posits between the mineral N taken by the biomass harvested above ground and the grain yield collected after threshing, which also depends on plant varieties and harvest indexes between grain and straw. All of these relationships vary depending on two types of conditioning factors, either natural ones or others technologically linked to farm management.

Among the natural factors, temperature is of particular interest in a period of climate change like the Maunder Minimum. Unlike weather oscillations that tend to even out in the short term, yearly average trends of temperature and precipitation were subject to profound change from 1645 to 1715; seasonal and annual variations were also more extreme than in the preceding or following decades. As noted, microbial populations, and their activity, heavily depend on soil temperature and water content. Leaching of nutrients from the soil also depends on the timing, as well as the amount and intensity, of precipitation. Other things being equal, the lower temperatures during the Maunder Minimum would have had an impact on microbiological activity by reducing soil N mineralization; the more intense spring and summer storms would have involved a stronger N leaching—perhaps countered by a greater flow of organic matter in the soil—and caused waterlogging and fungi diseases, thereby affecting wheat yields.\(^\text{15}\)

Other things, however, did not remain equal, because crop yields depend on a variety of biocultural factors that create path dependencies. Allen’s model assumes that soil N was the only limiting factor for crop yields. However, in the Broadbalk experiment in Rothamstead at the beginning of the twentieth century, yields were much higher for N mixed with P and K than for N alone. Similarly, in the Hoosfield experiment, current yields from soils with a low humus content are 75 percent of those from soils rich in organic

matter, even with annual applications of up to 100 kg of mineral N/ha. Hence, organic-matter content—which can be taken as an indicator of the physical and biological properties of the soil—together with P and K, as well as pH, can also be a limiting factor in crop productivity. As a case in point, soil compaction reduces N uptake and wheat yields, whereas greater P availability increases crop N uptake and yields (although the effect depends on other soil characteristics as well). Furthermore, a number of authors suggest that traditional organic agriculture was P-limited rather than N-limited, thus stressing the role of compost, manure, and “humanure” in closing nutrient cycles in agro-ecosystems. A more realistic approach would consider N as one among a set of interlinked limiting factors.16

Given that bacterial growth and the activity of other decomposing micro-organisms, like fungi, are also N-limited processes, the mineralization rate varies according to the mineral N content of soils. Instead of being constant, it is lower when the soil lacks mineral

N—a situation that leads to a self-reinforcing virtuous circle when soil is enriched with N or to a vicious circle when it is depleted of N. However, these mineralization processes also depend on the type of organic matter being incorporated into the soil. When the C-to-N ratio in the organic matter incorporated is low, as in raw manures or in legume crop by-products, mineralization no longer depends on the N available in the soil. When the C-to-N ratio in the biomass that is incorporated is high, such as in mature compost, the mineralization rate depends on the quantity of N already available in the soil. Hence, even accepting Allen’s assumption of an N-limited agriculture in seventeenth-century England, farmers’ efforts to increase the flow of organic matter that was incorporated in the soil would have found an increasing reward in yields sooner or later.

Yet, the quantity of mineral N available in the soil is one thing, and the N uptake by plants is another issue altogether. This point leads to another important missing variable, namely, the change of crop varieties. In an N-poor agriculture, like the one that Allen considered, farmers would have adapted traditional seed varieties to this environment. Current experiments show that simply adding N to existing varieties may result in decreased harvest indexes—that is, a lower proportion of grain relative to straw.17

Economic and agricultural historians tend to overlook that a great share of what usually passes statistically as yield increases is in fact the result of harvest indexes that became more favored from a market standpoint—that is, those showing more grain weight per plant rather than a higher amount of total biomass grown in the fields. Harvest indexes vary with plant breeding, but Allen’s N-model assumes a constant harvest index of 0.45 without leaving room for changes in crop varieties. Historically, farmers tended to grow crop varieties with a relatively low harvest index (0.4) because straw was an important by-product for livestock feeding and bedding, roof thatching, and other uses. Modern varieties bred for higher harvest

