The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients

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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

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Roberto García-Ruiz is Professor in Ecology, University of Jaén. He is the author of, with Manuel González de Molina et al., "Guidelines for Constructing Nitrogen, Phosphorus, and Potassium Balances in Historical Agricultural Systems," *Journal of Sustainable Agriculture*, XXXVI (2012), 650–682; co-author of "Agrochemical Characterization, Net N Mineralisation and

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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?[1]

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

Potential N Leaching of Composted Olive Mill Pomace Currently Produced in Southern Spain," *Journal of Plant Nutrition and Soil Science*, CLXXVI (2013), 655–664.

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Nikola Koepke is postdoctoral researcher at the Institute of Evolutionary Medicine, University of Zurich. She is the author of, with Joerg Baten, "Climate and Its Impact on the Biological Standard of Living in North-East, Centre-West and South Europe during the Last 2000 Years," *History of Meteorology*, II (2005), 147–159; "The Biological Standard of Living in Europe during the Last Two Millennia," *European Review of Economic History*, IX (2005), 61–95.

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1 For a summary of the climatological state of the art regarding the Little Ice Age, see Ulf Büntgen and Lena Hellmann, "The Little Ice Age in Scientific Perspective: Cold Spells and Caveats," *Journal of Interdisciplinary History*, XLIV (2014), 353–368—a reply to the skepticism of Michael Kelly and Cormac O'Gráda, "The Waning of the Little Ice Age: Climate Change in Early Modern Europe," *ibid.*, 301–325; *idem*, "Debating the Little Ice Age," *ibid.*, XLV (2014), 57–68. See also Sam White, "The Real Little Ice Age," *ibid.*, XLIV (2014), 327–352. For an overview of long-term climate changes, see Philip D. Jones, Timothy J. Osborn and Keith R. Briffa, "The Evolution of Climate over the Last Millennium," *Science*, CCXCII (2001), 662–667. According to the best climatic models and available evidence, the Late Maunder Minimum had relevant effects in all regions of the globe, as explained in Hubertus Fischer et al., *The Climate in*

of the nutrients caught into the soil organic matter, why did they adopt these new crops?[2]

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

Historical Times: Towards a Synthesis of Holocene Proxy Data and Climate Models (Berlin, 2004), 397–414; Yasuhiko T. Yamagucki et al., "Synchronized Northern Hemisphere Climate Change and Solar Magnetic Cycles during the Maunder Minimum," *Proceedings of the National Academy of Sciences*, CVII (2010), 20697–20702. For the shifts reducing cultivation in England's hills during this period, see E. L. Jones, *Seasons and Prices: The Role of the Weather in English Agricultural History* (London, 1964); Martin L. Parry, *Climatic Change, Agriculture and Settlement* (Hamden, Conn., 1978); P. R. Galloway, "Long-Term Fluctuations in Climate and Population in the Preindustrial Era," *Population and Development Review*, XII (1986), 1–24; Mark Overton, "Weather and Agricultural Change in England 1660–1739," *Agricultural History*, LXIII (1989), 77–88; Axel Michaelova, "The Impact of Short-Term Climate Change on British and French Agriculture and Population in the First Half of the 18th Century," in Philip Jones, et al. (eds.), *History and Climate: Memories of the Future?* (New York, 2001), 201–216; for these shifts as a worldwide phenomenon, J. Holopainen and S. Helama, "Little Ice Age Farming in Finland: Preindustrial Agriculture on the Edge of the Grim Reaper's Scythe," *Human Ecology*, XXXVII (2009), 213–225; Bruce M. Campbell, *The Great Transition: Climate, Disease and Society in the Late Medieval World* (New York, 2016).

2 Robert C. Allen, "The Nitrogen Hypothesis and the English Agricultural Revolution: A Biological Analysis," *Journal of Economic History*, LXVI (2008), 182–210.

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.[3]

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

3 For the general context of the seventeenth century, see Theodore K. Rabb, "The Persistence of the 'Crisis,'" and Jan de Vries, "The Economic Crisis of the Seventeenth Century after Fifty Years," in the special issue "The Crisis of the Seventeenth Century: Interdisciplinary Perspectives," *Journal of Interdisciplinary History*, XL (2009), 145–150, 151–194, respectively. For agricultural diversification in the seventeenth-century, see Joan Thirsk, *Alternative Agriculture: A History from the Black Death to the Present Day* (New York, 1997); Wilhelm Abel, *Agricultural Fluctuations in Europe: From the Thirteenth to the Twentieth Centuries* (New York, 1980); de Vries, *Economy of Europe in an Age of Crisis: 1600–1750* (New York, 1976); *idem*, "Measuring the Impact of Climate on History: The Search for Appropriate Methodologies," *Journal of Interdisciplinary History*, X (1980), 599–630; Hubert H. Lamb, *Climate, History and the Modern World* (London, 1982), 192–224; for the climate history of the period, John A. Eddy, "The Maunder Minimum," *Science*, CXCII (1976), 1189–1202; Jürg Luterbacher, "The Late Maunder Minimum (1675–1715)—Climax of the 'Little Ice Age,'" in Jones et al. (eds.), *History and Climate*, 29–54; see also Luterbacher et al., "The Late Maunder Minimum (1675–1715): A Key Period for Studying Decadal Scale Climatic Change in Europe," *Climatic Change*, XLIX (2001), 441–462; for the agricultural impact, Michaelova, "Impact of Short-Term Climate Change"; Campbell and Overton, "A New Perspective on Medieval and Early Modern Agriculture: Six Centuries of Norfolk Farming c.1250–c.1850," *Past & Present*, 141 (1993), 38–105; for the long-run feedback between climate and land-use changes, Marie-Jose Gaillard et al., "Holocene Land-Cover Reconstructions Studies on Land Cover-Climate Feedbacks," *Climate of the Past*, VI (2010), 483–499.

