The Origins of the Nitrogen Revolution*

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Abstract

Many important technologies throughout history have been spatial: their local benefits depend on natural endowments. This paper studies one such technology that revolutionized 19th-century agriculture: nitrogen fertilizer. We leverage natural variation in soil nitrogen across England and the sudden introduction of *guano*, a nitrogen-rich fertilizer sourced from Peru. Drawing on newly digitized data, we first establish that nitrogen deficiency historically shaped crop choices. After guano's arrival, nitrogen-deficient places shifted toward nitrogen-demanding crops. Effects are largely concentrated in places that (i) had lower agricultural productivity before guano and (ii) lie farther from major urban centers. Our findings indicate that fertilizer drove convergence in economic activity across space. We evaluate the welfare implications of this technology through a quantitative spatial model of the English agricultural sector. Fertilizer raised welfare substantially. Yet, by reducing specialization, this "converging" technology lowered the gains from trade and thus would have been most beneficial under low market integration.

Keywords: spatial technologies, economic convergence, nitrogen, fertilizer, Second Agricultural Revolution, England.

JEL Codes: N53, O13, O33, Q15, Q55, R12.

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1 Introduction

Technology is neither good nor bad;
nor is it neutral

Kranzberg's First Law of Technology

New technologies have been a major driver of the unprecedented rise in living standards in the Western world over the past two centuries (Mokyr, 1990; Aghion and Howitt, 1998). A common supposition about technologies is that they can be fruitfully employed everywhere, or that they are *spatial*, in the sense that they can only be used in places with certain natural endowments (new crops require appropriate climates, improved steel production requires nearby coal, better shipbuilding requires deep harbors). However, technologies could be spatial in a different sense: they could compensate for, rather than amplify, disadvantages in natural endowments. We will call these *converging* technologies: by reducing the constraint of natural endowments in shaping productivity, they allow the type of economic activity to become more homogeneous across space.[1] However, such technology-driven convergence is in tension with the notion of Ricardian specialization: as places become more similar to each other, comparative advantage narrows, reducing the scope for beneficial trade. In this sense, the spatial dimension of technologies determines their aggregate welfare implications.

In this paper, we study one of the most important technologies of the 19th century, nitrogenous fertilizer, and show how it acted as just such a *converging* technology. Fertilizers alleviated a major constraint that existed since the dawn of agriculture: the limited availability of nutrients, in particular of nitrogen, in the soil (Leigh, 2004). By addressing this natural limitation, the usage of nitrogenous fertilizers ultimately triggered a population boom that has enabled around 40% of the world's current population to be alive (Smil, 2004). Yet nitrogen deficiency is not uniform across space: it depends in part on a soil's parent material – the weathered rock from which it was originally formed. Similarly, not all crops are equally affected by nitrogen deficiency: grains and fodder crops are "nitrogen-intensive", requiring large quantities of the nutrient, while "nitrogen-light" crops like legumes replenish soil nitrogen levels. These two distinctions generate variation – both across space and across crops – making this an ideal setting for investigating how technology drives spatial changes in the composition of economic activity.

We focus on the first stage of the "Nitrogen Revolution", which involved the sudden

[1] Mann (2011) has dubbed the era following the Columbian Exchange as a "Homogenocene" that has seen convergence in the kind of economic activity at a global scale.

arrival of Peruvian *guano* and the related nitrates to England, their principal customer. Our empirical analysis relies on a wealth of newly-digitized data from 19th-century England, novel measures from soil science, and further descriptive material from the large body of written evidence about this new technology. We ask two questions: What role did natural endowments play in shaping the distribution of land use before fertilizers? And how did land use change with the introduction of this new technology? We provide reduced-form evidence on both of these questions, using cross-sectional and difference-in-differences designs. Our findings support the notion that fertilizers acted as a *converging* technology. Motivated by this evidence, we develop a quantitative spatial model that account for spillovers across locations in equilibrium to study how convergence shapes the welfare effects of this technology. We find that fertilizers increased welfare, with the greatest gains when trade costs were high. Intuitively, by reducing specialization and making economic activity more homogeneous across space, converging technologies effectively serve as a substitute to trade.

Historical Setting and Empirical Findings. The introduction of fertilizers to Britain can be seen as one of the last stages in a centuries-long process to cultivate a capitalist, highly productive agricultural sector that in many ways mirrored the transformative impacts of the largely concurrent Industrial Revolution.[2] The introduction of guano fertilizers as a new technology, many decades after its "discovery" by Europeans in the early 1800s, was the result of a circuitous sequence of events that arose from backhaul problems in the Pacific whaling industry; its rapid commercial success then set off a scientific feedback loop that eventually recognized the key importance of nitrogen as an input to agricultural production (Cushman, 2013).[3] The widespread use of guano was a hallmark of the "high farming" era of mid-19th century British history, which saw the shift towards a more modern form of input-intensive agriculture during a period of high prices and enthusiasm toward the sector (Thompson, 1968), in part manifested by dozens of field trials conducted by individual farmers and subsequently reported in contemporary periodicals. However, the "grain invasion" of the late 1860s and 1870s put an end to these halcyon days (Heblich et al., 2024); the "guano age" also came to

[2] The enclosure movement eliminated common land that contemporary observers regarded as being inefficiently used (Heldring et al., 2022). The mechanization of some tasks like wheat threshing proceeded apace, although accompanied by disturbances like the Swing Riots (Caprettini and Voth, 2020). The importance of a missing piece of this agricultural puzzle, nitrogen deficiency, was slow to be recognized due to widespread misunderstandings of the chemical nature of plant growth (cf. Davy, 1846).

[3] At the Rothamsted estate in Hertfordshire, the first agricultural experiments demonstrating the beneficial effect of nitrogen fertilization on crop harvest were conducted by John Bennet Lawes and Joseph Henry Gilbert starting in 1843. Despite the initial resistance from concurrent theories, the results were soon embraced by the scientific community of the time and would shape the understanding of nutrient requirements in agriculture in the years to come.

an end, replaced with Chilean nitrates and ultimately with the artificial synthesis of ammonia using the Haber process.

We collect several novel data sources to investigate the effects of the "Nitrogen Revolution" on England's agriculture. Firstly, we construct the first panel of land use in English parishes throughout the 19th century, combining previously-digitized land surveys from the early part of the century with the later annual Agricultural Censuses, which we digitize from handwritten archival materials using AI-based optical character recognition software.[4] Secondly, we use a novel measure from soil scence, the carbon-to-nitrogen (C:N) ratio, which captures the balance between two of the key nutrients necessary for plant growth, with a higher value of the ratio indicating that the soil is more deficient in nitrogen. Although soil nitrogen levels are partially anthropogenic, the estimates we use are from a model of this variable that largely uses exogenous characteristics of the soil's parent material to predict the distribution of the variable across space.]

Our empirical analysis starts by exploring the cross-sectional patterns of land use before the introduction of fertilizers. Consistent with the C:N ratio capturing some of the constraints parishes face in their cropping decisions, we find that nitrogen-deficient places devote more land to nitrogen-light crops like legumes and correspondingly less land to nitrogen-intensive, more lucrative crops, such as wheat and turnips. This pattern that holds with both continuous and discrete measures of nitrogen deficiency, and not driven by regional differences or climatic suitability for growing crops. We interpret this as evidence that natural endowments shaped the types of economic activity places could pursue. At the same time, endowments created a natural form of specialization across regions.

We next turn to a simple difference-in-differences (DiD) design that leverages the first imports of guano in 1841 as an exogenous event and cross-sectional variation in C:N ratio as a measure of exposure to such shock. Nitrogen-poor places change their crop mix after the arrival of guano, substantially reallocating land towards nitrogen-demanding crops while keeping total acreage fairly constant. Importantly for our identification argument, this reallocation is not due to differential trends prior to the guano shock, confirming that the level difference we documented in our first finding was stable. In effect, our results imply convergence in economic activity, where regions that are heterogeneous in their natural endowments began to engage in more similar forms of

[4] We complement these data with weekly grain sales data for a panel of 150-290 market towns during the first decades of the "guano age", from the *London Gazette*.

production as constraints were mitigated by the newly available technology. Further outcomes reveal that there was no differential increase in total crop acreage, meaning that our results purely rest on reallocations of existing cropland, and that the nitrogen-deficient parishes differentially increase their counts of livestock, consistent with high farming narratives. We document two margins of heterogeneity that support our interpretation of these findings as convergence: first, our effects are largely driven by places that had low crop yields prior to the introduction of fertilizer. Second, our effects are entirely concentrated in parishes far from major urban centers, who had limited to access to urban wastes, which were an important source of farm nutrients before the introduction of guano. Finally, we find qualitatively similar results when we use a proxy of local agricultural production as our outcome instead of land use.

Quantitative Spatial Model. Our empirical findings point to the "Nitrogen Revolution" as being a qualitatively distinct phenomenon from many other momentous technological changes, including the more familiar Industrial Revolution. While many transformations create new patterns of economic activity or strengthen existing patterns, the Nitrogen Revolution instead promoted convergence and homogenization, at least within agriculture. A natural question arises: what are the implications of the converging aspect of this spatial technology on aggregate welfare? To quantify welfare, it is not sufficient to consider the direct effects of the technology on places that were ex ante more exposed to nitrogen deficiency; we must also account for spatial spillovers – transmitted via trade in general equilibrium – to places that were less exposed. welfare, it is necessary to consider not only the direct effects of the technology on places that we define as (more strongly) treated, but also the places that were untreated but interact through general equilibrium forces.

A natural framework to explore these questions is the Ricardian model pioneered by Eaton and Kortum (2002), which parsimoniously captures the relationship between productivity, trade costs, and welfare. The innovations of our model are twofold: (i) we explicitly incorporate nitrogen deficiency as a factor that influences crop production, in line with the biochemical principle of the "law of the minimum,"; (ii) we add fertilizer as an input that locations can choose to purchase in order to reduce their level of nitrogen deficiency. We then add realistic geography, trade cost parameters both in 1830 and following the rapid growth of the railway network from 1840-60, and the local C:N ratio.

The first result of the model is that nitrogen fertilizers, as a productivity-enhancing technology, increased welfare to a first order. Total welfare gains are around 3%, which represents approximately 20 years worth of productivity gains according to conventional estimates from 19th-century England. The second, and more insightful, result of the model is that there is a second-order effect whereby nitrogen fertilizers were most beneficial when trade costs were high. Under the high trade cost regime in 1830, welfare gains were 5% higher than under the low trade cost regime that prevailed after the construction of the railway network. When trade costs are high, locations are forced to reduce their degree of specialization because they will be the lowest-cost source for a relatively large share of their consumption (in the limit of autarky, there is no specialization at all). This situation makes converging technologies relatively more beneficial: as long as all locations have the same preferences, then there are high returns to increasing productivity in sectors where you are relatively unproductive. By contrast, if trade costs are low, then specialization will be greater and the welfare gains from improving productivity in the least-productive places will be relatively low. Although the introduction of guano was effectively an exogenous event, we believe that this analysis can inform some underexplored considerations in the realm of endogenous technological change: which types of innovation are most valuable to pursue depends on how these technologies interact with spatial endowments, and how integrated markets are with one another.

Related Literature. A wide body of literature in economics studies how new technologies drive convergence or divergence in economic activity across space. Much of this literature, however, is concerned primarily with how new technologies change the *level* of economic output, population, employment, or health, particularly in agriculture[5] but also in other sectors of the economy.[6] By contrast, we focus on how technologies change the *composition* of economic activity across places, which is an important outcome in its own right and also suggests mechanisms by which technologies can generate spatial spillovers that either enhance or attenuate their effects on welfare.[7] Rather than reinforcing existing patterns of economic activity, guano fertilizer attenuated such disparities, underscoring that technological innovations can allow places to compensate for natural disadvantages.

[5] Research exploring how new technologies shape the levels of economic outcomes such as: demographics (Nunn and Qian, 2011; Dall Schmidt et al., 2018; Cherniwchan and Moreno-Cruz, 2019; Gollin et al., 2021), health (Bharadwaj et al., 2020; von Der Goltz et al., 2020; Sekhri and Shastry, 2024), labor markets and structural transformation (Foster and Rosenzweig, 2004; Bustos et al., 2016; Moscona, 2019; Moorthy, 2025), and political economy (Mayshar et al., 2022).

[6] For example, Bleakley (2007) documents how human capital levels converged after malaria was suppressed in the US South, and Fernihough and O'Rourke (2021) finds demographic divergence stemmed from historical access to coal.

[7] An exception in this literature is Hornbeck and Keskin (2014), who document how new irrigation technology drove a divergence in crop mix across places.

Our next contribution is to a methodologically distinct literature that uses quantitative spatial models of interregional or international trade to understand how technologies or other changes in productivity impact welfare. The implication that convergence in productivity levels can reduce the gains from trade, harming welfare in regions that were initially more advanced, has been especially noted in the context of U.S.-China trade by Di Giovanni et al. (2014) and Samuelson (2004). The interplay between market integration and technological change has been explored by Trew (2020) and Henderson et al. (2018), although using theories that emphasize agglomeration forces. We build on both of these strands by emphasizing that the benefits of technology are impacted both by whether it induces convergence or divergence in productivity levels in a Ricardian sense and by the level of market integration in the economy. The structure of our model is inspired by a body of work exploring the spatial economy of the agricultural sector, such as Farrokhi and Pellegrina (2023) and Costinot et al. (2016). We build on this strand by highlighting a novel force for spatial convergence induced by new technologies, which can inform how investments in innovation should be directed across space. Although guano disproportionately benefited places that were disadvantaged, this pattern of productivity gains substituted instead of complemented other types of efforts to promote welfare, such as greater market integration.[8]

Our empirical evidence relates to a literature in development economics that focuses on the diffusion and benefits of novel agricultural technologies.[9] The setting of 19th-century English agriculture – characterized by relatively large, capitalist farms subject to few credit and information constraints – offers a striking contrast to the small landholding farms found both in 19th-century continental Europe and throughout developing countries today. Our descriptive analysis, drawing on novel textual data from newspapers, books, and agricultural magazines, supports the view that the adoption of guano was rapid and geographically widespread, suggesting that the economic structure of Victorian "high farming" may have mitigated some of the barriers to technology adoption commonly observed in developing-country agriculture.

Finally, we contribute to the substantial and growing literature on the "Second Agricultural Revolution" of 19th century Britain. An older literature in economic history em-

[8] Kantor and Whalley (2019) document the important role played by the spatial distribution of research in US agriculture before 1920: proximity to experimental stations increased farm yields, with effects dying out only 50 years after station opening. Moscona and Sastry (2023) and Moscona (2024) show how technological change endogenously favors locations harmed by climate change and natural disasters, respectively, attenuating a divergence in outcomes that might otherwise have taken place.

[9] Reviews on different aspects of this wide-ranging literature can be found in Binswanger-Mkhize and McCalla (2010), Foster and Rosenzweig (2010), De Janvry et al. (2017), Bridle et al. (2020), and Suri and Udry (2022).

phasized the important changes that occurred during this period, which is sometimes overlooked in favor of the 18th century "First Agricultural Revolution" as advances in industry and transportation overtook those of agriculture: we add to accounts like Thompson (1968), Jones (1962), and Mingay (1963) that emphasize the growing use of inputs during this era with new data and empirical methods to investigate some of their more speculative claims. In his major history of English agriculture, Overton (1996) describes the advent of fertilizers in the mid-19th century as breaking the "closed system" of nutrients that hitherto prevailed, while emphasizing that other fundamentals, such as the crop mix, remained relatively unchanged. Recent work using modern econometric methods has emphasized the importance of institutional factors (Heldring et al., 2022), labor scarcity (Voth et al., 2023), and endogenous changes in Britain's trade position (Heblich et al., 2024) in shaping productivity, technology adoption, and the size of the agricultural labor market. We supplement this body of work both by focusing instead on the impacts of an exogenous technology that affected the supply side of agriculture and by introducing several novel data sources to study this era of history.