17 Thomas R. Sinclair, “Historical Changes in Harvest Index and Crop Nitrogen Accumulation,” *Crop Science*, XXXVIII (1998), 638–643. The N intake by crops could also have varied with colder temperatures; we know that leaf N content declines toward the equator where temperatures and the length of the growing season increase: See Reich and Jacek Oleksyn, “Global Patterns of Plant Leaf N P in Relation to Temperature and Latitude,” *Proceedings of the National Academy of Sciences*, CI (2004), 11001–11006. The N/P foliar ratio also increases with average temperature toward the equator, because P is a major limiting nutrient in older tropical soils; N is the major limiting nutrient in younger temperate and high-latitude soils.
indexes do not always entail the translocation of more N into the grain. Even more, harvest index, crop biomass harvested, and N absorbed are not independent but interrelated variables.  

Another issue that prevents assuming a constant mineralization rate is the legume’s adaptive responses to the soil N content. Legumes absorb more soil mineral N when the amount available in the soil is high. Otherwise, leguminous crops fix more N from the atmosphere by supplying more C to the root system that stimulates their Rhizobium colonies. Thus, under Allen’s hypothesis of an N-poor farm system, pulses and legumes would have acted as net N fixers, not net N absorbers, as he assumed. Furthermore, equations A3 and A4 in Allen’s model include a fixed productive-response coefficient to mineral N in the soil for both grains and legumes (8.34 kg of yield per 1 kg of soil available N), which is not correct. Leguminous crops can have a depressive effect on subsequent wheat yields due to factors other than N availability (for instance, pulses require relatively high amounts of P).

Allen’s model also downplays the fertilizing role of livestock. Livestock’s net contribution to the nutrient content of cropland soils undoubtedly depends on the balance between its uptake and excreta from arable land, grassland, and rough grazing areas, albeit in complex, variable, and site-specific ways. But animal bioconversion also accelerates nutrient turnover, making a higher proportion of mineral N available for the following crop. The model of Scholefield et al. assumes that 100 percent of the N content in urine and 22 percent in dung will be available within the first year after being applied—partly because the C-to-N ratio of dung is lower than 25. Without livestock, it would take much longer to mineralize stubble and other crop by-products. These observations point to the importance of farmers’ husbandry with respect to livestock densities in barns and


folds, the use of straw as bedding to retain urine in manure, and the amount of N lost during composting a manure heap. All of these factors were variable rather than fixed.\textsuperscript{20}

To what extent did the introduction of oats, clover, and fodder roots like turnips into new rotations (such as the one in Norfolk) allow a longer confinement of livestock, improve the care of dung heaps, and provide more and better manure for arable land? As stated above, the colder temperatures and shorter growing seasons during the Maunder Minimum would have entailed a longer confinement of animals in stalls and yards, where they could produce more and better manure.

Allen’s assumption of a constant lixiviation rate of N (50 percent of soil available N) for a process that is highly variable in space and time has an obvious effect on the stock of mineral N in soils given in his model. Nonetheless, farmers could have reduced lixiviation rates by enhancing the organic matter content of soils to improve water-retention capacity. Grain root systems can reach down a full meter under favorable soil conditions, but Allen’s model considers only the first 23 cm of soil. The organic matter content in 1 m may be four times that of the first 15 cm of soil; mineralization rates of 5 to 15 kg N/ha/year at depths of 30 to 60 cm have been reported in the literature. Furthermore, Allen does not take into account crop roots that may contain 50 percent of the total N in a plant.\textsuperscript{21}