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]

4 Galloway, "Long-Term Fluctuations in Climate and Population," 20; Peter J. Bowden, "Agricultural Prices, Farm Profits and Rents," in Thirsk (ed.), *Agrarian History of England, and Wales* (New York, 1967), 650–663; William G. Hoskins, "Harvest Fluctuations and English Economic History, 1620–1759," *Agricultural History Review*, XVI (1968), 15–31; de Vries, "Measuring the Impact"; Allen, "The Great Divergence in European Wages and Prices from the Middle Ages to the First World War," *Explorations in Economic History*, XXXVIII (2001), 411–447. The European series of Koepke and Jorg Baten, in "Climate and Its Impact on the Biological Standard of Living in North-East, Centre-West and South Europe during the Last 2000 Years," *History of Meteorology*, II (2005), 147–159, show that the lowest levels of temperature and heights appear in the seventeenth century. For the capacity of England and Wales to endure and overcome the climate shock of the Maunder Minimum, see Richard W. Hoyle, "Why Was There No Crisis in England in the 1690s?" in *idem* (ed.), *The Farmer in England 1650–1980* (Farnham, 2013), 67–98; 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, 2015).

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]

Economy of Europe; Thirsk, *Alternative Agriculture*; Mauro Ambrosoli, *The Wild and the Sown: Botany and Agriculture in Western Europe: 1350–1850* (New York, 1997); Michael E. Turner, John V. Beckett, and Bethanie Afton, "Agricultural Sustainability and Open-Field Farming in England, c.1650–1830," *International Journal of Agricultural Sustainability*, I (2003), 124–140; for English trends in population and urbanization, E. Anthony Wrigley, *People, Cities and Wealth: The Transformation of Traditional Society* (New York, 1987); Allen, *Global Economic History: A Very Short Introduction* (New York, 2011); for these English trends in population, urbanization, food production, and diet as opposite to the prevailing ones in Europe at the time, Maria Waldinger, "The Economic Effects of Long-Term Climate Change: Evidence from the Little Ice Age, 1500–1750," LSE Working Paper, available at http://etheses.lse.ac.uk/963/1/Waldinger_Historical_Events_Effects_LongTermEconomic_Social_Development.pdf (accessed January 17, 2015).

6 For the general picture of English agricultural innovation, see E. L. Jones, "Agriculture and Economic Growth in England, 1660–1750: Agricultural Change," *Journal of Economic History*, XXV (1965), 1–18; Overton, *Agricultural Revolution in England: The Transformation of the Agrarian*

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 landownership 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]

Economy 1500–1850 (New York, 1996), 76–80; *idem*, "English Agrarian History 1500–1850," available at http://www.neha.nl/publications/1998/1998_04overton.pdf (accessed January 17, 2015); Turner, Beckett, and Afton, *Farm Production in England, 1700–1914* (New York, 2001), 117–133; Broadberry et al., "British Economic Growth"; for the role of barley and other crops in preventing famines, Andrew B. Appleby, "Grain Prices and Subsistence Crises in England and France, 1590–1740," *Journal of Economic History*, XXXIX (1979), 865–887; *idem*, "History Epidemics and Famine in the Little Ice Age," *Journal of Interdisciplinary History*, XX (1980), 643–663; Michaelova, "Impact of Short-Term Climate Change"; Campbell and Overton, "New Perspective"; Hoyle, "Why Was There No Crisis in England"; for the predominance of barley and oats in English grain exports, Ormrod, *English Grain Exports*, 22, 26, 45–69; Craig Muldrew, *Food, Energy and the Creation of Industriousness* (New York, 2011); for the increase in livestock from 1500 to 1700, followed by stagnation until 1750, except for hogs and horses, Allen, "English and Welsh Agriculture, 1300–1850: Outputs, Inputs and Income," Oxford University Working Paper (2005), available at http://economics.ouls.ox.ac.uk/13622/1/Allen%20-%20English%20and%20Welsh%20agriculture.pdf (accessed January 17, 2015); Jules N. Pretty, "Farmers' Extension Practice and Technology Adaptation: Agricultural Revolution in 17–19th Century Britain," *Agriculture and Human Values*, VIII (1991), 132–148. Broadberry et al., "British Economic Growth," 34, show little or no increase, except in sheep, and a cattle decrease in stock densities per sown area. See also Broadberry et al., *British Economic Growth, 1270–1870* (New York, 2015), 99–113. In any case, bovine cattle declined (calves and cattle for milk and beef), whereas pigs and sheep (mainly for wool) increased. For the high land cost of animal feeding, see Gloria Guzmán and Manuel González de Molina, "Preindustrial Agriculture versus Organic Agriculture: The Land Cost of Sustainability," *Land Use Policy*, XXVI (2009), 502–510; for the increase in stone barns during this period, Maurice W. Barley, "Rural Building in England," in Thirsk (ed.), *Agrarian History of England and Wales. V. 1640–1750* (New York, 1985), 667–671.