2 Historical Background

«God bless you – guano sea-gull,
Of the far away coast of the west:
In spite of my countryman Hegel,
The stuff which you make is the best.»

— *Guano Song*,
from *Gaudeamus! Humorous Poems*,
by Joseph Victor Scheffel, translated
by Charles Godfrey Leland, 1872.

2.1 Agricultural Progress

In 1840, the German chemist Justus von Liebig wrote his landmark textbook *Agricultural Chemistry* in which he asserted and popularized one of the most important principles of agricultural science: the "law of the minimum", which states that the growth of plants is limited by the availability of the scarcest nutrient (von Liebig, 1855). The growth of plants involves, effectively, a chemical reaction whose ingredients are not substitutable: if a certain key nutrient is lacking, then only an increase in that nutrient will allow the plant to continue to grow. For many times and places, the least abundant nutrient was nitrogen, which is essential for constructing the amino acids that comprise proteins; despite the abundance of diatomic nitrogen in the atmosphere (as N_2), the pathway to "fix" this nitrogen in a form that usable for plants is highly energyintensive (Leigh, 2004). Nevertheless, not all soil types suffer equally from problems of nitrogen depletion; some fundamental soil characteristics like bulk density mediate nitrogen levels, and there are other constraints like excessive acidity that are binding in other cases (Henrys et al., 2012).

Without being cognizant of the scientific principles at work, the productivity of agricultural societies was thus tied to their ability to manage the nutrients available to their crops. In England and Europe, the most common system was the use of increasingly elaborate crop rotations, beginning with the two-field system (one year cultivated, one year fallow), and culminating in the Norfolk four-course system that successively planted wheat, turnips, barley, and clover on the same plot of land (Overton, 1996). Clover, along with peas and beans played an important role in crop rotations: these leguminous crops naturally fix nitrogen from the atmosphere, and thus can better recycle nutrients within the local environment. By contrast, the major grain and fodder crops like wheat and turnips require large amounts of nitrogen to grow (Leigh, 2004).

Crop rotations were not the only (partial) solution to the problem of maintaining soil nitrogen levels, however. In Southern China, the fish-rice system, where carp where raised in the midst of rice paddies, functioned in part to fertilize the rice as well as helping with weed and pest control (Kangmin, 1988). Similarly, in land-rich African societies, slash-and-burn agriculture provided a ready initial source of nutrients that then became depleted over time (Ruthenberg, 1976). Another mainstay of agricultural societies across the world was the use of animal manure as a fertilizer; although very heavy and thus impossible to transport substantial distances, manuring allowed nutrients previously used to grow crops to be partially "recycled" back into the soil (Allen, 2008). In a similar vein, human waste was also used as a fertilizer; this "night soil" was particularly valued in Edo-period Japan, where a lively trade developed (Ferguson, 2014), and was part of a package of "off-farm manures" that may have raised English crop yields by up to 20% in the first decades of the 19th century (Brunt, 2007). The problem with both of these products is that they were extremely heavy and were thus difficult to transport; as a result, manure had to be used close to where it was produced and night soil was only used by farms in close proximity to major urban centers.

Nonetheless, all of these traditional techniques have largely been replaced, at least in the most advanced agricultural producers, with the widespread use of fertilizers due to the artificial synthesis of ammonia pioneered by the Haber process (Smil, 2004). By directly importing key nutrients like nitrogen into the soil (modern fertilizers typically consist of "NPK": nitrogen, phosphorus, and potassium), fertilizers break the traditional model of agricultural where nutrients had to be carefully recycled. However, the usefulness of fertilizers from a theoretical perspective was not clear until well into the 19th century. The major text on agricultural science of the early 19th century, Humphrey Davy's 1813 *Elements of Agricultural Chemistry*, claimed that nitrogen was not essential for the growth of most plants (Davy, 1846). The picture improved once Liebig turned his attention to the subject, where as part of his work on the "law of the minimum" he recognized the importance of nitrogen; however, he falsely believed that the abundance of nitrogen in the atmosphere implied that it was not, in fact, the scarcest nutrient.[10]

2.2 The Arrival of Guano

Although nitrogen was scarce in many English soils during the 19th century, a lack of both scientific understanding and a commercially viable product meant that the situation remained largely unresolved throughout the first part of the century. This would change with the importing of *guano*, a form of concentrated seabird excrement that is rich in nitrogen, and which is widely considered to be the first commercial fertilizer in history (Kinsley, 2022). The story of guano fertilizer begins along the coast of Peru, where indigenous peoples have been harvesting this nitrogen-rich material for millennia to fertilize the region's marginal agricultural land (Murra, 1980)[11]; the resulting boost to agricultural productivity has been cited as a reason for the particular concentration of major pre-Columbian civilizations emanating from this region, which culminated in the rise of the Inca empire (Rodrigues and Micael, 2021; Santana-Sagredo et al., 2021). The fact that this practice arose in Peru and in few other areas of the world can be attributed to the Chincha Islands about 20 kilometres off the coast possessing both of the key criteria for the emergence of viable guano deposits: low precipitation due to cold ocean temperatures and rain shadows from the Andes mountains, and the presence of large colonies of nesting birds that feed on the rich marine life of the nearby ocean currents.[12]

[10] To that end, he promoted his own mineral-based fertilizer which, like many of his forays into commerce (including diverse products like baby formula and meat extracts), proved ineffectual (Brock, 2002).

[11] The first use of the word "guano" dates back to the beginning of the 17th century. It was adapted in Spanish from the Quechua "huanu", which means "dung" or "fertilizer".

[12] This lack of rainfall means that very few of the nutrients present in the guano are leached away over time, retaining highly concentrated soluble nitrates; the bird droppings, instead, become hardened in a form that is easy to mine. Concomitantly, the Humboldt Current that runs along the coast of South America is rich in nutrients, supporting huge stocks of fish and, in turn, seabird species like the guanay cormorant, Peruvian pelican, and Peruvian booby. While there are other locations around the globe that also possess these two key attributes, the Chincha Islands feature both exceptional high-quality and abundant reserves of guano.

Europeans first became aware of guano in the first decade of the 19th century following the South American travels of the German adventurer and naturalist Alexander von Humboldt, who remarked on its local use as a fertilizer and brought samples home (Cushman, 2013). Chemists across Europe set their minds to work analyzing the stuff, which was found to contain large quantities of ammonia (NH_3, a chemical compound of nitrogen and hydrogen).[13] The implications of this early interest were limited, though; the samples Humboldt brought back were too small for field trials, and Humboldt was under the mistaken belief that guano deposits were formed over thousands of years and could thus be rapidly depleted, dampening interest. Shortly after Humboldt's visit, the Napoleonic Wars and Latin American wars of independence resumed with increased vigor, which equally prevented the formation of a viable export industry for several decades.

The impetus to begin exports in the 1840s occurred via a circuitous sequence of events: the Humboldt current that enabled the existence of the guano islands also supported large whale populations, which were prized for their skins and oils by European and American whalers. However, the trade goods these whalers brought on their ships to exchange for provisions in South American ports, such as textiles and manufactures, tended to be bulkier than the products they were shipping back, resulting in a backhaul problem where ships would sail home with spare capacity (Cushman, 2013). In November 1840, local businessman Francisco Quirós y Ampurdia negotiated with the Peruvian government and the English merchant house Antony Gibbs & Son, which had existing operations in Peru to export products like alpaca wool, to send the first shipment of twenty casks of Chincha guano to England to take advantage of these asymmetric transport costs (Maude, 1958). The timing of this event was thus essentially independent of events in Great Britain and particularly in its agricultural sector.

Antony Gibbs & Son would retain a monopoly on the export of Peruvian guano for around twenty years, a concession which proved highly financially lucrative for the firm: William Gibbs, one of the brothers who ran the firm, became among the very richest commoners in England (Dennis, 2020). Within only a few years of the start of guano exports, the Royal Navy found further sources such as Ichaboe Island off the coast of Namibia, although most of these deposits proved low-quality and were rapidly exhaused (Kinsley, 2022). Other countries considered guano to be a critical resource as well: United States passed a "Guano Islands Act" in 1856 which enabled citizens

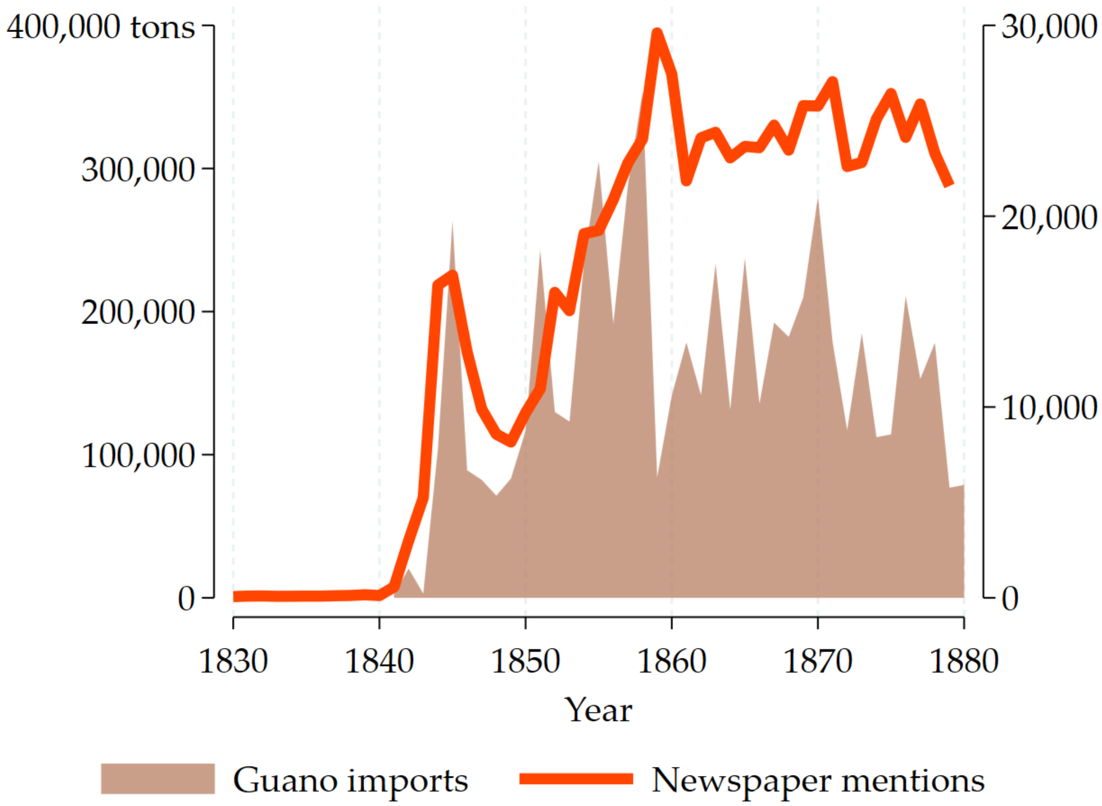
[13] A series of small shipments to the United States followed this discovery, including the editor of the *American Farmer*, based in Baltimore, in 1824, and the governor of Maryland few years later. Tests conducted on their farm confirmed the effectiveness of guano as a fertilizer.

to claim for the United States any uninhabited guano islands, which resulted in the annexation of numerous remote outcroppings (Immerwahr, 2019).[14]

The result of an English company being the monopoly-holder was also that a disproportionate share of guano was ultimately used in UK – upwards of 50% of all Peruvian guano exports in the 1850s, according to Mathew (1970). The level of imports would ebb and flow over time based on the discovery and depletion of various sources of guano and the vagaries of transportation over far distances, but would remain significant for the next forty years (Figure 1 – brown plot, left y-axis).

[14] Yet another early enthusiast of guano was Camillo Benso, Count of Cavour, the first Prime Minister of Italy. Eager to enhance the productivity of his maize and wheat fields as well as increase fodder for cattle, Cavour began importing guano through the ports of Genoa and Nice. He then experimented with its application on his several farms in the province of Vercelli, Piedmont, frequently praising its virtues in correspondence with Giacinto Corio (his farm associate) and Emile de la Rue (his financial adviser) during the 1840s. To verify the chemical contents of this novel fertilizer, he entrusted Angelo Abbene (a Turinese chemist) to analyze some samples of Peruvian guano. Convinced of the transformative potential of chemical fertilizers for Italian agriculture, he supported an early attempt to manufacture sulfuric acid and phosphorus in Piedmont (Loria, 1967). A few years later, guano's appeal attracted another Italian patriot to the coast of Peru: in 1851, Giuseppe Garibaldi visited the Chincha Islands himself as a mercant ship captain to acquire a load of guano before continuing his voyage to China (Garibaldi, 1889).

Figure 1. Sudden and rapid diffusion of guano across England



Notes: The left y-axis indicate the annual imports of guano from various issues of the annual Accounts Relating to Trade and Navigation. The right y-axis measures the total number of annual mentions of the word "guano" in England an Wales from the British Newspaper Archive.

This sudden "guano mania" is also evidenced from other sources, such as the counts of the word "guano" in British newspapers of the time. During most of the period from 1840-1880, the number of mentions of the term "guano" on the British Newspaper Archive is between 20 and 30 thousand per year (Figure 1 – orange-red line, right y-axis).[15] An opinion article in an 1854 issue of the *North British Agriculturist* is representative:

> *It is impossible to reflect upon what guano has accomplished during the past 10 years, without suggesting ideas as to the possible effects which its introduction at the period [fifty years prior] might have produced—what debates in Parliament, and what debates out of Parliament, would have been avoided, in connection with a Corn Law, which would never have been called into existence, and consequently never repealed, had this potent fertilizer been duly appreciated by the then Board of Agriculture. And what is still more important, what would have been the present*

[15] A similar trend arises when looking at the frequency of the work "guano" among the universe of English books available on Google Books (Appendix Figure B1).