Allen’s model wrongly adds the N in rain to the pool of organic N instead of accounting for it as a direct entry of mineral N into the soil. Last but not least, equation 1 in Allen’s model is based on references that assume a linear relationship between yield and fertilizer N applied but not between yield and free N in soil as he assumes. The concentration of N in fertilizers (20 to 40 percent) is much higher than that of free N in soil (about 0.01 percent). Allen mistakenly equates the mineral N input with the free N available in the soil, assuming a direct proportional relationship with yields. Although this direct relationship has actually been observed with high applications of N fertilizer, it is not at all certain that it still holds when the N sources are less concentrated, as in N mineralization driven by traditional organic farm systems.\(^{22}\)

Moreover, the absorption of N occurs with the flow of water into a plant. An N mineralization rate, as well as a crop’s capacity of N intake, is amenable to improvement in accord with the physical properties of soil, such as porosity and moisture, which are related to soil organic matter content. Such improvement would require either soil conditioning (usually a highly labor-intensive task) or longer fallow and grassland periods within crop rotations. Swedes, turnips, and other tubers (such as mangel beets) can also alter soil structure and the water flowing through it for the better, thus making a greater N flow accessible to a plant—contrary to Allen’s notion that turnips play no role in N availability. Older varieties of grains, usually adapted to environments with low water and N availability, show a greater ability to extract moisture deeply from the soil and are more efficient in N uptake.\(^{23}\)

Although all of the factors discussed above are important, the whole is more than the sum of its parts. Various synergies can move a soil system beyond critical thresholds, leading to unexpected


developments, as happened in the grassland soils of the North American Great Plains during the second half of the nineteenth century. In this true natural experiment, reductions in soil N content were not necessarily tied to a decrease in wheat yields until they reached a certain threshold. Even in this farming system that remained relatively unchanged for a long period, it took more than fifty years after the start of cultivation in the prairies for the land to reach equilibrium. The opposite would also be true. We cannot assume that a stabilization in yield is always related to a stabilization in the mineral N content of soil, as the linearity of Allen’s N model does.

Hence, Allen’s model, which highlights the historical importance of the N issue, is no help in answering the question of why farmers decided to enrich their soils with greater flows of manure and organic matter, despite the wait for higher yields. When English peasants, the yeomanry, or the gentry started to develop their responses to the challenges and opportunities of the time, they adopted strategies that changed the N mineralization rate in their soils, took advantage of many synergistic relationships between factors thought to be independent, and benefited from the multiple effects of variables that Allen’s N model cannot accommodate.

This article views the start of the English Agricultural Revolution as based more on the use of synergies than on the optimization of single factors. After all, the agriculturalists of the time had a specific understanding of their farm systems as a whole, and a perception of


how it might be improved, but they did not discriminate between
nutrients, let alone between their mineral and organic forms. They
worked in an economy in which labor and capital were seriously
constrained, and yields were inelastic and highly volatile in the short
term. Farmers relied on experience. When yields tended to decline
during the harsher climate of the Maunder Minimum, they reacted
by altering a pre-existing combination of strategies (by increasing
tillage and manure) and therefore intervening into the synergetic
possibilities of their agro-ecosystems.\textsuperscript{25}

Allen’s problem with farmers’ incentives emerges again when
considering the time frame of their expectations with regard to the
customary short-term volatility of their yields. The discoveries of
Gregory King and Charles Davenant in 1696 about the quantita-
tive inverse relationship between prices and quantities are telling
on this score. Although seventeenth-century common farmers
were probably as unaware of the King–Davenant formula of price
elasticity as they were of the English translations of ancient agricul-
tural treatises of Columela or Palladius or Samuel Hartlib’s corre-
spondence about gardening, they were certainly familiar with large
yearly variations in yield and the ensuing price changes. Any
attempt at modifying crop rotations and fertilizing methods had
to discount these market ups and downs.\textsuperscript{26}

As Loomis and Conor pointed out, there is no way to predict
accurately the exact amount of nutrients necessary for a crop to
avoid both a surplus and a deficit during the growing season.
Farmers, unaware of the mechanisms but well aware of the effects,
had to rely on field histories and past experience, hoping to apply
just the right dose, or maybe a little extra that would remain in the
soil and profit future crops. The cost was one year’s interest on
the investment. Most likely, farmers would have put any available
manure, latrine sludge, and vegetable fertilizers on the fields
to counteract the risk of serious nutrient deficiencies. Such is the