7 E. L. Jones, "Agriculture and Economic Growth," already pointed out the differences between light and heavy soils. For the mixed-farming innovations adopted early in areas of light soils, see J. A. Yelling, "Probate Inventories and the Geography of Livestock Farming: A

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

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Study of East Worcestershire, 1540–1750," *Transactions of the Institute of British Geographers*, LI (1970), 111–126; Paul Glennie, "Continuity and Change in Hertfordshire Agriculture, 1550–1700: I, Patterns of Agricultural Production," *Agricultural History Review*, XXXVI (1988), 55–75; *idem*, "Continuity and Change in Hertfordshire Agriculture 1550–1700: II, Trends in Crop Yields and Their Determinants," *ibid.*, 145–161; Overton and Campbell, "Norfolk Livestock Farming 1250–1740: A Comparative Study of Manorial Accounts and Probate Inventories," *Journal of Historical Geography*, XVIII (1992), 377–396; Jonathan Theobald, "Agricultural Productivity in Woodland High Suffolk, 1600–1850," *Agricultural History Review*, L (2002), 1–24; Turner et al., *Farm Production in England*, 71; Hadrian Cook, Kathy Stearne, and Tom Williamson, "The Origins of Water Meadows in England, *Agricultural History Review*, LI (2003), 155–162; for the relationship between these changes and colder temperatures, Overton, *Agricultural Revolution in England*, 112; Turner et al., *Farm Production in England*, 70; for the importance of proximity to London regarding regional differences in farming, Wrigley, *People, Cities and Wealth*; Allen, *The British Industrial Revolution in Global Perspective* (New York, 2009).

The impact of London's demand mostly affected southeastern England, where large, capitalist estates, with their daily laborers and casual workers, adopted the market-driven changes in farming earlier than did the northwestern areas, where many poor family peasants farmed their own plots, taking advantage of the commons, and provided servants to wealthy yeomen until the last parliamentary enclosures in the nineteenth century. The Midlands had a number of intermingled, evolving situations. Within all of these regions, the geography of light soils in the highlands and heavy soils in the lowlands resulted in various forms of cultivation and animal husbandry not always related to the size and type of landownership. See David Grigg, *The Agricultural Revolution in South Lincolnshire* (New York, 1966); Victor Skipp, *Crisis and Development: An Ecological Case Study of the Forest of Arden 1570–1674* (New York, 1978); Ann Kussmaul, *Servants in Husbandry in Early Modern England* (New York, 1981); *idem*, *A General View of the Rural Economy of England: 1538–1840* (New York, 1990); Per K. D. M. Snell, *Annals of the Labouring Poor: Social Change and Agrarian England, 1660–1900* (New York, 1985); Leigh Shaw-Taylor, "Family Farms and Capitalist Farms in Mid-Nineteenth Century England," *Agricultural History Review*, LIII (2005), 158–191; *idem*, "The Rise of Agrarian Capitalism and the Decline of Family Farming 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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in England," *Economic History Review*, LXV (2012), 26–60; Sebastian A. J. Keibek and Shaw-Taylor, "Early Modern Rural By-Employments: A Re-Examination of the Probate Inventory Evidence," *Agricultural History Review*, LXI (2013), 244–281.