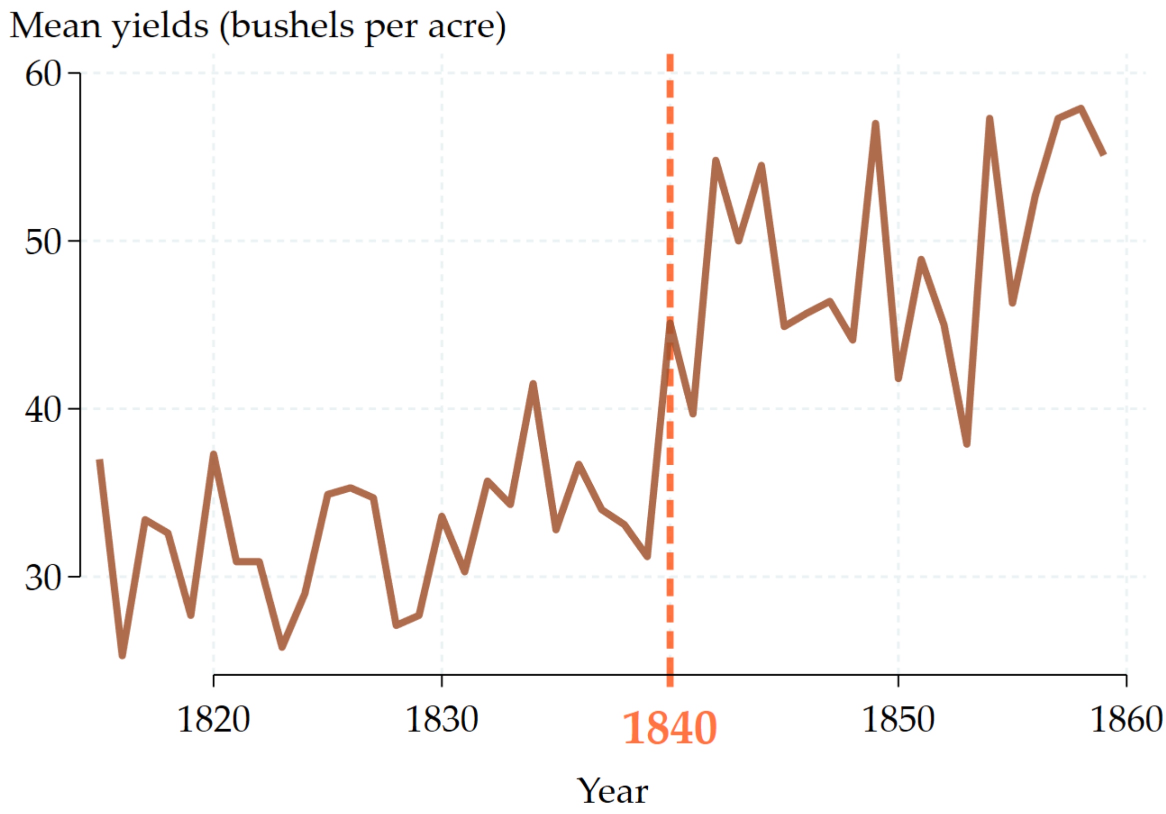
> *position of British agriculture, and that of the British nation, as to wealth and population.*[16]

It is difficult to ascertain the precise effects of guano and related fertilizers from the existing historical evidence, which largely consists of aggregated data at the county level, and even then is not available for each year. However, the timing of the introduction of fertilizer roughly aligns with a very substantial increase in wheat yields documented in Healy and Jones (1962).[17] The time series in Figure 2 shows much higher yields throughout the 1840s and 50s relative to the decades prior, with an average increase in yields of around 15 bushels per acre. This suggestive evidence accords the opinion of Lord Ernle, an authority on British agriculture during the 19th century, who claimed that the major increases in wheat yields observed in the two decades following 1840 compared to the years prior were due to increases in the intensity of input usage (cited in Jones, 1962).

[16] This article in fact captures precisely the counterfactual analysis we are interested in: using the difference-in-differences approach, we can explicitly compare outcomes in the period after guano is introduced to the regime that existed prior to its widespread usage in England.

[17] These unique, albeit limited, data stem from the efforts of two Liverpool merchant houses to predict the English wheat harvest so as to make better-informed business decisions. A set of around 40 locations throughout England were selected and visited each year by survey teams to measure the wheat yield.

Figure 2. Wheat yields jump after guano introduction



Notes: Data from Healy and Jones (1962).

More precise evidence on the effectiveness of the new fertilizer comes from field trials, which were pursued by dozens of farmers and subsequently reported in agricultural publications of the time. These typically consist of a simple experiment where one acre (or a fraction thereof) is planted with guano and comparable parcels are planted with various other fertilizers, including bones, animal manure, and a "pure control" of no additional input. These field trials are conducted of land of different qualities and growing different crops so the results are not comparable across trials; they are, however, comparable *within* trials.

In Figure 3, we show a scatter plot that displays the yield under guano fertilizer versus the comparison technology. Unsurprisingly, guano increases yields substantially relative to no input, with smaller increases in comparison to bones and animal manure. It should be noted, though, that even increases in yield on the order of 10-20% are economically significant in this context, and we see very few cases of lower yields under guano. Nonetheless, pure yield increases are not the first-order concern for farmers, who seek to maximize profits. Guano is, perhaps surprisingly, on solid ground here as well: although of course more expensive than not employing any input, it was generally comparable in price or cheaper than bone dust or animal manure. Guano outlays were typically on the order of £2 per acre, which was roughly the same as bone manure. Farmers valued the animal manure they employed at substantially higher rates, with costs of £4 per acre being commonly reported.

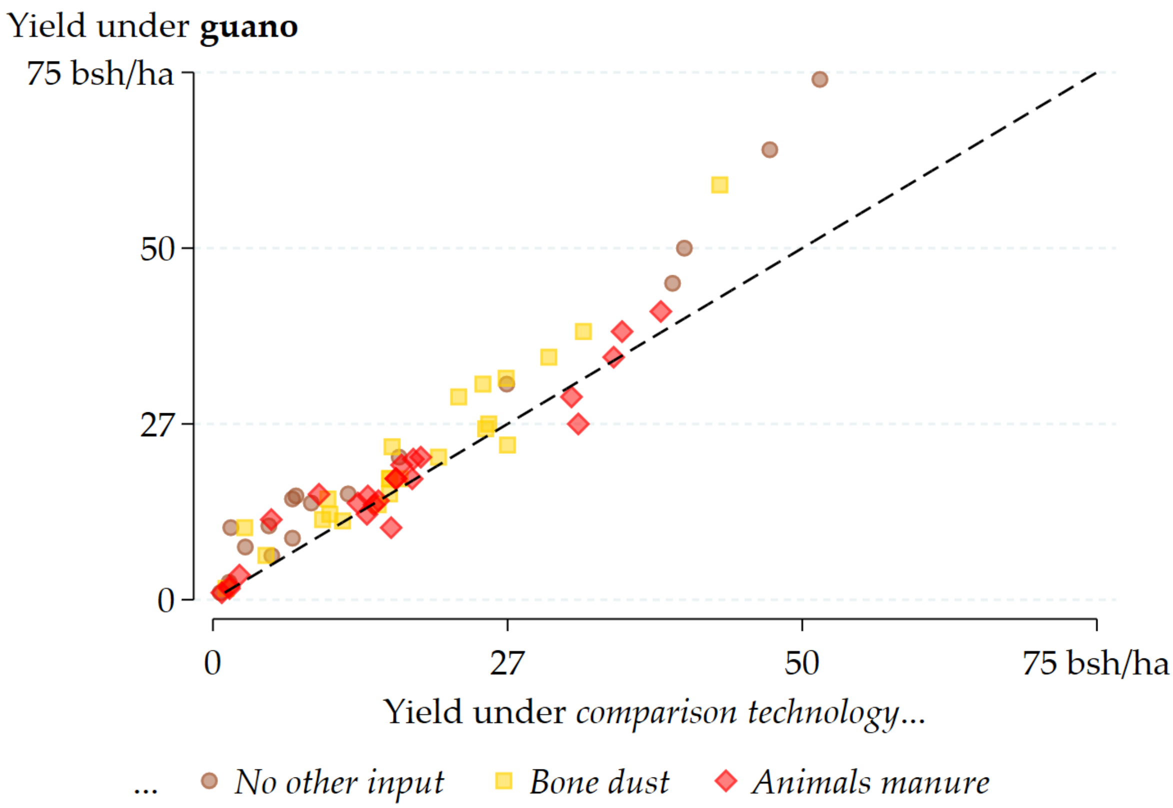


Figure 3. Guano outperforms alternative technologies

Another variable of interest that can be calculated using the field trial data is the typical usage of guano per acre, averaging roughly 300 pounds per acre. Provided an annual import volume of between 200 and 300 thousand tons, approximately 1.5 million acres of land could be fertilized at the typical rate per year. Given the estimates of English arable land in Broadberry et al. (2015), this would imply that between 10-15% of all arable land in England could be fertilized per year, which is significant when we consider that crop rotations were still widely employed and so farmers would not necessarily fertilize every year.

Although guano's high nitrogen content made it an attractive fertilizer in a variety of situations, both agricultural commentators of the time and our own analysis of periodicals confirm that it was primarily used on turnips and grains. One reason for this is the perilously low levels that turnips yields could fall in the absence of fertilization: as cited by Hall (1915), the long-running Rothamsted experiments (see Footnote 3) found that continuously unfertilized turnip plots saw yields collapse by up to 90 percent. Regarding wheat, the renowned agricultural commentator James Caird averred in 1853 how "[the] use of guano has been with me, as with many others for the last ten years, a matter of system... To apply it to the wheat crop is the rule – not to apply it, the exception." In the empirical analysis that follows, we will primarily rely on a more direct measure of soil nitrogen levels, inspired by these observations about the heterogeneous impacts of guano within England.

Although we focus primarily on guano in this paper, we note that nitrates, the main other commercial nitrogenous fertilizer during this period, were introduced at a similar time to guano and were largely sourced from nearby Chile and, to a lesser extent, from India. Although guano generally reigned supreme until around 1870, nitrates became more prominent in the following decades (Cushman, 2013). For the purpose of our empirical analysis, we do not attempt to distinguish between these two products given that they solved similar problems and were subject to similar constraints surrounding availability and cost.

2.3 English Agriculture and Economy

On the eve of the introduction of guano fertilizer in the 1840s, agriculture still occupied a privileged place in the English economy despite the major changes wrought by the Industrial Revolution starting in the mid-18th century. It remained the largest employer in the nation, boasting a one-third share by the time of the 1841 census (Crafts and Harley, 2004), and this rough share had been fairly stable over time as the agricultural work force had already fallen to less than half of the population by the 18th century (Wallis et al., 2018). The same era witnessed a substantial rise in agricultural productivity, which has been variously described as an "Agricultural Revolution", although the suddenness of this transformation has been debated (Clark, 1999). Scholars who emphasize the more gradual nature of change during this time period, such as Allen (2008), point to increasing soil nitrogen as being a key mechanism behind this increase. Yet, the essentially closed nutrient system that existed before the advent of imported fertilizers both limited the maximum extent of such a boost in nitrogen levels and rendered the process of increasing yields slow.

Progress was much faster in other agricultural domains, especially machinery and property rights. Threshing, a highly labor-intensive component of the harvesting process, was an early task to be mechanized, although this led to substantial social unrest and machine destruction during the "Swing" riots of the 1830s (Caprettini and Voth, 2020). The later part of the century saw the mechanization of further parts of the production process, embodied in reaping machines, seed drills, and other implements, as well as technologies to improve drainage such as the cylindrical clay pipe (Jones, 1962). One of the most important, yet controversial, institutional changes to affect English agriculture, the enclosure movement, was also largely complete by the mid-century (Heldring et al., 2022): this involved the transfer of common lands to freehold, a move the neoclassical economists argued would increase productivity.

Government policy towards agriculture was a major political cleavage at the time, as it pitted the landed Tories against the more commercially-oriented Whigs. The first part of the 19th century featured a succession of parliamentary acts dubbed the "Corn Laws", which levied import duties on foreign grain and thus protected British farming interests (Heblich et al., 2024). These duties were repealed in 1846 by sometime-agricultural enthusiast prime minister Robert Peel, although there was no immediate surge of imports, due both to relatively low foreign supply and the fact that the duties automatically adjusted downwards when prices became too high (Fairlie, 1965). Following the American Civil War, a "grain invasion" did take place, with import volumes increasing and the domestic sector suffering a depression by the 1870s. This downturn marked the end of the "high farming" period that characterized mid-century Victorian agriculture, where high input usage was needed to meet high demand. The introduction and repeal of the "Corn Laws" do highlight an important tension within the agricultural sector of the age: while grain could in principle be imported and exported easily, animal products, which were in increasing demand as the country industrialized and became richer (Oddy, 1970), could not be traded until the advent of refrigeration in the closing decades of the 19th century. As a result, there was particular interest in increasing livestock counts, and in improving productivity in the major fodder crops such as turnips.

The agricultural sector also interacted with changes in other parts of the economy, particularly in transportation. By the 1830s, Britain had developed an enviable system of internal transportation, consisting of mostly-private turnpike roads, canals, ferries, and coastal shipping networks (Alvarez-Palau et al., 2025). Transportation costs within this network were already relatively low, but they would decline further with the advent of the "railway mania" in the 1830s and 1840s, which saw significant investor interest in rapidly expanding (and in some cases over-expanding) Britain's railway network (Bogart, 2014). This infrastructure transported people and goods, including agricultural goods, which were still almost entirely domestically produced until the last decades of the century.

3 Data

3.1 Agricultural Data

England has a rich, if unfortunately mixed, record of collecting agricultural statistics, and we rely on three distinct sources to compile data for our paper. We are the first to assemble these data sources into a consistent panel covering most of the 19th century, as detailed below.

Our primary data contribution is the digitization of three waves of the English Agricultural Census for 1866, 1877, and 1884.[18] Activists such as James Caird had urged the government sponsorship of agricultural censuses for some years before the measure was finally adopted (Fussell, 1944). Opposition mainly came from farmers wary that the census was aimed at increasing tax compliance, which led to the decision to only inquire about land use and not crop yields. This opposition also led to the decision, in the first several years (including 1866) to separately report data that was directly measured and to data obtained by estimates, which we aggregate together. These data were previously accessible to researchers only as county-level aggregates published in the Parliamentary Papers and in compendium volumes published by the UK government (Ministry of Agriculture, Fisheries and Food, 1968). We are the first to systematically digitize the parish-level data collected by these censuses, found in the UK National Archives under series MAF 68, using advances in the machine learning-driven optimal character recognition of handwritten data using the Transkribus platform. The data for each year comprise about 1000 handwritten tables with around 30 rows and up to 30 columns, and thus are prohibitively expensive to manually transcribe.[19] With the exception of missing crop yield data, the the census records a large number of variables for the near-universe of parishes: as of 1866, data is collected on 15 crops and the presence of fallow, and on several species of livestock and their age breakdown. This only increases in the second and third waves we collect, in 1877 and 1884, to include several more crops and livestock species. Sample tables are found in Appendix Figures A2 and A3.

[18] A one-time pilot agricultural census was conducted in 1853; however, the data only cover a small subset of counties and are reported at a much larger unit of analysis (poor law unions) than the rest of our data. As a result, we have elected not to incorporate them into the analysis.

[19] We acknowledge the efforts of Coppock (2005), who did manually transcribe part of the 1877 census for the southeastern counties of England and make these efforts available to researchers.

We also use two data sources that are already well-known to English and agricultural historians due to prior digitization efforts. The first agricultural survey that covers a wide geographic sample of England was conducted in 1801, and is referred to in the literature as the "Crop Returns" (Turner, 2005). These data are fairly extensive in terms of geographic coverage but include the smallest number of variables. They are generally thought to be reliable and are the subject of several existing analyses, culminating in the national arable estimates produced by Turner (1981). The justification for carrying out this survey stemmed from poor harvests throughout the 1790s and the economic shocks induced by the Napoleonic Wars, leading to government fears over the food security of the realm (Minchinton, 1953). The Home Office therefore distributed standard forms that were sent to local bishops and from there to the clergymen of their diocese, asking them to list the acreage sown with seven different crops: wheat, barley, oats, potatoes, beans, peas, and turnips. In the margins, some clergy also recorded acreage sown with other crops such as rye and vetches. The zeal of dioceses for collecting the requisite information varied, but in total around 50% of the land area of England is directly included in the existing data (Turner, 1981).

The second source of agricultural data comes from the Tithe Surveys conducted between the years 1836-1841, as collected as the "Atlas of Agriculture in England and Wales" by Kain et al. (1986). These data are less extensive in geographical coverage but record more variables than the 1801 Crop Returns. In particular, the data include yield estimates for various crops, although we are not able to use these data in a panel setting as yields are not reported in other years. Grassland and other types of land use such as woodland and fallow are recorded, as are livestock in some cases.[20] The origin of these data stem from the Tithe Commutation Act of 1836, which reformed the ancient system of tithing, where farmers were required to give around ten percent of the annual produce of their farm to the church. Under the previous system, enterprising farmers who increased their output were penalized by having to pay higher taxes, which was widely viewed as unfair (Kain et al., 1986); this was replaced with a system of cash payment. We should note that parishes are not missing at random, as tithes were already commutated for parishes subject to enclosure acts (Prince, 1959); nonetheless, the sample covers a large part of the country. Additionally, some data may have been based on estimates, since a major purpose was to ascertain "typical" or long-run averages, not necessarily the precise data during the year surveyed (Cox and Dittmer, 1965). Annotations were made by the tithe commissioners to reflect some as-

[20] Livestock count were only recorded if a parish filled out a "pastoral return", and thus are only available in a small fraction of parishes, mostly in the southwest of England.

pects of data quality, such as whether small landholdings were excluded, that we use in robustness exercises.