\textsuperscript{25} Pretty, “Farmers’ Extension Practice and Technology”; Turner et al., “Agricultural
Sustainability and Open-Field.” For the agro-ecosystem’s synergies, and the holistic approach
to agro-ecology, see Stephen R. Gliessman (ed.), \textit{Agroecology: Ecological Processes in Sustainable
Agriculture} (Boca Raton, 1998); Miguel A. Altieri and Clara I. Nicholls, \textit{Agroecology and the
Search for a Truly Sustainable Agriculture} (Mexico City, 2003).

\textsuperscript{26} Wrigley, \textit{People, Cities and Wealth}; John Creedy, “On the King–Davenant ‘Law’ of
as Historical Protagonist,” 288, 292.
assumption from which we launch a reconstruction of the incentives that lay behind the first steps that farmers took in the management of soils during a time of climate change that eventually led to the English high farming.\textsuperscript{27}

**TESTING ENGLISH FARMING ADAPTATION TO CLIMATE CHANGE**

During the first phase of the Maunder Minimum, from 1645 to 1695, annual average temperatures in central and southern England decreased; they were 5 percent lower than they were during the subsequent rise, which lasted up to the 1730s. Average rainfall from May to August decreased 10 percent; storms became more intense; and agricultural production was 3 percent lower (Figure 1a and 1b).

From our perspective, the colder temperatures would have reduced wheat yields by shortening the growing season and by diminishing soil microbial activity and N mineralization. Farmers might have compensated to some extent by improving manuring and tillage and growing more legumes. While temperature kept falling, investments would have led to a small and delayed reward that was good enough to withstand the Maunder Minimum and to justify the attempt to boost fertilization. The rising temperatures that followed stimulated bacterial activity and fostered soil N mineralization during a time when the wheat-growing season extended again, producing a striking mid-term effect. The greater reward from wheat yields due to the improvements of the earlier period induced farmers to continue their approach.\textsuperscript{28}

If this reconstruction is correct, the English wheat output should be correlated with temperature and rainfall variations throughout the Maunder Minimum—as already compiled in previous scholarship. Wheat harvests are obviously influenced by weather oscillations, as well as by climate gradients. Even today, a highly homogeneous type of industrial farming results in different agricultural outputs in different agro-climatic regions of the world. For our hypothesis to be fully confirmed, wheat production in the first, colder period, when English farmers scrambled

\textsuperscript{27} Loomis and Conor, *Crop Ecology*, 332.

\textsuperscript{28} Michaelova, “Impact of Short-Term Climate Change.” Besides being congruent with the national aggregate data provided in Broadberry et al., “British Economic Growth,” 36–44, which contributes to our statistical model, our hypothesis also fits with the evidence about the long-term trends of grain yields in Norfolk collected by Campbell and Overton, “New Perspective,” 70–71, 79, particularly with the slight fall that occurred in Norfolk from 1640 to 1709 in spite of the increased livestock densities of the time.
Fig. 1  (a) Annual Mean Temperature and Wheat Output in England, 1640–1740. (b) Spring and Summer Rainfall and Wheat Output, England, 1640–1740

to offset its negative effect, would have to differ from wheat production later, when temperatures rose, and farmers reinforced the positive effect not only by their ongoing methods but also by the delayed cumulative benefits of their earlier innovations.\textsuperscript{29}