8 Thirsk, *Alternative Agriculture*; Ambrosoli, *The Wild and the Sown*. For the importance of manure in the English agricultural books of the time, see Ambrosoli, *The Wild and the Sown*, 283, 325–329; Andrew McRae, *God Speed the Plough: The Representation of Agrarian England, 1500–1660* (New York, 1996); Pretty, "Farmers' Extension Practice"; Robert A. Dodgshon, "Strategies of Farming in the Western Highlands and Islands of Scotland prior to Crofting and the Clearances," *Economic History Review*, XLVI (1993), 679–701; *idem*, "Budgeting for Survival: Nutrient Flow and Traditional Highland Farming," in Sally Foster and Thomas Christopher Smout (eds.), *The History of Soils and Field Systems* (Aberdeen, 1994), 83–93; John Shaw, "Manuring and Fertilising the Lowlands 1650–1850," *ibid.*, 111–118; Donald A. Davidson and Ian A. Simpson, "Soils and Landscape History: Case Studies from the Northern Isles of Scotland," *ibid.*, 66–74; Donald A. Woodward, "Gooding the Earth: Manuring Practices in Britain, 1500–1800," *ibid.*, 101–111; *idem*, "An Essay on Manures: Changing Attitudes to Fertilization in England, 1500–1800," in John Chartres and David Hey (eds.), *English Rural Society, 1500–1800: Essays in Honour of Joan Thirsk* (New York, 2006), 251–327; S. Todd Lowry, "The Agricultural Foundation of the Seventeenth-Century English Oeconomy," *History of Political Economy*, XXXV (2003), 74–100; Paul Warde, "The Invention of Sustainability," *Modern Intellectual History*, VIII (2011), 153–170. Except for Robert Shiel, "Improving Soil Productivity in the Pre-Fertiliser Era," in Campbell and Overton (eds.), *Land, Labour and Livestock* (Manchester, 1991), 51–75, and G. P. H. Chorley, "The Agricultural Revolution in Northern Europe, 1750–1880: Nitrogen, Legumes, and Crop Productivity," *Economic History Review*, XXXIV (1981), 71–93). The issue of nutrient balances in soil fertilization has received little historiographical attention in the United Kingdom. The key reason to adopt a perspective that includes nutrient balances is to avoid useless speculation about whether legumes, manure, or something else "did the job." All that matters is the N-P-K contribution that replenishes the nutrients extracted by crops in the soil. See Garcia-Ruiz et al., "Guidelines for Constructing Nitrogen, Phosphorus, and Potassium Balances in Historical Agricultural Systems," *Journal of Sustainable Agriculture*, XXXVI (2012), 650–682. For examples of this approach, see Tello et al., "Fertilizing Methods and Nutrient Balance at the End of Traditional Organic Agriculture in the Mediterranean Bioregion: Catalonia (Spain) in the 1860s," *Human Ecology*, XL (2012), 369–383; Simone Gingrich et al., "Providing Food While Sustaining Soil Fertility in Two Pre-industrial Alpine Agroecosystems," *Human Ecology*, XLIII (2015), 395–410.

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]

The search for historical explanations of farmers' responses to detrimental climate changes, and for answers to Allen's N question,

knowledge about legumes' fertilizing properties, John R. McNeill and Winiwarter (eds.), *Soils and Societies: Perspectives from Environmental History* (Winwick, U.K., 2006); *idem*, "Breaking the Sod: Humankind, History, and Soil," *Science*, CCCIV (2004), 1627–1629; for the roles of women and men, Carolyn Merchant, *Death of Nature: Women, Ecology and the Scientific Revolution* (San Francisco, 1983); Thirsk, *Alternative Agriculture*; Ambrosoli, *The Wild and the Sown*; for yeomen and gentry in raising land yields or labor productivity, Overton, *Agricultural Revolution*; Allen, "The Growth of Labor Productivity in Early Modern English Agriculture," *Explorations in Economic History*, XXV (1988), 117–146; *idem*, "Enclosure, Farming Methods and the Growth of Productivity in the South Midlands," *Research in Economic History*, V (1989), 69–88; *idem*, "The Two English Agricultural Revolutions, 1459–1850," in Campbell and Overton (eds.), *Land, Labour and Livestock*, 236–254.

10 For the European circulation of knowledge and germplasm, see Ambrosoli, *The Wild and the Sown*, 399, 426–430; Chorley, "Agricultural Revolution"; Fridolin Krausmann, "Milk, Manure, and Muscle Power: Livestock and the Transformation of Preindustrial Agriculture in Central Europe," *Human Ecology*, XXXII (2004), 735–772; for the lack of moisture to spread Mediterranean leguminous plants, Molina, "Environmental Constraints on Agricultural Growth in 19th Century Granada (Southern Spain)," *Ecological Economics*, XLI (2002), 257–270.

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

11 Liam Brunt, "Nature or Nurture? Explaining English Wheat Yields in the Industrial Revolution, c.1770," *Journal of Economic History,* LXIV (2004), 193–225; *idem*, "Weather Shocks and English Wheat Yields, 1690–1871," *Explorations in Economic History*, LVII (2015), 50–58; Campbell, "Nature as Historical Protagonist: Environment and Society in Pre-Industrial England," *Economic History Review*, LXIII (2010), 281–314; Hoyle, "Why Was There No Crisis in England"; Waldinger, "Economic Effects of Long-Term Climate Change."

12 Allen, "Nitrogen Hypothesis."

(P) through manure or the N immobilization during the decomposition of organic matter with a high C-to-N ratio.[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

13 Robert S. Loomis and David J. Connor, *Crop Ecology: Productivity and Management in Agricultural Systems* (New York, 1992), 199–202; Laurie E. Drinkwater, P. Wagoner, and Marianne Sarrantonio, "Legume-Based Cropping Systems Have Reduced Carbon and Nitrogen Losses," *Nature*, CCCXCVI (1998), 262–265. Allen's model does not explicitly state whether it assumes a net mineralization rate—that is, a deduction of N immobilization from gross mineralization.

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

14 Stefano Manzoni and Amilcare Porporato, "Soil Carbon and Nitrogen Mineralization: Theory and Models across Scales," *Soil Biology and Biochemistry*, XLI (2009), 1355–1379. The orders of magnitude of N mineralization in the text come from Peter B. Reich et al., "Nitrogen Mineralization and Productivity in 50 Hardwood and Conifer Stands on Diverse Soils," *Ecology*, LXXVIII (1997), 335–347; Yao Huang et al., "Agr-C: A Biogeophysical Model for Simulating the Carbon Budget of Agroecosystems," *Agricultural and Forest Meteorology*, CXLIX (2009), 106–129; Oliver Koch, Dagmar Tscherko, and Ellen Kandeler, "Temperature Sensitivity of Microbial Respiration, Nitrogen Mineralization, and Potential Soil Enzyme Activities in Organic Alpine Soils," *Global Biogeochemical Cycles*, XXI (2007), GB4017.