A table summarizing the different variables included in our distinct data sets can be found in Table 1. Together, these data for the first time enable the construction of a panel of parishes across the entire 19th century in England. Although each of the data sources are distinct and have their own strengths and shortcomings, we are fortunate that they contain many comparable variables over time.

Table 1. Agricultural Variables, by Data Set

Year	1801	1836-41	1866	1877-1884
Wheat Acreage	✓	✓	✓	✓
Barley Acreage	✓	✓	✓	✓
Oats Acreage	✓	✓	✓	✓
Beans and Peas Acreage	✓	✓	✓	✓
Potato Acreage	✓	✓	✓	✓
Turnips and Rapeseed Acreage	✓	✓	✓	✓
Rye Acreage	✓		✓	✓
Grassland Acreage		✓	✓	✓
Hops Acreage		✓	✓	✓
Gardens Acreage		✓		✓
Fallow Acreage		✓	✓	✓
Clover Acreage		✓	✓	✓
Orchard Acreage		✓		✓
Woodland Acreage		✓		
Heads of Cattle		✓	✓	✓
Heads of Sheep		✓	✓	✓
Heads of Horses		✓		✓
Crop Yields		✓		
Mangold Acreage			✓	✓
Carrot Acreage			✓	✓
Cabbage Acreage			✓	✓
Vetches and Lucerne Acreage			✓	✓
Beet and Sugar Beet Acreage				✓
Flax Acreage				✓
Heads of Pigs				✓

3.2 Soil Data

Despite its relatively small geographical extent, England contains a wide variety of climatic and soil conditions. Its geological history includes major flooding during the Cambrian period, intense volcanic activity during the Ordivician period, and depositions of sandstone during the Devonian period to be among the most diverse of any country (Woods and Lee, 2018).[21] The primary soil characteristic we will use in our empirical analysis is novel in the economics and economic history literature: the carbon-to-nitrogen ratio (C:N ratio). This ratio captures the balance between the two main components necessary for plant growth: carbon is a necessary component of all organic compounds, and nitrogen is necessary for the synthesis of amino acids. With an ideal level at around 10, many soils possess higher values, up to a maximum of around 30. Soils which have a high C:N ratio have a large quantity of carbon relative to nitrogen and thus should benefit more strongly from the use of nitrogenous fertilizers (Brust, 2019). Farmers in 19th century England would have been unaware of this variable; however, by trial and error could have learned that their cropping and fertilizing decisions needed to vary based on the land's nitrogen deficiency.

We use data from the Countryside Survey topsoil maps, which have been developed by the Centre for Ecology and Hydrology (CEH). The CEH takes over hundreds of soil samples from across the UK, measures the C:N ratio and several other variables in each, and then extrapolates across the country using the British Geological Survey's Soil Parent Material Model (SPMM) and broad habitat classification to maximize fit between the sample data and over 30 soil characteristics measured in the SPMM (Emmett et al., 2016). Importantly, a soil's parent material, which refers to the weathered rock from which it is formed (e.g., glacial till), is determined by external forces that are not subject to human intervention (Olson, 2005). The resulting data set provides an estimate of the C:N ratio at a 1×1 kilometer grid covering almost the entirety of Great Britain except for some urban cores. Our preferred interpretation of the data construction is that it is analogous to the predicted variables obtained from the first stage of a 2SLS design, where we are predicting a potentially endogenous variable (the C:N ratio) using the variation from an exogenous variable (the soil parent material). The primary difference between the data construction for this variable and the first stage of an IV is that the researchers collected data on the endogenous variable from only a sample of locations.

We also employ two sources of soil and climatic data that are more familiar to economists and economic historians. The first of these is soil texture. A widely-cited distinction present in English soils is that between "heavy" clay-rich soils and "light" sand-rich soils. Although there are clear spatial patterns of this variable across England, there also exist many light and heavy soils in close proximity throughout the country. We

[21] The great variety of rock strata found in Great Britain inspired the birth of the discipline of geology, as exemplified by William Smith's pioneering geological map of the country in 1815 (Winchester, 2001). Many geological periods, including the above-mentioned Cambrian, Ordovician, and Devonian, were named for places or historical peoples of the British Isles.

take a classification developed by the British Geological Survey, which reports a five-point scale from "lightest soils" to "heaviest soils." There is little concern about this variable being influenced by human activity, as the formation of light and heavy soils is based on deep geological processes. The reason we do not rely on this distinction as strongly is because the direction of the effect of nitrogenous fertilizer is *a priori* less clear, with evidence that guano and related products were effective both in light and heavy soils (Mathew, 1970). We should note that there is almost precisely zero correlation between our soil texture measures and the C:N ratio (see Table 2).

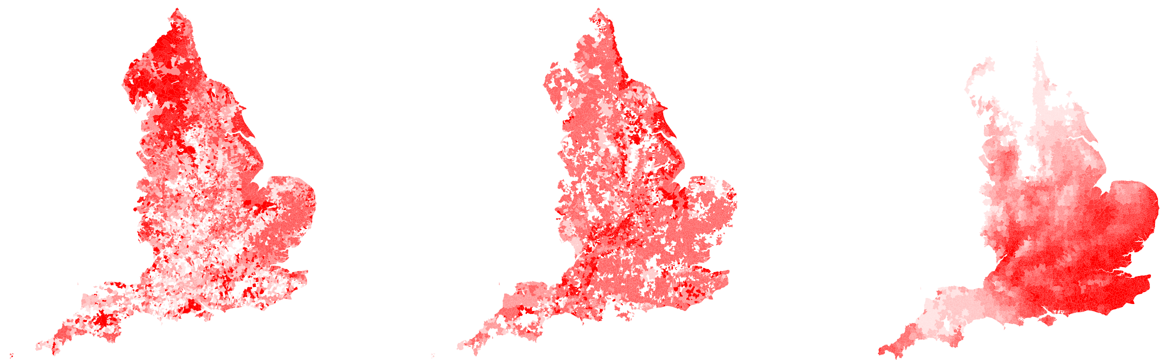
Finally, the most famous geographical division in English agriculture was noted by Caird (1852), who included a famous map in his seminal monograph tracing a line between the eastern "corn counties" (i.e., grain-growing counties) and western "grazing counties." A modern analogue of this distinction can be found in the Food and Agriculture Organization (FAO)'s "Global Agro-Economic Zones" (GAEZ) project, which aims to reconstruct using agronomic models which crops are most suitable to grow in a particular location. These data have been widely used in economics, and in economic history in particular (see for instance Nunn and Qian, 2011 and Heblich et al., 2024), but are the subject of recent critiques due to a lack of transparency and (in the US context) incorrect location of the suitable growing regions for crops (Rhode, 2024). We will rely less on this data source in our paper for differences reasons: namely, that the FAO-GAEZ project predicts crop suitability at a relatively low-resolution grid of 5 arc-minutes (about 9 km $\times$ 9 km at the Equator), which is large compared to the size of the typical parish ($\approx$ 12 square km). Furthermore, there tends to be substantial spatial autocorrelation across parishes. Nonetheless, we will show some results controlling for this data source as it is a standard one in economics; the correlation between FAO-GAEZ wheat suitability and our other measures is found below in Table 2. Maps of all three variables can be found in Figure 4, where red respectively denotes high C:N ratios, heavy soils, and high suitability for wheat.

Table 2. Correlation Matrix

(obs=11,624)	C:N Ratio	Heavy Soil	FAO-GAEZ Wheat
C:N Ratio	1.0000		
Heavy Soil	-0.0693	1.0000	
FAO-GAEZ Wheat	-0.2855	-0.0009	1.0000

3.3 Textual Data

A wide variety of rich textual data exist in England during the 19th century that we draw upon in our empirical strategy. The first major source is the newspaper data



Carbon-to-nitrogen ratio | Heavy vs. light soil | FAO-GAEZ Wheat Suit.

Figure 4. Maps of soil characteristics

collected at the British Newspaper Archive, who have digitized millions of pages of newspaper throughout our sample period. We measure the interest in guano by simply using the number of hits for the search term "guano" in a particular location in a particular year. Following Beach and Hanlon (2023), we also count the mentions of a neutral word, "Monday", which allows us to adjust for changes in the extent of the available newspaper corpus across time.

The second major source is agricultural periodicals and books of the time, which are available in digital form through HathiTrust. The most relevant periodicals are the *Farmer's Magazine* (published 1834-1881), the *The Gardeners' Chronicle and Agricultural Gazette* (published 1844-1873), and the *Journal of the Royal Agriculture Society* (published 1839-2002); we also rely on accounts from several contemporary books about guano.[22] Helpfully for us, all of these publications frequently contain references to the use of guano in specific locations.[23] We have already presented some data derived from these periodicals and books in the discussion of experimental field trials and the typical usage rates of guano.

3.4 Grain Market Data

We augment our newly-constructed data panel on parish land use with data from the "Corn Averages" that were published weekly in the London Gazette between 1828-

[22] In order of publication: *"Guano," & its Returns* (Alexander Macdonald, 1842), *Guano: Its Analysis and Effects* (Antony Gibbs and Son, 1843), *On Guano as a Fertilizer* (Cuthbert Johnson, 1843), *Practical Instructions for using Guano as a Manure* (James Clark, 1845), *English Agriculture in 1850-51* (James Caird, 1852)

[23] A typical example, from 1842, describes how Samuel Linley, of Hackenthorpe near Sheffield, mixed 12 hundredweight of guano with sod ashes and drilled it on five acres of turnips, leaving three acres fertilized only with bones. Although the harvest had not yet concluded, his impressions were favourable, since the plants where he used guano "are looking *much better and healthier than those manured with bones*, and will, I doubt not, produce a much more abundant crop" (emphasis in original).

1864. The purpose of these data was to ascertain the average price of grains across the country; if this price rose too much, then the tariff rate on grain imports from the Corn Laws would be automatically lowered. Even after the abolition of the Corn Laws, these data continued to be collected for many decades due to government concerns over social unrest caused by high prices. This source, although well-known to economic historians, has not been widely used in empirical work despite the relatively high quality of the data during this time period (Vamplew, 1980).[24] For the first 14 years until 1842, these data list the real quantities sold and revenues of six grains (wheat, barley, oats, rye, beans, and peas) sold in 150 market towns across England and Wales; this sample expands to 290 towns for the remainder of the time period. Of particular note is that the grain is only *domestic* in origin: sales of imported foreign grain are not recorded. This helps with our interpretation of the sales quantities as proxies of production in the surrounding area, although of course both sales volumes and prices may be affected by foreign imports in equilibrium.

4 Empirical Strategy

Parish-Level Analysis. Our main analysis considers data at the level of the consistent parishes defined by the Integrated Census Microdata (I-CeM) project. Consistent parishes are designed for comparison across time, taking into account changes in parish boundaries during the 19th century. All soil and geographical variables, including the C:N ratio, are measured by taking the value of the centroid cell in the consistent parish; for robustness, we consider the median value across all cells within the parish boundary.[25]

Key to our identification strategy is a novel metric of the expected "returns to guano" in a particular geography. We define this metric based on the C:N ratio, as detailed in the data section above, and posit that places with high C:N ratio, which are nitrogen-poor due in part to exogenous soil characteristics, would disproportionately benefit from the use of nitrogen-rich fertilizers, such as guano. Depending on the specification, we use either continuous or categorical (above versus below the sample median, by quartile) versions of this variable.

We start by establishing cross-sectional patterns of agricultural activity before the in-

[24] There are more serious concerns with the data quality in earlier years, but most of these had been satisfactorily resolved by 1828 (Brunt and Cannon, 2013).

[25] We refrain from using a hexagonal spatial grid (c.f., Heblich et al., 2023, Voth et al., 2023) to aggregate outcomes because the variation in missing data across parishes in our agricultural panel would lead to irregular cell coverage across waves, potentially compromising comparability of spatial units over time.

troduction of guano by estimating the following fixed-effects regression on the sample of pre-guano years (i.e., $t \in \{1801, 1836\text{-}41\}$),

$$Y_{p,t} = \alpha_{c(p)} + \alpha_t + \beta \cdot Guano_p + \mathbb{X}_p' \gamma + \varepsilon_{p,t} \tag{1}$$

where Y is the outcome of interest in a parish p and a county c, *Guano* refers to the "returns to guano", and $\mathbb{X}$ is a vector of controls at the parish level. The inclusion of county and year fixed effects (α_c and α_t) account for constant features of the agricultural economy within a certain county, overarching time shocks, and potential differences in the data collection process across counties and census waves. Importantly, we also control for soil heaviness and crop suitability, which aim to capture other land characteristics of the parish that may matter for cropping choices. Standard errors are clustered at the parish level, the unit of variation in terms of soil characteristics, throughout the analysis. For robustness, we estimate Conley (1999) standard errors with different radii to account for spatial correlation between parishes.

Next, we leverage the panel structure of our data, which spans five time periods corresponding to the waves of agricultural land use and livestock count we assembled for this project, in an event study framework. We estimate the following two-way fixed effects specification,

$$Y_{p,t} = \alpha_p + \alpha_t + \sum_{\tau \neq 1836\text{-}41} \beta_\tau \cdot Guano_p \cdot \mathbb{1}\{t = \tau\} + \varepsilon_{p,t} \tag{2}$$

controlling for parish-specific characteristics that remain constant over time (α_p) as well as time-specific factors that affect all parishes uniformly (α_t). The wave 1836-41, the last pre-guano period, serves as the reference period, while we assess the parallel trends assumption by testing whether the coefficient β_{1801} is statistically indistinguishable from 0.[26] Provided that potential outcomes would have evolved similarly across parishes in the absence of guano, we can interpret the estimated coefficients, β_τ, as recovering the average effect of guano on our outcomes of interest after τ periods. We note that this is not a setting where treatment is staggered, so there is no concern over the two-way fixed effects specification possibly assigning observations negative weights.

Finally, we pool data to simply compare the pre-treatment periods with the post- peri-

[26] Note that, most of our analysis on agricultural outcomes will focus on logged dependent variables, implying that parallel trends should hold in percentage terms (and not necessarily in level). This is arguably more plausible if time-varying factors, such as changes in the macroeconomy, have a multiplicative impact on the regression outcomes.

ods in a simple DiD model,

$$Y_{p,t} = \alpha_p + \alpha_t + \beta^{DiD} \cdot Guano_p \cdot Post_t + \varepsilon_{p,t} \tag{3}$$

where $Post_t := \mathbb{1}\{t > 1836\text{-}41\}$. While still controlling for both parish and time fixed effects, we turn to this static specification as there are some variables of interest that are not reported in 1801, making it impossible to estimate pre-treatment coefficients. Assuming homogeneous effects across time, β^{DID} identifies the *average treatment effect* of guano *on the treated* parishes (ATT).

Market-Level Analysis. Data on grain sales are reported at the market-town-week level. Therefore, we replicate the empirical strategy used in Equation 3 as follows

$$Y_{m,t,w} = \alpha_m + \alpha_t + \alpha_w + \sum_{\tau \neq 1839} \beta_\tau \cdot \overline{Guano}_m \cdot \mathbb{1}\{t = \tau\} + \mathbb{X}'_{m,t}\gamma + \varepsilon_{m,t,w} \tag{4}$$

The subscripts indicate the following level of observation: m for market town, t for year, and w for week. In order to construct a cross-sectional measure of exposure, we define a market's catchment area using Voronoi polygons: our primary specification takes a simple average of the data points within a 5-kilometer radius surrounding the town, but excluding any parts of that radius that are closer to a different town; for robustness, we vary the length of the radius and assign distance-specific weights to parishes.[27] We control for a rich set of geographic covariates (i.e, distance to coastline, a dummy for the six largest industrial cities in 1839,[28] and wheat suitability), all interacted with year dummies, and clustered standard errors at the market level.