To test for this hypothesis, we used as dependent variable the series of wheat produced in England and Wales, as estimated by Martínez from previously published data about physical wheat product in 1700. We also turned the variation in price series into annual quantity variations in line with a price elasticity of $-0.4$, as observed by King and Davenant in 1696. We adopted this elasticity as an independent empirical observation made in England precisely during our period of study—that is, as a reliable historical source that prevents us from falling into the circularity of employing the same price data again to construct the series of the agricultural product. Our independent explanatory variables include the instrumental temperature record compiled for central England from 1659 onward (the longest one in the world) and the late spring and summer rainfall measurements derived from oxygen isotopes in tree rings. A dummy D1 differentiates the years before and after 1700. Finally, another dummy, “corn bounties,” tests the effect of export subsidies paid by the British government. The results are shown in Table 1.\textsuperscript{30}

The coefficient of temperature in regression 1 (Table 1) implies that a variation of 1° centigrade increased wheat production by nearly 1 million bushels (which represents 3 to 4 percent of the country’s wheat crop at the time). However, when applying a temporal dummy that interacts with temperature (D1 * Temperatures), the effect of warmer temperatures on wheat production is


\textsuperscript{30} We took multiple steps to construct the series used as a dependent variable in the regression: First, we obtained the variations of the product from the wheat-price series through the price elasticity inferred by King and Davenant and specified later in the King-Davenant-Jevons-Bouniatian equation $y = 0.757/(x-0.13)^2$. The implicit price elasticity of this formula is $-0.403$, which is situated between the higher ($-0.57$) and lower ($-0.23$) ranges proposed for the long-term price decreases in England from the years 1268–1480 to 1750–1850 by Campbell and Ó Gráda, “Harvest Shortfalls, Grain Prices, and Famines in Preindustrial England,” \textit{Journal of Economic History} LXXI, (2011), 859–886. Second, to give rise to a first approximation of the physical series in millions of bushels of wheat, we applied these variations to the wheat product estimated for 1700—a year of normal, average
### Table 1  Testing the Response of Net Wheat Production to Temperature, Rainfall, and Corn Bounties Paid for Exports, England and Wales, 1659–1740

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
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<tbody>
<tr>
<td>Constant</td>
<td>2.90e+07***</td>
<td>4.32e+07***</td>
<td>4.00e+07***</td>
<td>4.46e+07***</td>
<td>3.62e+07***</td>
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<td></td>
<td>(0.001)</td>
<td>(&lt;0.001)</td>
<td>(0.001)</td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
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<tr>
<td>Temperatures</td>
<td>1.00e+06*</td>
<td>500,641</td>
<td>223,901***</td>
<td>262,911***</td>
<td>871,837**</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.24)</td>
<td>(&gt;0.001)</td>
<td>(&lt;0.001)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>D1 * Temperatures</td>
<td>181,314**</td>
<td>261,837**</td>
<td>223,901***</td>
<td>262,911***</td>
<td>871,837**</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(&gt;0.001)</td>
<td>(0.02)</td>
<td>(&lt;0.001)</td>
<td>(0.02)</td>
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<tr>
<td>Summer rainfall</td>
<td>−16,888.8***</td>
<td>−11,181.0***</td>
<td>−11,790.6***</td>
<td>−11,790.6***</td>
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<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.01)</td>
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<tr>
<td>Summer rainfall</td>
<td>−17,052.8***</td>
<td>−12,820.0***</td>
<td>−18,838.2***</td>
<td>−18,838.2***</td>
<td>−17,321.6***</td>
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<tr>
<td></td>
<td>(0.001)</td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
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<tr>
<td>D1 * summer rainfall</td>
<td>11,394.4***</td>
<td>11,394.4***</td>
<td>11,394.4***</td>
<td>11,394.4***</td>
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<td></td>
<td>(0.001)</td>
<td>(0.001)</td>
<td>(0.001)</td>
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<tr>
<td>Corn bounties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.18e+06**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(&lt;0.001)</td>
</tr>
<tr>
<td>N</td>
<td>81</td>
<td>81</td>
<td>82</td>
<td>82</td>
<td>82</td>
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<tr>
<td>adj. R²</td>
<td>0.19</td>
<td>0.33</td>
<td>0.42</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>F</td>
<td>17.16</td>
<td>15.66</td>
<td>20.32</td>
<td>17.92</td>
<td>17.92</td>
</tr>
</tbody>
</table>