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.[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

15 For the impact of the Maunder Minimum on soils, see Campbell, "Nature as Historical Protagonist"; Luterbacher et al., "Late Maunder Minimum"; Lamb, *Climate History*, 199; Rudolf Brázdil et al., "Historical Climatology in Europe—The State of The Art," *Climatic Change*, LXX (2005), 363–430; for the dynamics of cold soils as driven by fungi rather than bacteria, Janna Pietikäinen, Marie Pettersson, and Erland Bååth, "Comparison of Temperature Effects on Soil Respiration and Bacterial and Fungal Growth Rates," *FEMS Microbiology Ecology*, LII (2005), 49–58.

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

16 Rothamsted Research, "Guide to the Classical and Other Long-Term Experiments, Datasets and Sample Archive 2006, Lawes Agriculture Trust Co. Ltd., Harpenden, UK," 8–18, available at http://www.era.rothamsted.ac.uk/index.php?area=home&page=index&dataset=4&sub=bbk_open_access (accessed January 17, 2015). Some nutrient balances calculated at farm level from a historical perspective suggest that P was more limiting for crop production than was K or N. See, for example, Edward I. Newman and Paul D. A. Harvey, "Did Soil Fertility Decline in Medieval English Farms? Evidence from Cuxham, Oxfordshire, 1320–1340," *Agricultural History Review*, XLV (1997), 119–136; Overton, "Agronomy and Agricultural History in England," in Paul Fobin, Jean Paul Aeschlimann, and Christian Feller (eds.), *Histoire et Agronomie: Entre Ruptures et Durée* (Paris, 2007), 247–258. Soil P exhaustion was avoided only when significant livestock numbers grazed on pastures during the day, or remained overnight either on arable land or locked in a fold where droppings were collected. See Newman, "Medieval Sheep-Corn Farming: How Much Grain Yield Could Each Sheep Support?" *Agricultural History Review*, L (2002), 164–180. For humanure in N-P-K cycling, see Mindy Schneider and Philip McMichael, "Deepening, and Repairing, the Metabolic Rift," *Journal of Peasant Studies*, XXXVII (2010), 461–484; Tina-Simone Schmid-Neset et al., "The Flow of Phosphorus in Food Production and Consumption—Linköping, Sweden, 1870–2000," *Science of the Total Environment*, CCCXCVI (2008), 111–120; D. N. Maitra et al., "Effect of Phosphorous and Farmyard Manure Applied to Sunnhemp (*Crotalaria Juncea*) on Yield and Nutrient Uptake of Sunnhemp-Wheat (*Triticum Aestivum*) Cropping System and Fertility Status in Typic Ustocrept of Uttar Pradesh," *Indian Journal of Agricultural Sciences*, LXXVIII, (2008), 70–74; Newman, "Phosphorus Balance of Contrasting Farming Systems, Past and Present: Can Food Production Be Sustainable?" *Journal of Applied Ecology*, XXXIV (1997), 1334–1347; Elena Valkama et al., "Phosphorus Fertilization: A Meta-Analysis of 80 Years of Research in Finland," *Agriculture, Ecosystems & Environment*, CXXX (2009), 75–85; for other factors affecting yields, Shiel, "Improving Soil Productivity," 52; Alfredo Tolon-Becerra et al., "Traffic Effect on Soil Compaction and Yields of Wheat in Spain," *Spanish Journal of Agricultural Research*, IX (2011), 395–403; Emmanuel Frossard et al., "Concepts and Practices of Nutrient Management in Agro-Ecosystems: Can We Draw Lessons from History to Design Future Sustainable Agricultural Production Systems?" *Die Bodenkultur*, LX (2009), 43–60.

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.[18]

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).[19]

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

18 Allen is a remarkable exception in this regard; his model of productivity in terms of grain N depends on the harvest index, the ratio crop biomass/N absorbed, and the ratio between N absorbed and soil available N. See Allen, "Nitrogen Hypothesis," 187; Sinclair, "Historical Changes in Harvest Index"; G. C. S. Negi, "High Yielding vs. Traditional Crop Varieties: A Socio-Agronomic Study in a Himalayan Village in India," *Mountain Research and Development*, XIV (1994), 251–254; Ming-Sheng Fan et al., "Evidence of Decreasing Mineral Density in Wheat Grain over the Last 160 Years," *Journal of Trace Elements in Medicine and Biology: Organ of the Society for Minerals and Trace Elements (GMS)*, XXII (2008), 315–324.

19 For the adaptive responses of legumes through symbiotic N fixation, see David F. Herridge et al., "Chickpea in Wheat-Based Cropping Systems of Northern New South Wales III: Prediction of N2 Fixation and N Balance Using Soil Nitrate at Sowing and Chickpea Yield," *Australian Journal of Agricultural Research*, XLIX (1998), 409–418. Allen's equations A3 and A4 are in "Nitrogen Hypothesis," 194–197, 205. For N-P interactions, see Frossard et al., "Concepts and Practices," 45.