Variable Transformations. Our outcome variables are typically a measure of crop acreage or livestock counts. These variables are weakly positive, which precludes us from applying a simple logarithm to transform the data. Despite their widespread use in applied work, log-like transformations, such as $\log(1 + Y)$ and $\text{arcsinh}(Y) = \log\left(\sqrt{1 + Y^2} + Y\right)$, have been shown to be arbitrarily sensitive to the units of the outcome variables (Aihounton and Henningsen, 2021; De Brauw and Herskowitz, 2021). In light of this concern, we follow the approach proposed by Chen and Roth (2024) for the DiD setting and estimate log-effects with calibrated extensive-margin value. Importantly, this approach focuses on a concave transformation of the outcome – therefore, less heavily influenced by observations in the tail – while explicitly weighting the

27 See Appendix Figure A4 for the distribution of market towns in our sample and an example of their catchment areas at our baseline specification of 5 kilometers. Notice that the average distance between a town and its nearest neighbor is 15 kilometers, with a minimum just above 5. Therefore, using large radii would imply having disproportionately bigger catchment areas for market towns in less densely populated regions.

28 These cities are London, Liverpool, Manchester, Birmingham, Sheffield, Leeds, and Bristol.

extensive margin relative to the intensive margin.

We first normalize the dependent variable, $Y_{p,t}$, by dividing it by $y_{min} \equiv \min_{Y_{p,t}>0} Y_{p,t}$, so that 1 corresponds to its minimum nonzero value in the estimation sample. Then, we estimate treatment effects on the transformed outcome $m(Y)$, where $m(y) = \log(y)$ for $y > 0$ and $m(0) = -x$ for some value of x. Armed with this transformation, the choice of x allows us to directly model the weight of the extensive-margin changes: setting $x = 0$ effectively "turns off" extensive-margin changes between 0 and y_{min}, focusing solely on intensive-margin changes among parishes with positive acreage or livestock; setting $x = 1$ implies that a change between 0 and y_{min} is valued as the equivalent of a 100 log-point change along the intensive margin, and so on. In a nutshell, raising the value of x places an increasingly large weight on the extensive margin.[29] As robustness, we estimate average proportional treatment effects, i.e., the percentage change in the average outcome for the treated group in the post-treatment period, using Poisson quasi-maximum likelihood estimation (QMLE).[30]

5 Results

5.1 Motivating Evidence

To support our identification strategy based on soil variations across space and motivate our subsequent analysis on the effects of guano on agricultural outcomes, we first document that nitrogen constraints were binding on farmers before the advent of nitrogenous fertilizers. Without a ready source of nutrients for purchase, farmers in nitrogen-deficient areas were forced to adopt different farming practices from those in nitrogen-rich areas. In particular, nitrogen-light crops such as peas, beans, and clover, which were less economically lucrative, were grown at substantially higher rates in nitrogen-deficient areas according to the 1801 and 1836-41 agricultural data.

Regression estimates in Table 3 shows that a one point increase in the C:N ratio – that is

[29] Expanding on Footnote 26, given that we employ different transformations of Y, the parallel trends assumption for the identification of treatment effects on $m(Y)$ applies to the transformation of the potential outcome $m(Y(0))$. Besides being specific to the functional form $m(\cdot)$, such identifying assumption will also depend on the units of the outcome (Roth and Sant'Anna, 2023). Therefore, we assess the sensitivity of parallel trends to the choice of x in Appendix B.

[30] This method is recommended by McConnel (2024) in order to avoid Jensen bias in multiplicative DiD models, first documented by Silva and Tenreyro (2006). However, Poisson regressions do not address the possibility that average effects might be dominated by observations in the tail of the outcome distribution (e.g., due to erroneous data digitization or other sources of mismeasurement), which can be a major issue in applications with historical data. We partially address this issue by comparing crop acreage with the total area of a certain parish and, therefore, dropping observations with unreasonably high values (see Appendix A.3).

roughly on a scale from 10 to 20 – corresponds to a 3-4 percent reduction in the acreage under nitrogen-intensive crops, and a similarly-sized increase in nitrogen-light crops of a similar magnitude. The coefficients remain statistically significant at the 5 percent level even after including county fixed effects and controlling for soil heaviness and suitability to those crops. The relationship between crop acreage and nitrogen deficiency in the pre-guano period is robust to using the median C:N ratio (Appendix Table B1), rather than the value at the parish centroid, and holds non-parametrically (Appendix Figures B2 and B3). The results are qualitatively similar when we instead use a binary variable based on whether the parish is above or below the median C:N ratio in the sample (Table 3, Column 5). These findings are consistent with our expectation that greater sources of nitrogen needed to be found, at an economic cost, in the nitrogen-deficient regions of the country.

Table 3. Nitrogen deficiency shapes planting prior to the introduction of guano

	(1)	(2)	(3)	(4)	(5)
Log-acreage under nitrogen-intensive crops					
Carbon:**N**itrogen ratio (%)	-0.043***	-0.043***	-0.047***	-0.034***	
	(0.012)	(0.012)	(0.012)	(0.011)	
Carbon:**N**itrogen ratio above the sample median (0/1)					-0.076***
					(0.027)
Number of observations	7,305	7,304	7,304	7,304	7,304
Number of parishes	6,330	6,329	6,329	6,329	6,329
Adjusted R-squared	0.006	0.168	0.174	0.194	0.193
Log-acreage under nitrogen-light crops					
Carbon:**N**itrogen ratio (%)	0.093***	0.027**	0.036***	0.031**	
	(0.014)	(0.012)	(0.012)	(0.012)	
Carbon:**N**itrogen ratio above the sample median (0/1)					0.111**
					(0.043)
Number of observations	7,320	7,319	7,319	7,319	7,319
Number of parishes	6,347	6,346	6,346	6,346	6,346
Adjusted R-squared	0.190	0.295	0.302	0.305	0.305
County fixed effects		✓	✓	✓	✓
Soil heaviness fixed effects			✓	✓	✓
Crop suitability controls				✓	✓

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Sample: 1801 and 1836. All regressions are least squares with fixed effects and controls (indicated in the last three rows of the table) and standard errors clustered at the parish level (in parentheses).

5.2 Where Was Guano Fertilizer Adopted?

Continuing from our motivating evidence, we ask whether guano adoption follows the patterns implied by the spatial variation in nitrogen deficiency. There are unfortunately no systematic data on guano usage in England. Nonetheless, there are a few possible ways to derive a "first-stage" where we empirically test whether the exogenous soil characteristics that we expect predict guano usage are in fact a valid measure of exposure. The first uses newspaper data from the British Newspaper Archive. In this test, we check whether the term "guano" appear more often in regions we deem to see greater "returns from guano" (i.e., regions with a high C:N ratio). It is not appropriate to estimate a DiD regression on this outcome variable, as the term "guano" appears extremely rarely everywhere before its introduction in 1840. In order to make our results easier to compare, we normalize the mentions of "guano" by the mentions of the word "Monday", in line with Beach and Hanlon (2023) who suggest using a neutral word to capture temporal trends in the size of the extant newspaper corpus.[31]

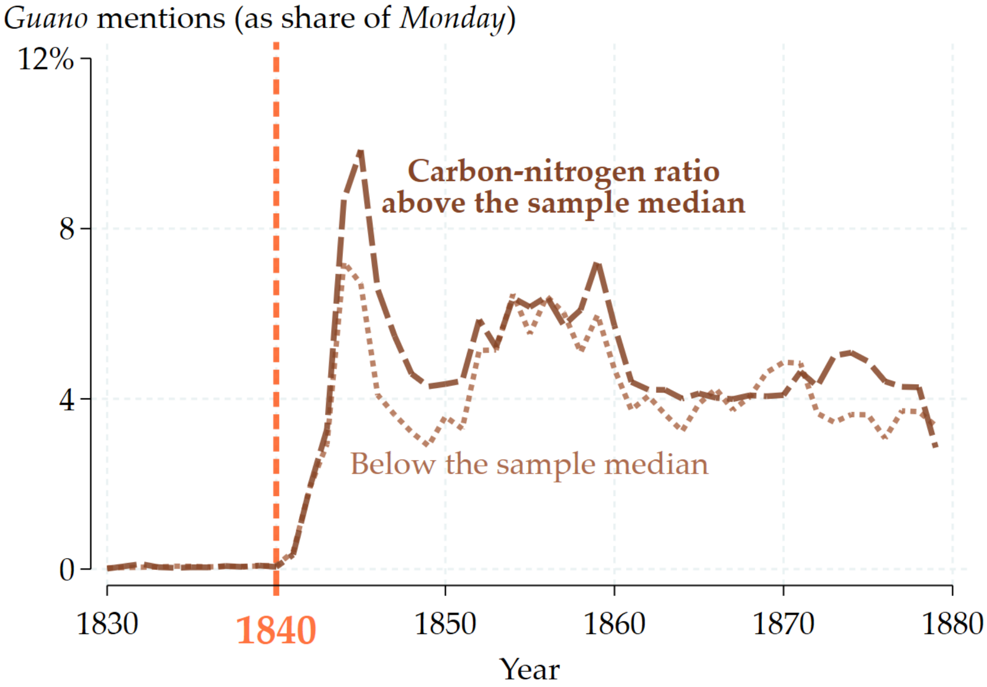
We compute the average value of the C:N ratio in each county, and compare the relative mentions of "guano" compared to "Monday" between either above-median and below-median counties or above-75th percentile and below-25th percentile counties, omitting the cities of London, Liverpool, Manchester, and Bristol.[32] The raw time series for each are reproduced in Figures 5a and 5b. In line with our hypothesis that nitrogen-poor areas are likely to benefit more from the use of guano and therefore be more likely to adopt it as an agricultural input, we observe more mentions of guano in above-median counties in most years, although the difference is relatively small. When comparing counties above the 75th percentile to counties below the 25th, however, the gap becomes substantial, with counties in the top quartile of C:N ratios reporting almost double mentions of guano in most years. The latter result is particularly meaningful because this is isolating a comparison between counties that are predominantly nitrogen-rich and predominantly nitrogen-poor; there are also a number of counties where there is substantial variation and where we might not expect stark differences on the aggregate level.

[31] For example, newspapers in Herefordshire in 1850 reported 65 mentions of the word "guano" and 1876 mentions of the word "Monday", so we would assign this observation a value of 0.035.

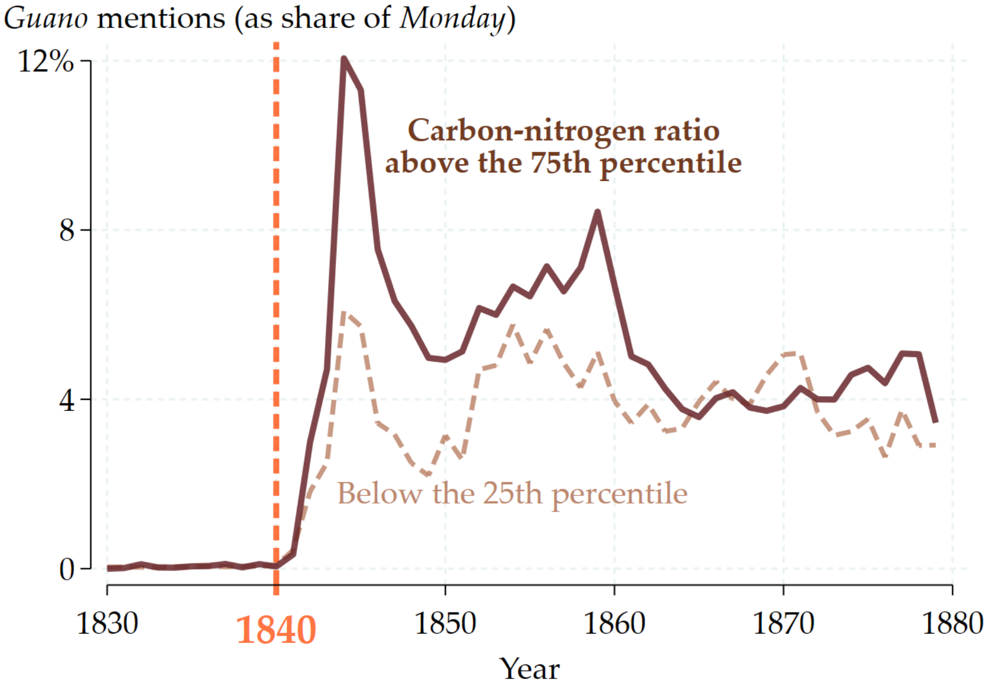
[32] These cities were home to national newspapers or newspapers that reported on shipping and other commercial news, such that mentions of "guano" are less likely to reflect local agricultural conditions.

Figure 5. Guano diffusion is higher in nitrogen-poor counties

(a) Above-median versus below-median



(b) Above-75th percentile versus below-25th percentile



Notes: The variable plotted on the y-axis is obtained by dividing the total number of annual mentions of the word "guano" by the total number of annual mentions of the word "Monday' from the British Newspaper Archive (after excluding the cities of Bristol, Liverpool, London, and Manchester). "Carbon-nitrogen ratios" are calculated by averaging the measure available in the Countryside Survey topsoil maps from the Centre for Ecology and Hydrology at the county level.

A more geographically disaggregated approach is to count mentions of guano usage in specific locations in England and Wales in the various agricultural magazines of the period. The advantage of this approach is that we have hard data on the particular farm or village where guano is being used. The downside, though, is that these data are unsystematic and we have little way of knowing the precise selection process into being mentioned in the magazine. To allay this concern, we compare locations where guano usage is mentioned in the years 1840-44 to locations that are mentioned in any context in the issue from 1839, before the introduction of guano. We find that parishes in England that report guano usage have higher average values of the C:N ratio than the parishes that are mentioned in the 1839 issue, which is robust to controlling for variables like distance to coastline that are themselves significant predictors of guano adoption.[33] In sum, we argue that evidence from two different types of textual sources, newspapers and agricultural periodicals, points to our measure of nitrogen deficiency as being predictive of the decision to adopt guano fertilizer.

5.3 Event Study and Differences-in-Differences

We now turn to our main empirical results, which we will report both as event study and as DiD regressions. The difference in presentation is driven largely by data constraints: in particular, there are discrepancies across years in the number of variables included in our different data sources and lingering concerns about the data quality of some observations in 1836-41. To better establish the plausibility of parallel trends of counterfactual outcomes with respect to the C:N ratio, we start by reporting results of an event study on the parish-level acreage of nitrogen-intensive crops in Figure 6.

We define nitrogen-intensive crops to be wheat, barley, potatoes, and turnips both because these are crops that we have data for in each of our five periods, and because these are crops that both modern scholarship (Sinclair et al., 2022) and contemporary sources (cf. Hall, 1915 and Caird, 1852) emphasize as benefiting from nitrogenous fertilizer. Reassuringly, the event study exhibits a clear lack of pre-trends in 1801 when comparing parishes with high and low values of the C:N ratio (as defined by being below or above the sample median, respectively). On the other hand, in the post-treatment periods we see a sizable increase in acreage of nitrogen-intensive crops, reaching 9% in 1884, in parishes with high C:N ratios.[34] The growing effect dynamics is in line

[33] The relevant regression is $Y_i = \beta_0 + \beta_1 \text{C:N Ratio}_i + \gamma X_i + \epsilon_i$, where Y_i is a dummy variable indicating whether a parish is mentioned in the 1839 sample or in the sample of guano-using places, and X_i is a possible control variable. In the regression with no controls, the p-value for the null hypothesis $\beta_{1,guano} = \beta_{1,1839}$ is 0.1039.