***1%-significance level.  
**5%-significance level.  
*0%-significance level.

**NOTES** The ordinary least square (OLS) regressions (1), (3), and (4) consider temperature, and a specific dummy for the period 1700–1740, as explanatory variables of the net production of wheat. OLS regression (2) considers summer rainfall and the same dummy for the period 1700–1740; values presented are estimated coefficients; p-values in parenthesis; F-statistic values confirm that a relationship between exogenous and endogenous variables exists. The dependent variable is the wheat physical output recalculated from Stephen N. Broadberry et al., “British Economic Growth: 1270–1870,” Working Paper of the Department of Economics (University of Warwick, 2011), available at http://www.grammatikhilfe.eu/economicHistory/pdf/Broadberry/BritishGDPappendix.pdf (accessed January 17, 2013), as explained in Figure 1. Explanatory variables: Temperatures=mean annual temperature in centigrade; summer rainfall (−1)=May to August rainfall, the previous year in mm. The dummy variable D1 takes value 1 after 1700 and value 0 before; 1700 is considered a breakpoint for the wheat physical output series following Bai–Perron’s methodology to obtain endogenous structural changes (Jushan Bai and Pierre Perron, “Estimating and Testing Linear Models with Multiple Structural Changes,” *Econometrica*, LXVI, 1 [1998], 47–78). Corn bounties=a dummy variable that takes value 1 when export subsidies were paid and 0 when they were not. VIF values are close to 1 in all regressions.

**SOURCE** Authors’ own work, based on the sources listed in Figure 1.
18 percent greater after 1700 than in the previous cooling period, a result that clearly fits with our hypothesis. To check the robustness of this test, we included both variables in regressions 3 and 4. The first effect is that rainfall renders temperature nonsignificant for the whole period under consideration. However, when the interaction of the temperature with the time dummy was introduced as a variable, we found in regressions 3 and 4 that the warmer temperatures from 1700 onward became significant and carried higher coefficients. This outcome further accentuates how temperature affected wheat production during the cooling and warming periods, thus bolstering the results obtained from temperature and spring/summer rainfall separately.\footnote{We obtained similar results from the smoothed series of output (with a Hodrick–Prescott filter), regressed with temperature and summer rainfall. That is, temperature is significant only after 1700; the coefficients remain in the same order of magnitude; and the values of R-squared adjusted are higher. When the actual values of the series are subtracted from the trend to capture}

In all of the regressions, the effect of spring/summer rainfall is significant—more than that of temperature—with a negative sign (Table 1). In an Atlantic bioregion where water was hardly a limiting factor late in the season, this result captures the damage that the waterlogging of soils from heavy rainfall did to ripening cereals, stimulating fungi diseases and perhaps increasing N leaching. Unlike
the yearly average temperatures, spring and summer storms are site-specific phenomena—against which the open-field system would have afforded some degree of protection. The amount of spring and summer precipitation in the previous year has a similar impact on agricultural production.32

The introduction of temporal dummies that interact with spring and summer rainfall also shows that heavy seasonal storms caused less damage to wheat crops after 1700, even though their frequency and intensity did not decrease (Figure 1). The English farm systems became more resilient to them. By increasing the flow of organic matter in the soil, by altering tillage to prevent waterlogging and nutrient leaching, and by adopting more resistant grain varieties, did English farmers become better prepared to endure heavy storms during the late ripening periods of their wheat crops? Answering this question requires research far beyond the scope of this article.33

Overall, the temporarily broken down statistical tests shown in Table 1 fit with our hypothesis that the changes in English farming might have partially counteracted the effect of the colder
temperatures on wheat yields because of a shortening of the growing season and a reduction in the N mineralization rate during the first period of the Maunder Minimum. Conversely, these new methods would have reinforced the effect of the temperature rise that occurred during the subsequent period of the Maunder Minimum. Nonetheless, these innovations in farming could only counter, not completely cancel, the effect of climate change on wheat production, thus explaining why we checked for correlations in both periods, with temperature taken alone but at different intensities. The clear effect of the temporal dummies indicates that we cannot interpret the trends in wheat production and yield as the result of a linear impact of temperature variation on harvests. The interplay between climate change and farmers’ responses to it is what matters, not climate change alone.