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.[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.[21]

20 Allen, "Nitrogen Hypothesis," 192; Turner et al., *Farm Production in England*, 83–85. For the site-specific character of nutrient cycling through animal bioconversion, see Shiel, "Improving Soil Productivity"; *idem*, "Nutrient Flows in Pre-Modern Agriculture"; N. Hofstra and A. F. Bouwman, "Denitrification in Agricultural Soils: Summarizing Published Data and Estimating Global Annual Rates," *Nutrient Cycling in Agroecosystems*, LXXII, (2005), 267–278; H. Van Keulen et al., "Soil–Plant–Animal Relations in Nutrient Cycling: The Case of Dairy Farming System 'De Marke,'" *European Journal of Agronomy*, XIII (2000), 245–261; Sonoko D. Kimura and Ryusuki Hatano, "An Eco-Balance Approach to the Evaluation of Historical Changes in Nitrogen Loads at a Regional Scale," *Agricultural Systems*, XCIV (2007), 165–176; D. Scholefield et al., "A Model to Predict Transformations and Losses of Nitrogen in UK Pastures Grazed by Beef Cattle," *Plant and Soil*, CXXXII (1991), 165–177; Garcia-Ruiz et al., "Guidelines for Constructing Nitrogen, Phosphorus, and Potassium Balances," 650–682; Sylvain Payraudeau, Hayo M. G. Van der Werf, and Françoise Vertès, "Analysis of the Uncertainty Associated with the Estimation of Nitrogen Losses from Farming Systems," *Agricultural Systems*, XLIV (2007), 416–430; Frederick C. Michel, Jr., et al., "Mass and Nutrient Losses during the Composting of Dairy Manure Amended with Sawdust or Straw," *Compost Science & Utilization*, XII (2004), 323–334.

21 William J. Parton, Dennis S. Ojima, and David S. Schimel, "Models to Evaluate Soil Organic Matter Storage and Dynamics," in Michael R. Carter and Bobby A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils* (Boca Raton, 1996), 421–448; Peter J. Gregory, "Growth and Functioning of Plant Roots," in Alan Wild (ed.), *Russell's Soil Conditions and Plant Growth* (Harlow, 1988), 113–167.

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 0.01percent). 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

22 K.W.T. Goulding, "Nitrogen Deposition to Land from the Atmosphere," *Soil Use and Management*, VI (1990), 1988–1990.

23 Allen, "Nitrogen Hypothesis," 197; Gražina Kadžiene, Lars J. Munkholm, and James K. Mutegi, "Root Growth Conditions in the Topsoil as Affected by Tillage Intensity," *Geoderma*, CLXVI (2011), 66–73; H. E. Mason and David Spaner, "Competitive Ability of Wheat in Conventional and Organic Management Systems: A Review of the Literature," *Canadian Journal of Plant Science*, LXXXVI (2006), 333–343; Anton Paul Wasson et al., "Traits and Selection Strategies to Improve Root Systems and Water Uptake in Water-Limited Wheat Crops," *Journal of Experimental Botany*, LXIII (2012), 3485–3498; Abdullah A. Jaradat, "Wheat Landraces: A Mini Review," *Emirates Journal of Food and Agriculture*, XXV (2013), 20–29;

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.[24]

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

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Michael J. Connell, R. John Raison, and Partap K. Khanna, "Nitrogen Mineralization in Relation to Site History and Soil Properties for a Range of Australian Forest Soils," *Biology and Fertility of Soils*, XX (1995), 213–220; Reich et al., "Nitrogen Mineralization and Productivity," 33–347; Ingrid C. Burke et al., "Nitrogen in the Central Grasslands Region of the United States," *BioScience*, LII (2002), 813–823.

When pH increases, showing lower acidity, biological activities change from slow, fungi-dominated processes to faster bacterial-dominated ones with higher N-mineralization rates. Liming or combining marling with manure can increases pH. See Winiwarter and Winfried E. H. Blum, "From Marl to Rock Powder: On the History of Soil Fertility Management by Rock Materials," *Journal of Plant Nutrition and Soil Science*, CLXXI (2008), 316–324. Earthworms can dramatically change the structure and chemistry of soils; in temperate grasslands, they can consume as much as 90 tons of soil per hectare per year, thus improving its porosity, aeration, water-retention, and drainage capacity. See Winiwarter, "The View from Below: On Energy in Soils (and Food)," in Richard W. Unger (ed.), *Energy Transitions in History: Global Cases of Continuity and Change* (Munich, 2013), 43–48.

24 Burke et al., "Nitrogen in the Central Grasslands Region"; Burke, William K. Lauenroth and Parton, "Regional and Temporal Variation in Net Primary Production and Nitrogen Mineralization in Grasslands," *Ecology*, LXXVIII (1997), 1330–1340; Geoff Cunfer, "Manure Matters

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.[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 quantitative 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 agricultural treatises of Columela or Palladius or Samuel Hartlib's correspondence 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.[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

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.), *Agroecology: Ecological Processes in Sustainable Agriculture* (Boca Raton, 1998); Miguel A. Altieri and Clara I. Nicholls, *Agroecology and the Search for a Truly Sustainable Agriculture* (Mexico City, 2005).