[34] The results are robust to varying the weight of the extensive margin as compared to the intensive margin.

with a gradual diffusion of guano over time and learning about how to change farming practices to best take advantage of the new product. These results build off our earlier evidence that farmers were indeed constrained by nitrogen levels in the early 19th century by showing more rigorously the response of acreage to these fertilizers.

Figure 6. Dynamic Effects on Nitrogen-Intensive Crop Acreage

Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 2 with year and parish fixed effects. Standard errors clustered at the parish level. Unit of observation: parish $\times$ year. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

We next turn to estimates from DiD regressions, as reported in Table 4. Column (1) presents average treatment effects on total crop acreage. The coefficient is a precisely estimated zero for the whole sample. This would indicate that the postulate of Kinsley (2022) and others that guano fertilizer led to an expansion of cultivation to more marginal land is at the very least not differentially true when comparing more- and less-exposed parishes. (It is the case that total area under cultivation increases across the board between 1836-41 and 1866.) What we instead see, reflected in Columns (2) and (3), is a significant reallocation towards nitrogen-intensive crops and away from other crops. Furthermore, we see in Column (4) that fallow land (which we omit from our main nitrogen-intensive and nitrogen-light variables) falls sharply in places with

Appendix Figure B5 presents several estimates, assigning a value of 100 x log points to an extensive-margin change between 0 and the minimum nonzero value of nitrogen-intensive crop acreage, according to the procedure detailed in the methodology section. Overall, this robustness check suggests that the extensive margin does not play a major role in explaining our main findings.

high C:N ratio after 1840. When combined with the previous motivating evidence, we interpret these results as indicative of convergence between high- and low-nitrogen parishes: that the nature of agricultural activity has become less dependent on the particular local conditions a farmer faces.

Table 4. Introduction of guano relaxes ecological constraints on crop allocation

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
High **C**arbon:**N**itrogen ratio × Post-1840	0.010	0.061***	-0.117***	-0.332***
	(0.022)	(0.023)	(0.042)	(0.093)
Number of observations	18,600	18,600	18,600	15,121
Number of parishes	4,927	4,927	4,927	4,889
Adjusted R-squared	0.679	0.705	0.540	0.525

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. All regressions are least squares as in Equation 3 with year and county fixed effects. Standard errors (in parentheses) are clustered at the parish level . 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

The second and third panel in Appendix Table B2 restricts the sample to parishes observed in either four census waves ("almost-balanced panel") or all five waves ('fully-balanced panel), respectively, instead of using the data on the whole sample, which is unbalanced across years. The small size of the most restrictive panel is due to an unfortunately low degree of geographical overlap between the 1801 and 1836-41 agricultural data; nonetheless, the sample is large enough to yield sufficient statistical power for nitrogen-intensive crops, and the results are quite comparable across samples.[35] Moreover, our estimates are robust to adjusting standard errors for spatial correlation (Appendix Table B2), to considering the median-based exposure (Appendix Table B3), to using a Poisson quasi-maximum likelihood regression (Appendix Table B4), to including region-by-year fixed effects (Appendix Table B5), and to controlling for wheat suitability interacted with year dummies (Appendix Table B6). The latter rules out that the effects of guano are explained by other contemporary shocks, such as the Corn Law repeal studied by Heblich et al. (2024).

35 When focusing on the balance panel, we find a marginally significant positive effect on total acreage. However, this effect is second-order compared to the increase in nitrogen-intensive crop, which is estimated to be 9 to 14%, on average, in the two alternative estimation samples.

We conclude with results on livestock counts, which we believe may also be an important part of the story of the Nitrogen Revolution in England. In this case, there is a fairly severe degree of unrepresentativeness in the pre-period data, as many parishes in England did not report any livestock figures for 1836-41.[36] The estimates in Table 5 show that the number of cows differentially increased in the low-nitrogen parishes after the introduction of guano. This is in line with the evidence that guano was largely used on turnips, which is an animal fodder. Data on horses are unfortunately absent in 1866 so there is a significant time gap between the two waves of data, although we estimate a similarly large increase in horse populations in low-nitrogen parishes. Finally, these is little evidence of differential effects for sheep population, which is unsurprising given that sheep rearing was not an important part of "high farming" practices.[37] The results on livestock remain robust to the wide array of sensitivity checks we implemented for crop outcomes (Appendix Tables B7, B8, and B9).

Table 5. Changes in cropping are accompanied by increased rearing of livestock

Fully-balanced panel			
Outcome:	*Cows*	*Horses*	*Sheep*
High **C**arbon:**N**itrogen ratio × Post-1840	0.187*	0.284**	0.041
	(0.107)	(0.133)	(0.157)
Number of observations	1,768	13,329	1,768
Number of parishes	442	6,391	442
Adjusted R-squared	0.599	0.558	0.416

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. All regressions are least squares as in Equation 3 with fixed effects (indicated in the last three rows of the table) and standard errors clustered at the parish level (in parentheses). 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

5.4 Heterogeneity Analysis

We explore the existence of heterogeneous effects of guano that may shed light on the underlying mechanisms behind our main findings. The first heterogeneity analysis we undertake is based on the crop yield data that we uniquely have access to from the 1836-41 Tithe Surveys. The event study, reported in Figure 7a, separates parishes based

[36] As a result, our pre-period data stem mainly from the mostly southwestern counties of Somerset, Devon, and Cornwall. Nonetheless, these counties still have wide variation in soil characteristics, and we can obtain a sizable balanced panel as we have data on most of these parishes from the 1866 and 1884 census waves as well. Data on count of horses are more extensive in the pre-period.

[37] Sheep rearing became less important over the 19th century, with cotton textiles increasingly dominating woolen textiles as the Industrial Revolution progressed.

on whether the average of their 1836-41 yields for wheat, barley, and turnips is above or below the median, based on the sample where these data are present. Again, there is no evidence of differential pre-trends among high- and low-yield parishes before the introduction of guano. Then in our first post-period year, it appears that the *less* productive parishes were the ones that increased their acreage by more, although this differential effect is not persistent over time. These results provide further evidence for the existence of "convergence" along the additional dimension of crop yields.

The second heterogeneity analysis we perform is based on a parish's distance to the closest of a set of 29 major English cities.[38] Parishes close to cities may have had access to cheap fertilizers in the form of nightsoil, horse manure, and other urban waste, which Brunt (2007) estimates as being significant in the first part of the 19th century. However, these substances were extremely heavy and uneconomical to transport over any significant distance, so parishes far away from major centers were unlikely to have benefited. Furthermore, parishes that were far away from cities had worse access to output markets, which put them at a further economic disadvantage. The event study, reported in Figure 7b, separates parishes based on whether they have above or below median distance to one of the major cities. We find no evidence of pre-trends, but a sharp change in the post period, with all of our effects driven by parishes that are farther away. We also interpret this dimension as a form of convergence, since the far-away parishes were able to overcome structural disadvantages through the introduction of fertilizers.

5.5 Grain Market Analysis

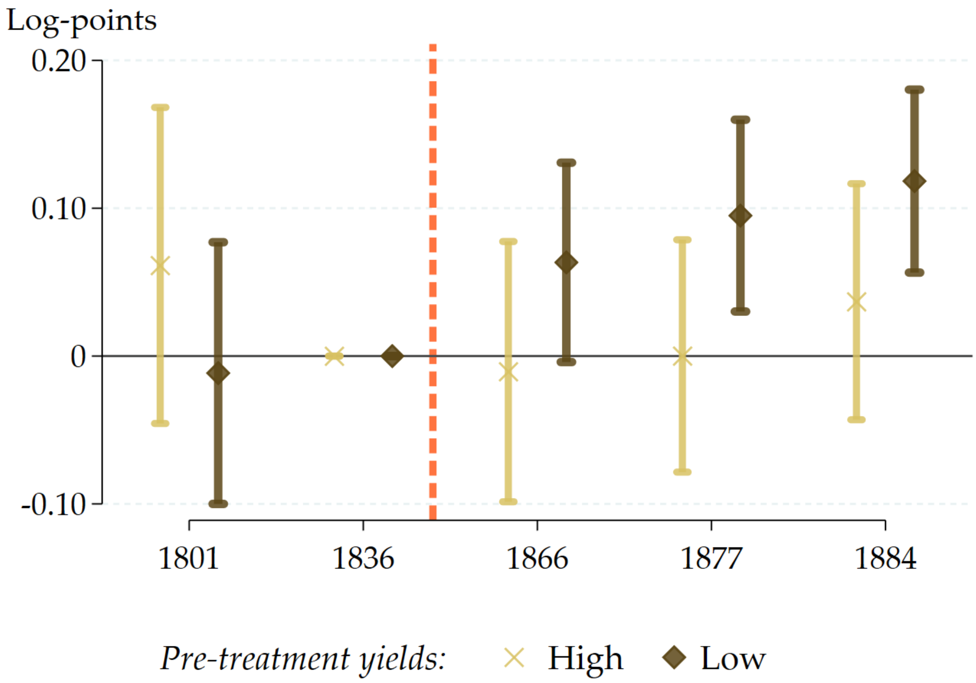
Given the time gap between the last pre-period data point (in 1836-41) and the first post-period data point (in 1866), we now turn to provide evidence on dynamics during the intervening years using our data on grain sales quantities in the panel of market towns between 1828-1864. In Figure 9, we observe no evidence of a pre-trend in the years prior to the introduction of guano when comparing log sales volumes in towns with nitrogen-rich versus nitrogen-poor hinterlands. After 1840, by contrast, we observe a gradual increase in sales volumes in nitrogen-poor towns relative to nitrogen-rich towns that typically reaches a level of around 0.10 log-points, indicating a 10% increase. If we compare this to our estimates of how the introduction of guano affected land use patterns by 1866 (approximately the end date of these data) where we find a reallocation of 5 log-points towards nitrogen-intensive crops, the effects on total pro-

[38] We take this list of cities from Walker Hanlon's Historical British City-Industry Database.

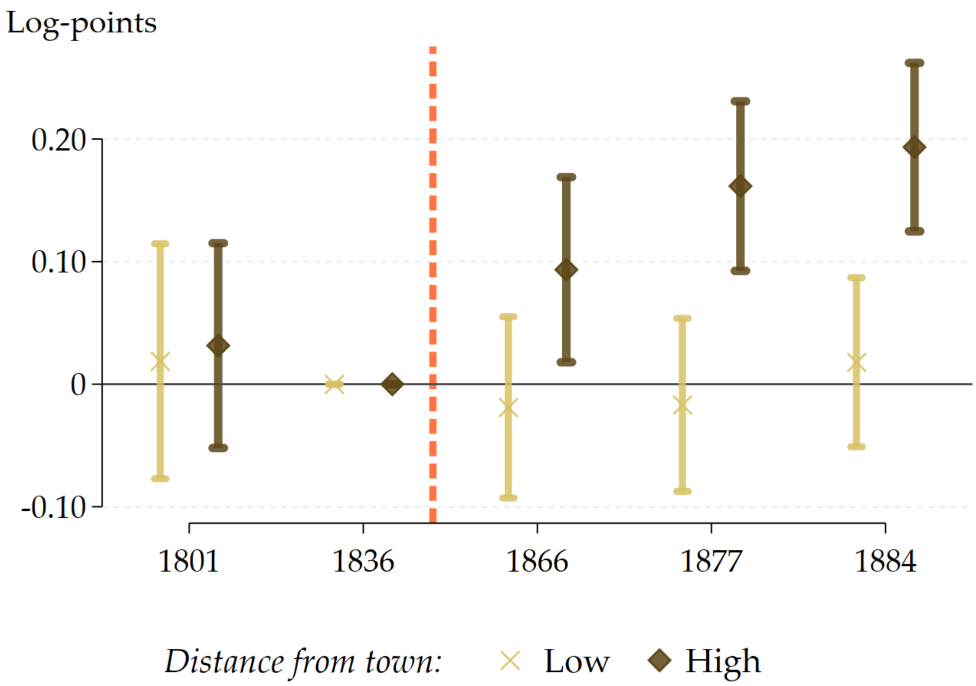
duction as proxied by sales appear to be quantitatively larger. This would be in keeping with a story that a large share of the effects of guano fertilizer were on improving productivity on inframarginal land that was previously cultivated with nitrogen-intensive crops, as opposed to merely inducing the switches towards these crops. These trends appear more sharply when we add the additional margin of heterogeneity based on soil heaviness in Figure 9, where it appears the effects are entirely concentrated in heavy soils similar to the results on land use.

Figure 7. Heterogeneous Dynamic Effects on Nitrogen-Intensive Crop Acreage

(a) By Pre-Guano Productivity



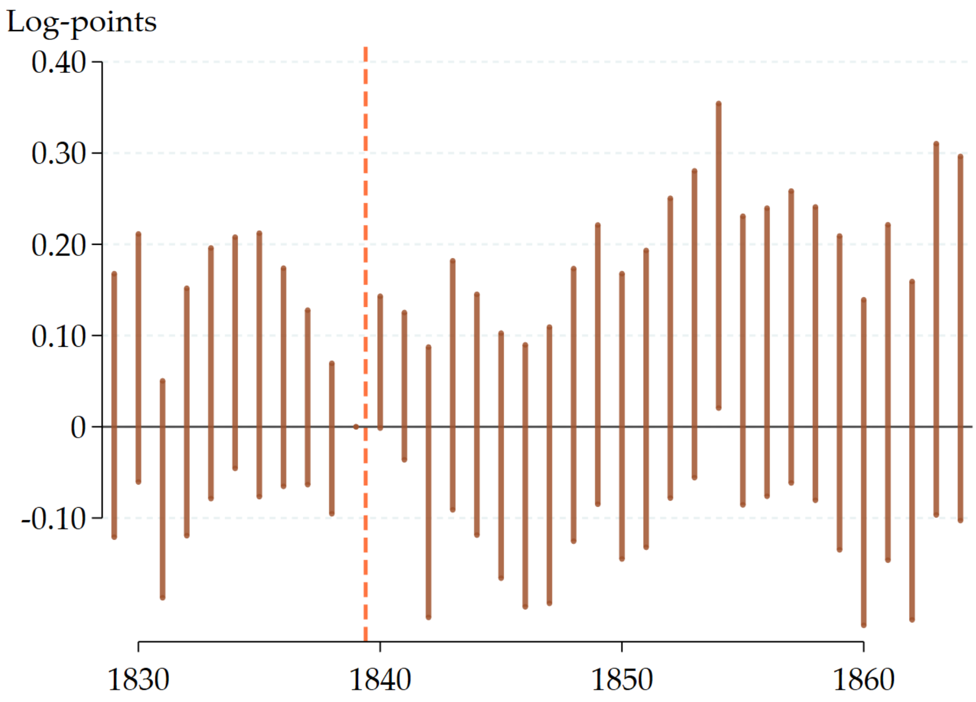
(b) By Output Market Access



Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 2 with year and parish fixed effects. Standard errors clustered at the parish level. Unit of observation: parish $\times$ year. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Figure 8. Effects on the Sales Volumes of Nitrogen-Intensive Crops

Figure 9. Overall



Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 4 with year, week of the year and market town fixed effects. Standard errors clustered at the market town level. Unit of observation: town × week. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

6 Model

Nitrogenous fertilizers were a novel technology that we argue allowed places that were constrained in their choice of economic activity to converge with less-constrained parts of the country. In this way, guano and nitrates differ from other types of spatially-embedded technologies studied in the literature, such as irrigation (Hornbeck and Keskin, 2014), the introduction of New World crops (Nunn and Qian, 2011), the diffusion of GMO soybeans (Bustos et al., 2016), among many others, which tend to drive divergence between those places which can adopt these technologies and those which cannot. The question we explore in this final section of the paper is the implication of "convergent" technologies on welfare, when we account for the ability of locations to trade with one another in an integrated national market. The main theoretical finding of our model is that, like any productivity-enhancing technology, guano and nitrates increased welfare. However, this welfare gain is sensitive to the level of market integration in the economy, with the technology providing a larger relative improvement when transport costs are high. The intuition for this is straightforward: by making places that were disadvantaged more similar to places that were advantaged, gains from trade are diminished due to reduced specialization. We can therefore think of the "Nitrogen Revolution" as being qualitatively different from the transformational developments occurring at the same time in industry, transportation, and other sectors of the economy, which instead created or encouraged new patterns of regional economic specialization and thus complemented the increasingly integrated nature of the English economy.