As stated at the outset, other climatic and socioeconomic variables affected net wheat production in England and Wales. Unfortunately, the same price series used to estimate our dependent variable cannot be included again in the regressions. Instead, we used a dummy in column 5 of Table 1 that tests the effect of corn bounties paid for English exports, or their absence. The results are statistically significant; the other climate variables remain significant; and the coefficient indicates that the matter of public subsidies is associated with a 5 percent variation in the amount of English wheat produced.

We acknowledge that the aggregated series used in the regressions can offer only limited and provisional results. They cannot
provide a definitive answer to either our research question regarding English farmers’ reaction to the Maunder Minimum or Allen’s the N-hypothesis. Instead of closing the discussion, they issue an invitation to scholars of the English Agricultural Revolution, as well as other European scholars, to join in an interdisciplinary research agenda that encompasses agricultural history, environmental history, and soil science.

To build on Allen’s research we need to go beyond the limited and static assumptions of his N-model to place a broader appreciation of soil-fertility issues into the changing contexts of economic, climate, and environmental history. When we focus on the onset of the English Agricultural Revolution during the second half of the seventeenth century, the role played by the harsh temperatures during the Maunder Minimum cannot be ignored.

Our statistical results confirm that the evolution of wheat production in England and Wales was correlated first with falling and later with rising temperatures during the Maunder Minimum (1645–1715). They also bring to light that the correlation was weaker from 1640 to 1700, when climate became colder, than from 1700 to 1740, when the trend reversed. In our view, the reason lies in English farmers’ innovations. During the first period, a greater concern with fertilizing was able to counteract, at least to some extent, the effect of lower temperatures on wheat yields. Conversely, during the second period, ongoing innovation contributed to the benefits conferred by the rise in temperatures and the delayed reward from the previous investments.

From the statistical results herein, interpreted in the light of Allen’s N-hypothesis and the models used in soil science, as well as from a large body of qualitative evidence, we infer that English farmers may have tried to diversify their crops and herds in order to adapt their farming to both a change in climate and a shift in the market that occurred during the second half of the seventeenth century. When their initiatives no longer had to compensate for the effects of cooling on soil N mineralization and the length of the growing season, they fortuitously found that the new methods of mixed farming that they had contingently adopted were more productive and profitable than their old methods. According to this interpretive hypothesis, the English agricultural revolution was more a discovery than an invention, induced by a combination
of climate challenges and market incentives. Our test of this hypothesis is based on the only aggregate data of the English wheat production currently available for some time points, which we turned into a series of yearly net wheat production, using the King–Davenant price elasticity of $-0.4$. Further research about this subject should involve a wider empirical base that would include regional and local series of other grain yields directly recorded in physical terms, and determine overall balances of nutrients (N-P-K) in different regions, farming types, and moments of time. Only with this information can we devise more advanced interdisciplinary, quantitative models to link economic, agro-ecological, and climate-history data.

A deeper understanding of the British case also requires a comparative, European-wide perspective. The collective task is to understand when, where, how, and why Europe’s diverse pre-industrial organic agricultures were able to achieve a higher cropping intensity without opening a rift in nutrient replenishment that would cause decreasing yields in the long run, or, conversely, when, where, how, and why they were not able to do so. This approach entails opening the agricultural black box, adopting an agro-ecological viewpoint that demands a close collaboration of historians with social and natural scientists.\(^{34}\)

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34 Some of the authors herein are planning to apply this approach to the Western Mediterranean basin in the near future.