26 Wrigley, *People, Cities and Wealth*; John Creedy, "On the King–Davenant 'Law' of Demand," *Scottish Journal of Political Economy*, XXXIII (1986), 193–212; Campbell, "Nature 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.[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).

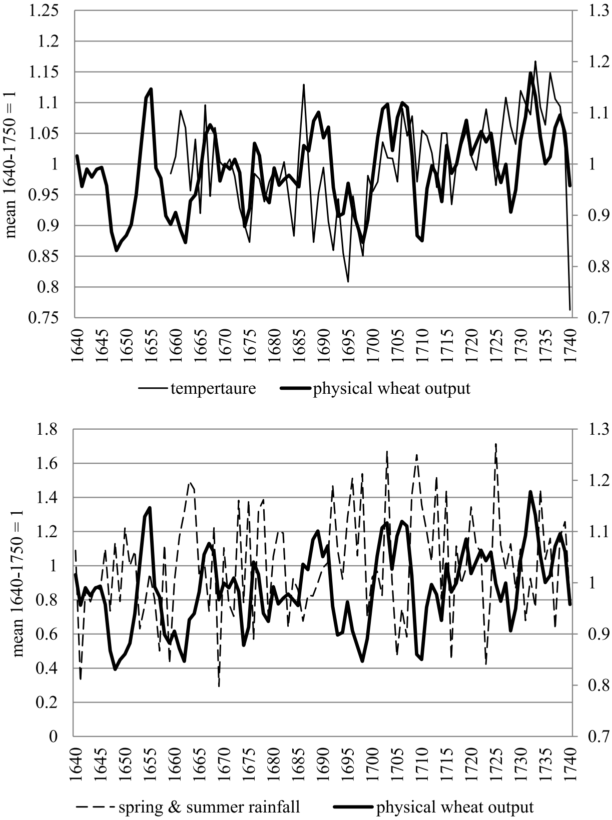
From our perspective, the colder temperatures would have reduced wheat yields by shortening the growing season and by diminishing soil microbial activity and N mineralization. Farmers might have compensated to some extent by improving manuring and tillage and growing more legumes. While temperature kept 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.[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

27 Loomis and Conor, *Crop Ecology*, 332.

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



SOURCES G. Manley, "Monthly Mean Central England Temperature" (1953), available at http://www.metoffice.gov.uk/hadobs/hadcet/ (accessed January 17, 2015); Katje T. Rinne et al., "400-year May–August Precipitation Reconstruction for Southern England Using Oxygen Isotopes in Tree Rings," *Quaternary Science Reviews*, LX (2013), 13–25. Martínez's elaboration of the English wheat output is based on Stephen N. Broadberry et al., "British Economic Growth: 1270–1870," Working Paper of the Department of Economics (University of Warwick, 2011); Phyllis Dean and William A. Cole, *Economic Growth, 1688–1959: Trends and Structure* (Cambridge, 1967); Gregory Clark, "The Price History of English Agriculture, 1209–1914," *Research in Economic History*, XXII (2004), 41–124; E. Anthony Wrigley, *The Population History of England 1541–1871: A Reconstruction* (London, 1989). For other references, see Martínez, "Did Climate Change Influence English Agricultural Development? (1645–1740)," EHES Working Paper in Economic History, LXXV (2015); *idem*, "Construyendo una serie física anual de trigo en Inglaterra (1645–1761)," Working Paper of the Spanish Society for Economic History, DT-AEHE n° 1613, available at http://www.aehe.es/wp-content/uploads/2016/07/dt-aehe-1613.pdf (accessed July 20, 2016).

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.[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.[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

29 For the correlation of temperature and yields in seventeenth-century England, see Michaelova, "Impact of Short-Term Climate Change"; Brunt, "Nature or Nurture?"; *idem*, "Weather Shocks and English Wheat Yields"; Waldinger, "Economic Effects of Long-Term Climate Change"; Martínez, "Did Climate Change Influence English Agricultural Development?" For the prevalence of bioregional agro-climatic endowment in agricultural production at present, see Giovanni Federico, *Feeding the World: An Economic History of Agriculture, 1800–2000* (Princeton, 2005).

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," *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

	(1)	(2)	(3)	(4)	(5)
Constant	2.90e+07***	4.52e+07***	4.00e+07***	4.46e+07***	3.62e+07***
	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
Temperatures	1.00e+06*		500,641		871,837**
	(0.07)		(0.24)		(0.02)
D1 * Temperatures	181,315**		223,901***	262,931***	
	(0.02)		(0.001)	(<0.001)	
Summer rainfall		−16,888.8***	−11,181.0***	−11,790.6***	−11,139.7***
		(<0.001)	(0.001)	(<0.001)	(0.01)
Summer rainfall (−1)		−17,652.8***	−18,200.0***	−18,838.2***	−17,321.6***
		(<0.001)	(<0.001)	(<0.001)	(<0.001)
D1 * summer rainfall		11,294.4***			
		(<0.001)			
Corn bounties					2.18e+06**
					(<0.001)
N	81	81	82	82	82
adj. R^2	0.19	0.33	0.42	0.42	0.46
F	10.20	17.16	15.66	20.32	17.92