Our model is in the spirit of Ricardian model proposed by Eaton and Kortum (2002), which has since been widely applied to the agricultural sector, both historically (Donaldson, 2018) and in the present day (Farrokhi and Pellegrina, 2023, Costinot et al., 2016). In particular, the Eaton–Kortum (henceforth, EK) model provides a tractable way of modeling both comparative and absolute advantage in an environment with many sectors and locations, which closely matches our historical setting. We note at the outset that this model only covers the domestic English economy, treating it in isolation from the world. Throughout much of the period we study, English agricultural imports were modest but relatively constant as a share of overall consumption; this relatively static international trade position does change towards the end of the 19th century, which may limit the applicability of our model. The model features a set of N parishes that produce K crops, each of which has a continuum of varieties indexed j. Each parish o possesses an endowment L_o of land, which is immobile and supplied inelastically. For simplicity, we abstract from the labor market (following Donaldson, 2018). A representative consumer in each parish possesses the identical utility function that is Cobb-Douglas across crops and constant elasticity of substitution for varieties within crops:

$$U_o = \sum_{k=1}^{K} \mu_k \log \int_0^1 \left(C_o^k(j) \right)^{\epsilon} \frac{1}{\epsilon} dj$$

where μ_k is the weight placed on each crops such that $\sum_k \mu_k = 1$, $C_o^k(j)$ is the consumption level, and $\epsilon \doteq \frac{\sigma-1}{\sigma}$. We assume that σ, i.e., the elasticity of substitution, is identical for each product.

Every variety j of crop k can be produced on any plot of the parish's land L_o using a constant returns to scale production function based on a variety-specific productivity shock $z_o^k(j)$:

$$Y_o^k(j) = z_o^k(j) L_o^k(j)$$

In common with the EK literature, we model these productivity shocks using a Fréchet distribution parametrized as follows:

$$F_o^k(z) \doteq \Pr\left\{ Z_o^k \leq z \right\} = \exp\left\{ -f^k(N_o) z^{-\theta} \right\} \tag{5}$$

where $f^k(N_o)$ represents the crop-specific penalty associated with having a high value of the carbon-to-nitrogen ratio and θ governs how dispersed productivity draws are across varieties of the same crop within a parish (with lower values indicating more heterogeneity).[39]

We parametrize $f^k(\cdot)$ as a decreasing function whose functional form is motivated by the observations that (1) the optimal ratio of C:N is approximately 10 (NRCS, 2022) and (2) the "law of the minimum" implies that there are diminishing returns to reducing the C:N ratio as we approach the optimum, as it becomes increasingly likely that nitrogen levels cease to be the binding constraint on crop growth. We thus choose the parsimonious functional form:

$$f^k(N_o) = 1 - \gamma_k (N_o - 10)^2$$

where γ_k is a crop-specific parameter representing how quickly crop production diminishes as we stray from the optimal carbon-to-nitrogen ratio of 10.[40] In particular, $\gamma_k = 0$

[39] In extensions to the model, we consider the addition of an additional crop- and parish-specific productivity parameter to capture forces that govern agricultural productivity that are distinct from the C:N ratio.

[40] It is possible for this $f^k(N)$ to become negative for large values of N. In these cases, we censor this variable at a value just below the maximum non-negative value, although this adjustment affects only a

for a crop whose production is unaffected by soil nitrogen levels (our "nitrogen-light crops"), whereas $\gamma_k > 0$ for "nitrogen-intensive" crops.

Before the introduction of fertilizer, $N_o = \bar{N_o}$: each parish is endowed with an exogenous carbon-to-nitrogen ratio. But, the advent of fertilizers allows the option to alter this natural endowment with imported nutrients. We model each unit of fertilizer as being able to reduce nitrogen deficiency by one unit per unit of land. Furthermore, fertilizer is only applied towards the land devoted to nitrogen-intensive crops, not towards land devoted to nitrogen-light crops. Denoting the share of land devoted to nitrogen-intensive crops as α_o^N, the resulting level of nitrogen deficiency in parish o after purchasing M_o units of fertilizer is: $N_o = \bar{N_o} - \frac{M_o}{\alpha_o^N L_o}$. This captures the intuitive property that in order to achieve an equivalent reduction in the carbon-nitrogen ratio, large parishes need to purchase more fertilizer than small parishes.

In autarky, each parish must consume each variety based on its own production, at the "free-on-board" price, i.e., the price the variety sells at in the parish where it is produced, which is equal to the marginal cost. Holding the (potentially endogenous) nitrogen level constant, this price is equal to the following expression:

$$p_{oo}^k(j) = \frac{r_o}{z_o^k(j)}$$

We next turn to equilibrium price setting in the model. To start, consider the distribution of the price of varieties of crop k that could be produced in parish o and consumed in parish d, subject to an iceberg trade cost T_{od}:

$$G_{od}^k \doteq \Pr\left\{P_{od}^k \leq p\right\} = 1 - \exp\left\{-f^k(\tilde{N_o})\Big(r_o T_{od}\Big)^{-\theta} p^\theta\right\}$$

The final distribution of prices p_d^k depends on the realized distribution of prices G_{od}^k for each origin parish. If $p_d^k > p$, it must be the case that we do not observe a price less than p from any possible origin parish, generating the following CDF:

$$G_d^k(p) \doteq \Pr\left\{P_{od}^k \leq p\right\} = 1 - \Pi_{o=1}^D\Big[1 - G_{od}^k(p)\Big]$$

For any given vector of endogenous nitrogen levels $\tilde{N_o}$, the price distribution $G_d^k(p)$ is Weibull-distributed, which means we can calculate the mean price of crop k in parish d as follows:

$$p_d^k = \mathbb{E}\Big[p_d^k(j)\Big] = \Gamma\left(1 + \frac{1}{\theta}\right)\left[\sum_{o=1}^D f^k(\tilde{N_o})\Big(r_o T_{od}\Big)^{-\theta}\right]^{-1/\theta} \tag{6}$$

small number of parishes.

where $\Gamma(\cdot)$ represents the gamma function. By re-arranging this price-setting equation and using properties of the Fréchet distribution, we can calculate another variable of interest, the probability that parish d sources a variety of crop k from parish o:

$$\pi_{od}^k = \Gamma\left(1+\frac{1}{\theta}\right)^{-\theta} f^k(\tilde{N}_o)\left(r_o T_{od}\right)^{-\theta}\left(p_d^k\right)^{\theta}$$

In order to close the model, we finally impose market clearing conditions. The balanced trade conditions stipulate that the total revenue earned by factors in parish o (both land and fertilizer) must equal the total revenue the parish receives by selling its output X_{od}^k to all other parishes including itself. This in turn is a function of the probability that parish o is the lowest-cost supplier of a variety of crop k in parish d, the consumption share of crop k, and the factor revenue in parish d consisting both of the land rent and the returns to a parish's exogenous supply of fertilizer $\bar{M}_d$.[41] The total demand for the input must equal its exogenous supply $\bar{M} \equiv \sum_o \bar{M}_o$. We therefore obtain the following set of market clearing equations:

$$\forall o: \; r_o L_o + m M_o = \sum_d \sum_k X_{od}^k = \sum_d \sum_k \pi_{od}^k \mu_k (r_d L_d + m \bar{M}_d)$$

$$\sum_o M_o = \bar{M}_o$$

We also require a set of first-order conditions that capture the optimal choice of fertilizer use in the parishes that choose to augment their natural nitrogen endowment. Because it is possible for a parish to not buy any nitrogen in equilibrium, we employ complementary slackness conditions that impose that *either* parish o buys guano and so has marginal product of guano equal to marginal cost *or* does not buy guano and so has marginal product of guano less than marginal cost. These can be summarized as follows:

$$M_o \cdot (m - MRPN_o) = 0$$

where $MRPN_o$ is the negative derivative of the revenue product function $RP(N) = \sum_k \alpha_o^k p_o^k f^k(N)$ with the term α_o^k denoting the share of land that parish o devotes to crop k.[42] The condition can be satisfied either if $M_o = 0$ (corner solution) or if $m - MRPN_o = 0$ (interior solution).

The complementary slackness conditions, market clearing conditions for goods and

[41] This representation embeds the more realistic specification where one or more parishes/ports $m_1, ..., m_n$ have no supply of land ($L_{m_n} = 0$) and the entire supply of fertilizer ($\sum_{m_n} \bar{M}_{m_n} = \bar{M}$).

[42] By a property of the Fréchet distribution, the share of land devoted to any crop k is equal to the following: $\alpha_o^k = \frac{\left(p_o^k f^k(\tilde{N}_o)\right)^{\theta}}{\sum_k \left(p_o^k f^k(\tilde{N}_o)\right)^{\theta}}$

market clearing condition for fertilizer combine to create a system of $2N$ equations in $2N$ unknowns.

As is standard in EK-type models, we will define welfare to be the real agricultural income of factor owners: i.e., the income of owners of land and fertilizer divided by the price index of agricultural goods.

$$W_o = \frac{r_o L_o + mM_o}{P_o} \propto \frac{r_o L_o + mM_o}{\prod_k (p_o^k)^{\mu_k}}$$

6.1 Simulation

The rich general equilibrium forces of the model here preclude an analytic solution for the effect of input access on the gains from trade, as the relevant intermediate market clearing equations are implicit.[43] To generate model prediction, we instead consider simple simulations of our model with only two sectors and two parishes. We begin with a simulation that is implicit in the discussion of the "Nitrogen Revolution" so far: a comparison between a parish r that is rich in nitrogen, and a parish p that is poor in nitrogen, but that are otherwise identical. When fertilizer is introduced, they can both purchase fertilizer on the market at an endogenous price m. When a small amount of nitrogen becomes available for sale, the marginal revenue product of nitrogen will be higher in parish p than in parish r: as a result, all of the fertilizer will be purchased by parish p in a corner solution. This pattern will continue until the $MPN_p = MPN_r$, at which point both parishes will purchase equal amounts of additional fertilizer (note, though, that $r_p < r_r$ due to the superior endowment in parish r).

So, given any supply of fertilizer, it is possible to compute equilibrium rental prices and fertilizer prices, fertilizer usage by parish, and ultimately welfare. The first, and most basic, question is whether fertilizer does indeed raise welfare aggregate welfare, as opposed to merely redistributing welfare from the nitrogen-rich parish to the nitrogen-poor parish. Under a wide variety of configurations, the answer is an unambiguous "yes": and welfare is raised in both parishes even though prices fall. The reason for this is part of the structure of the EK model: when each crop consists of many different varieties, all of which consumers want to consume, then any increase in productivity, anywhere, allows all other locations to gain access to a larger supply of cheap varieties. Insofar as the assumption of differentiated varieties may not be realistic in an agricultural setting that is a limitation of the present analysis; we do note, however,

[43] Many articles using the EK model, such as Di Giovanni et al. (2014), derive analytic solutions in the presence of a constant returns to scale sector that pins down factor prices. However, in this paper we are studying model experiments that may change relative land rental prices.

that the EK model has been frequently applied to agricultural settings in the literature (cf. Donaldson, 2018, Costinot et al., 2016, Farrokhi and Pellegrina, 2023, etc.).

Our second, and more nuanced, question is whether do the benefits of the technology change as we vary how integrated the markets of the two parishes are. To answer this, we consider the total welfare of both parishes under various iceberg trade cost parameters, comparing the welfare they receive with access to fertilizer with the welfare they receive without: that is, the welfare increase due to the technology. Then, we compare how these welfare gains vary across different levels of iceberg trade costs, ranging from $T_{rp} = 1$ (frictionless trade) to $T_{rp} = 3$ (highly fractured market). We find that the welfare gains from the technology are consistently higher in the cases where iceberg trade costs are high, a finding that is robust to excluding income from the fertilizer endowment in the welfare calculation. When we compare the welfare improvement from fertilizer at high trade cost values to a benchmark of frictionless trade, we find that less-integrated markets see a larger welfare increase from the technology, although a variety of magnitudes are possible depending on the parameters chosen. A series of these simulations, which vary based on whether the gap in nitrogen deficiency (i.e. $\bar{N}_r - \bar{N}_p$) is relatively big or small and whether the fertilizer endowment $\bar{M}$ is relatively big or small, are shown below in Figure 10. The clearest pattern is that the gap in nitrogen deficiency between parishes dominates differences in the fertilizer endowment; the result that the benefits of technology depend on the degree of market integration does not strongly depend on the *degree of availability* of the technology in this model. They do, however, depend, on how severe the pre-existing productivity gap is.

6.2 Model Calibration

The model, as outlined in the previous section, depends on various parameters and elasticities, which we summarize in Table 6. To begin with, we measure two key model variables with data sources we have already discussed: measures of nitrogen endowments $\bar{N}_o$ (the C:N ratio) and and land areas L_o (agricultural census and other sources).[44] The most important new element of the model is estimates of iceberg trade costs T_{od}, which we require for each origin-destination pair and under two sets of transportation parameters (pre-railway and post-railway). We calculate transport costs for the pre-railway era using the network developed by Alvarez-Palau et al. (2025), which includes turnpike roads, canals, coastal shipping, and ferries along with associated

[44] In extensions that include parish-by-crop specific productivity terms, we use potential yields from the FAO-GAEZ project, also previously discussed.

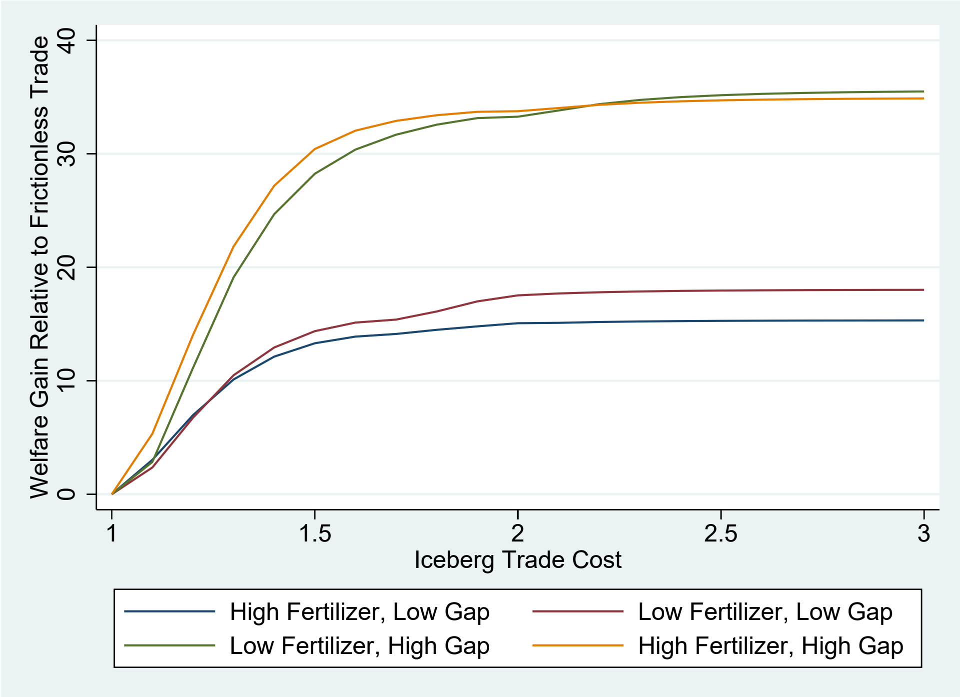


Figure 10. Simulations of a simple 2×2 economy

cost parameters for each mode. For the post-railway era, we add 1861 train network shapefiles from Marti-Henneberg et al. (2018) to the 1830 network, and calculate costs for railway transport by comparing the costs used by Alvarez-Palau et al. with those used by Donaldson (2018), who deals with a similar set of modes in the context of colonial India.[45] We then include all non-urban parishes in the network, and use ArcGIS's OD Cost Matrix functionality to compute the least-cost distance between each pair of parishes under both sets of cost parameters using Dijkstra's algorithm (Esri, 2024). We then calculate the iceberg trade cost based on the following formula:

$$T_{od} = 1 + \frac{C_{od}}{P} \tag{7}$$

where C_{od} is the transport cost in monetary terms and P is an agricultural price index computed by Alvarez-Palau et al. (who also include coal as a second good in their own calculations). Since these iceberg trade costs are computed directly for each pair of locations, they are guaranteed to satisfy the important triangle inequality that for any three parishes a, b, and c: $T_{ac} \leq T_{ab}T_{bc}$.