***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, 2015), 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.[31]

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

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harvest—by Broadberry et al., "British Economic Growth," as well as to the one estimated by Phyllis Deane and William A. Cole, *Economic Growth, 1688–1959: Trends and Structure* (New York, 1967). The resulting series met the price-elasticity equation given above but lacked trend. Third, to rectify the situation, we used the English-population series to infer an initial trend of wheat demand. Fourth, we refined this demand by adding a rent elasticity that starts from a low level and grows at a slow pace along the series, in accord with the English per capita GDP given in Broadberry et al., "British Economic Growth." Fifth, we applied the same steps either to the gross or net estimates of wheat product given for 1700 in "British Economic Growth" or in *Economic Growth*, and adjusted the evolution of net trade balance to approximate the data obtained from the production or the demand side. Sixth, we compared the range of variation in the series obtained in this way with all of the previous long-term estimates in the literature—with shorter local series directly compiled in physical terms from probate inventories and bookkeeping, and with the yields resulting from the division of our series with the available estimates of wheat sown acreage—to choose the more plausible figures. Finally, in order to check its coherence, we tested that the series that we chose has a good splice with the official statistics of wheat product that start in 1884, and an average rent elasticity of 0.6 from 1645 to 1884 that fits well with the existing literature on the subject. For other details about the criteria for selecting the most coherent data, see Martínez, "Construyendo una serie física annual de trigo en Inglaterra (1645–1761)." We also used two different regression models before and after 1695 with similar results. However, the number of observations is so small that we prefer a single model with temporal dummies. We also ran other regressions using interactions with other temporal dummies and including different climatic variables (volcanic eruptions and yearly rainfall) that led to similar results. See Martínez, "Did Climate Change Influence the English Agricultural Revolution?"

31 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

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

the series' volatility, only the summer rainfall remains significant. Instead of a simple annual average of temperature, we also tried as a variable the seasonal accumulated temperature of growing degree-days along the wheat vegetative period, but the results were nearly the same, probably because the thermal integral was calculated from mean monthly data, since daily averages are available only starting in 1772 (see footnote 33).

32 According to the available sources, only in 1637 did drought severely damage a harvest; waterlogging was far more frequent. See Bowden, "Agricultural Prices, Farm Profits and Rents," 625–626. For open fields as a land-use strategy to minimize weather risks, see Donald N. McCloskey, "The Prudent Peasant: New Findings on Open Fields," *Journal of Economic History*, LI (1991), 343–355; Turner et al., "Agricultural Sustainability and Open-Field Farming." The series of precipitation available captures the cyclical variations in summer rainfall better than does the short-term effect of great storms. For that reason, we do not emphasize stalk lodging of ripening cereals that lay on the ground in strong rain. In his diary, Ralph Joselin mentions the shorter growing season and the danger of strong summer storms as his major problems. See Joyce Macadam, "English Weather: The Seventeenth-Century Diary of Ralph Josselin," *Journal of Interdisciplinary History*, XLIII, 2 (2012), 221–246. Unfortunately, accurate data about the variation in the length of the thermal growing season in central England is available only from 1772 onward when the recording of mean daily temperatures began. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/192601/thermal_growing_season_summary_report.pdf (accessed July 10, 2016).

33 The white-eared red wheat introduced in the 1650s and the stalked wheat in 1670s were more resistant to cold and humidity, and thus to the smut fungi. See Thirsk, "Farming Techniques," 168. For how climate change factored into Scottish farmers importing these improved wheat varieties from England, see Mary Young, "Scottish Crop Yields in the Second Half of the Seventeenth Century: Evidence from the Mains of Castle Lyon in the

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

Carse of Gowrie," *Agricultural History Review*, LV (2007), 51–74, esp. 24. Without better soil drainage, turnips would have been difficult to add into the rotations, since they are vulnerable to fungi; we know that drainage became relevant later in the English Agricultural Revolution. A large-scale construction of hollow draining systems, which was incompatible with the open fields, required a previous land consolidation. Hence, it had to await the second wave of improvements linked to the parliamentary enclosures of the eighteenth and nineteenth centuries. See Allen, "Enclosure, Farming Methods and the Growth of Productivity"; *idem*, *Enclosure and the Yeoman: The Agricultural Development of the South Midlands, 1450–1850* (New York, 1992), 165–167; Andrew Gritt, "Making Good Land from Bad: The Drainage of West Lancashire, c.1650–1850," *Rural History*, XIX (2008), 1–27. Other soft improvements in drainage, such as plowing the fields gradually to create a convex profile that led runoff toward the margins, predated the deep hollow drains and other heavy hydraulic works. See, for example, Turner et al., "Agricultural Sustainability and Open-Field Farming." Furthermore, farmers could have had recourse to other harder tubers like swedes (*Brassica napobrassica*) and other fodder beets like the German mangel-wurzel (*Beta vulgaris*) before the diffusion of turnips (*Brassica rapa*).

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]

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