[45] Specifically, we note that Alvarez-Palau et al. provides a cost of 0.00456 pence per meter-ton, and Donaldson finds that railway transport in India was 4.5 times cheaper than road transport. From this, we obtain our primary cost parameter of 0.00101 pence per meter-ton by railroad. We note that the two sources disagree on the relative cost of road transport vs. shipping, with Donaldson finding that shipping was only slightly cheaper than road transport, whereas Alvarez-Palau et al. find that shipping was much cheaper. If we elected to instead take the British shipping cost estimate (0.000578 pence per metre-ton) and then apply Donaldson's finding that coastal shipping was 2.25 times more expensive than rail, we would obtain implausibly low transport cost estimates for rail.

To these we also add several elasticities which are drawn from the literature or estimated from historical sources. We choose as our baseline parameter θ, which captures the dispersion of productivity draws within a crop, as 8.28, following the estimate of Eaton and Kortum (2002) and noting that this value falls roughly in the midpoint of the crop-specific θ terms estimated by Donaldson (2018). Estimates of the crop consumption shares μ_k are taken in part from the sales price and quantities data in the *London Gazette* and from existing work by Oddy (1970). We approximate crop-specific nitrogen intensities by assuming that $f^k(N)$ reaches 0 for carbon-to-nitrogen ratios of 20 (the 95th percentile value), which yields $\gamma_k = 0.01$ for nitrogen-intensive crops and $\gamma_k = 0$ for nitrogen-light crops.

To solve for the model after the introduction of fertilizers, we adopt the following iterative approach: given the vector of baseline equilibrium rental rates $\{r\}$, we solve for the optimal fertilizer usage by parish in *partial equilibrium*. That is, we hold prices and land allocation fixed, and calculate each parish's marginal revenue of product using only variation in the last term, which captures the direct effect of nitrogen deficiency on productivity:

$$\widetilde{MRPN}_o = \sum_k \bar{\alpha}_o^k \bar{p}_o^k \left(-\frac{df^k}{dN}\right)$$

Then, we calculate the equilibrium price m that would be necessary so that the demand for fertilizer equals its supply, noting that if a parish makes the extensive margin decision to use fertilizer it must be the case that in the partial equilibrium $\widetilde{MRP}_o = m$. Finally, we iterate between these two approaches, solving for the vector of solutions to $\{r\}$ and the solution for m (and thus each parish's fertilizer usage) until we have converged: that is, until a full iteration does not change any parish's extensive margin decision to consume fertilizer.[46]

6.3 Model Results

The central result from our simulation was that fertilizer raises welfare (even when excluding income stemming from the fertilizer endowment) and that the increase in welfare from fertilizer diminishes as market integration increases. We are now in a position to take our model to the data and estimate the welfare implications of various

[46] Note as well that there is a co-dependence between nitrogen deficiency N and the vector of crop shares $\{\alpha_o^k\}$. Recall that $\alpha_o^k = \frac{\left(p_o^k f^k(\tilde{N}_o)\right)^\theta}{\sum_k \left(p_o^k f^k(\tilde{N}_o)\right)^\theta}$ and $N_o = \bar{N}_o - \frac{M_o}{\alpha_o^N L_o}$ where α_o^N is the share devoted to nitrogen-intensive crops. At each step we thus need to solve the fixed-point problem: taking prices and fertilizer allocation as given, what vector $\{\alpha_o^k\}$ and level of nitrogen deficiency N_o are consistent with each other?

Parameter	Value or Range						Source
θ	8.28						Eaton and Kortum (2002)
T_{od}	1-2.2						Extension of Alvarez-Palau et al. (2025)
N_o	0-9.99 "Nitrogen Deficiency" (from C:N ratio)						Centre for Ecology and Hydrology
L_o	371-84,256 acres						GIS area from I-CeM project
	Crop-specific						
	wheat	**barley**	**oats**	**beans**	**turnips**	**potatoes**	
μ_k	0.256	0.121	0.270	0.064	0.211	0.077	London Gazette and Neild (1842)
γ_k	0.01	0.01	0	0	0.01	0.01	Nitrogen-intensity of production

Table 6. Summary of Sources of Model Parameters

scenarios related to the introduction of guano fertilizer.

To begin with, we consider the "baseline" version of the model with no fertilizer sector and where every parish is constrained to produce based on its carbon-to-nitrogen ratio. Under this baseline, we are able to test whether our model is able to capture untargeted moments successfully. The main equilibrium object of the model is the parish's rental rate of land, for which we can observe a rough proxy in the form of the Rateable Values found in the Parliamentary Papers. These are available for a variety of years, and we choose the 1843 data to effectively correspond with the pre-guano equilibrium. These data capture something close to what we would like to observe: they measure the value of buildings and land that are taxable ("rateable") to support local public goods. As such, they are not limited to only agricultural land (as we would ideally want) and also include forests, mines, and the value of any buildings or structures. Nonetheless, we expect that in many parishes the value of agricultural land was a significant portion of this rateable value, and that there should be a reasonable correlation between our observed and predicted values of this variable. We find that one standard deviation increase in the log predicted rental value is associated with a a 0.23 standard deviation increase in the log observed 1843 rateable value, in a highly statistically significant relationship (t-statistic of 26). Given the relative parsimony of the quantitative model, and the fact that the model and data variables are not defined in precisely the same way, we think the prediction of this moment validates our model approach.

When we move to the model with fertilizer, we begin by considering modest endowments of fertilizer: enough to reduce the carbon-nitrogen ratio in each parish by 0.1 on all their land, provided they have the mean parish size of around 12 square kilometers. Given that only around 2/3 of land will be used for growing nitrogen-intensive crops in equilibrium, this is equivalent to an average reduction of around 0.15. At this fertilizer endowment, around 15% of parishes use any appreciable amount of fertilizer (usage > 0.01), which roughly aligns with our back-of-the-envelope calculation based on the amount of land that could be fertilized each year at the guano import levels and typical per-acre usage rates.

Our first result is that guano raised welfare, and did so for the vast majority of parishes. On average, this endowment of fertilizer increased welfare by just under 4%, with a maximum increase of 23% and a minimum of -0.2%. The histogram of welfare changes (under 1830 transport costs) is plotted in Figure 11. This increase is concentrated in parishes that were nitrogen-deficient at baseline: a one standard deviation increase in nitrogen deficiency is associated with a 0.74 standard deviation increase in the welfare increase from fertilizer. There is a similar concentration of the benefits among the parishes that endogenously choose to use nitrogen fertilizer (not perfectly correlated with nitrogen deficiency due to the realistic geography of the model), and in a horse race regression both initial nitrogen deficiency and the extensive margin decision to use fertilizer have standardized coefficients of around 0.4. Although these welfare increases may seem relatively small, they are fairly large compared to the estimates of per annum agricultural productivity growth cited in Temin (1997), which generally agree on a range of 0.12-0.19 percentage points. The average increases in welfare that we observe would thus represent around 20 years of agricultural productivity growth.

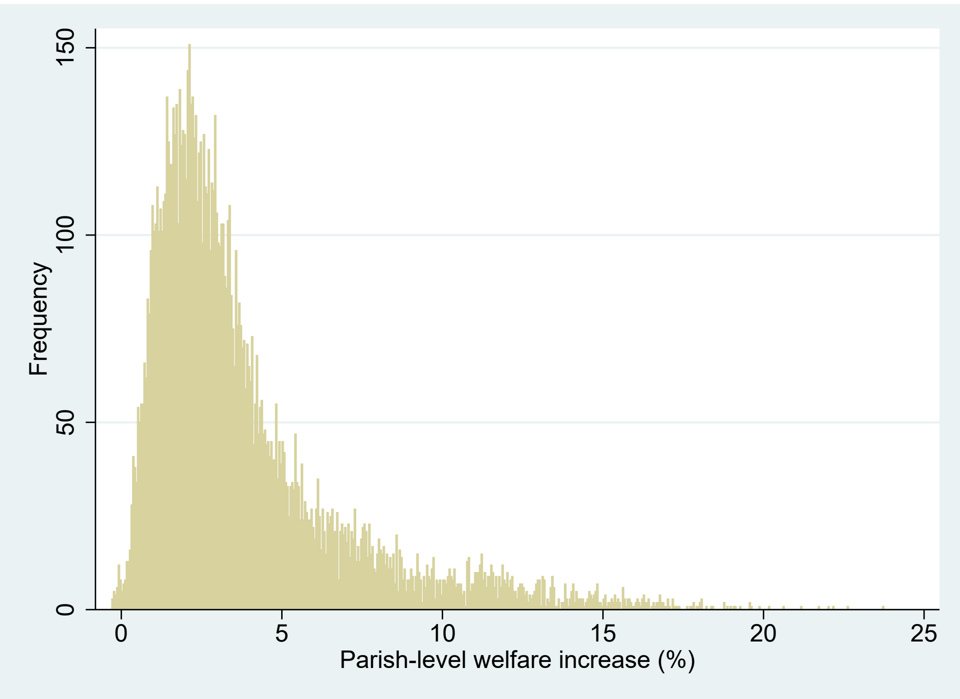


Figure 11. Welfare Gains from Fertilizer

Turning to our main theoretical prediction from the model, we compare four situations: equilibria using 1830 trade costs (with and without fertilizer) and equilibria using "railway mania" trade costs (with and without fertilizer). This allows us to summarize our results in the 2×2 matrix found in Figure 12.

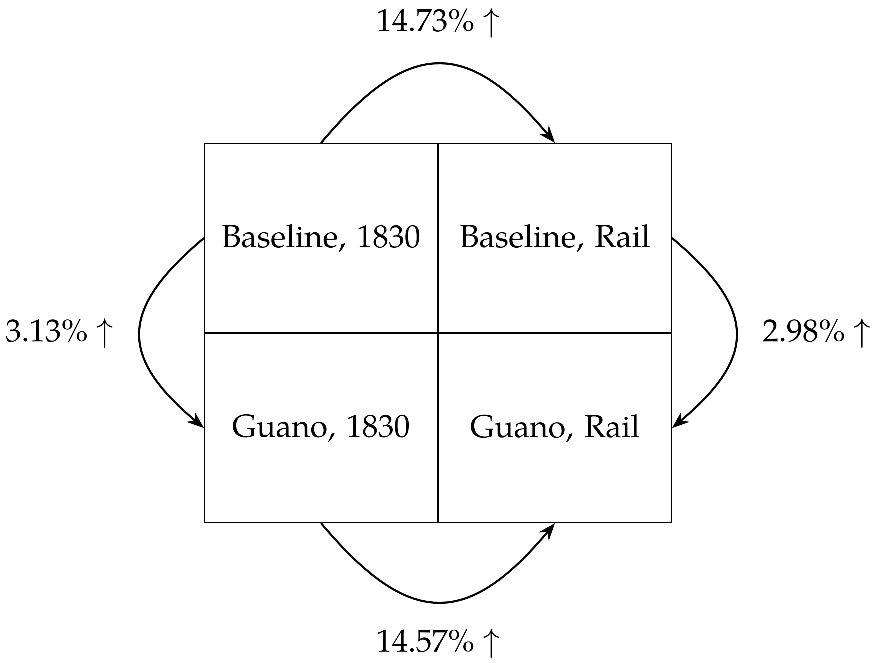


Figure 12. Counterfactual Welfare Increases

There is a modest, but still economically meaningful, heterogeneity in the welfare gains from guano when we compare the transport cost regime that prevailed in 1830 to the one that prevailed after the "railway mania". The introduction of guano causes a welfare increase that is around 5% larger in the scenario with less market integration. There is a very minor difference in what we might describe as the pure "gains from trade", the heterogeneity in the welfare benefits of building railroads based on the presence of fertilizer, but the direction of this effect points to similar forces. The magnitude of these differences is somewhat smaller than the ones from the simulation; this is mostly due to the fact that neither the baseline transport network nor the transport network after the "railway mania" approach the conditions of frictionless trade or near-autarky that the extremes in the simulation represented.[47] We therefore provide a novel demonstration of an important property of "converging spatial" technologies: they are most beneficial when markets are not integrated. Although the railways had other virtues, not least the large direct impact on welfare predicted by the model, the enhancement of the benefits of this new technology were not among them.

[47] We obtain similar, although somewhat weaker, results using a model extension where we include the FAO-GAEZ crop-specific productivity indices as additional parameters. It should be noted, however, that this augmented model does not outperform our version with just nitrogen deficiency in terms of its fit of observed parish rateable values.

7 Conclusion

In this paper, we have explored the effects of a new technology, guano fertilizer, on the distribution of economic activity across space. The exuberant farmers and publicists of the day were not entirely misplaced in their optimism about guano and the wave of related fertilizers that rapidly swept across the country. What they may not have realized, however, was that guano drove a substantial convergence in economic activity across space, "flattening the landscape" by making formerly heterogeneous locations more similar to each other.

Our results began by documenting the rapid diffusion of guano and its empirical success in raising agricultural productivity through a variety of field trials. We then showed that locations within England that we define as exogenously more constrained in their nitrogen endowments do indeed look different from places that are nitrogen-rich, growing a substantially different crop mix. In our main results, we showed that guano subsequently drove converge across space, reducing the specialization of agriculture. Consistent with narratives about the "high farming" era, we find that this change in land use was accompanied by increases in livestock rearing. Building on our interpretation of our results as demonstrating spatial convergence, we document that our results are drive by two types of places that were disadvantaged at baseline: parishes with relatively low yields, and parishes that were located far from major cities. We were also able to qualitatively verify our results with data on weekly grain sales in a panel of over 150 English towns during the same period.

Finally, we turned to a structural spatial model to explore the consequences of this new technology on welfare. Guano is a technology that was most beneficial in places that were disadvantaged by their natural endowments, and it is in those locations that principally benefited from the technology. However, given its nature as a "converging" technology that makes places more similar to each other, its welfare impacts were reduced by the major investments in transportation infrastructure that occurred in precisely the same years. Although guano fertilizers and the "Nitrogen Revolution" emerged during an era of industrialization and alongside revolutionary improvements in transportation, the impacts of this technology were qualitatively different in their effects on what economic activity was pursued across 19th century England. More broadly, the forces we have explored speak to what sorts of innovations it is most rewarding to pursue: in the past, when travel and transport were difficult, it would have been especially beneficial from an aggregate welfare perspective to raise the productivity of disadvantaged places. But in today's highly globalized world, our focus should instead shift to *diverging spatial* technologies that complement, instead of substitute for, the growing interconnectedness of the global economy.

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APPENDIX
for "The Origin of the Nitrogen Revolution"
by Matteo Ruzzante and Christopher W. A. Sims

A Data: Details

A.1 Additional Historical Data Sources

Trade Statistics. We digitize annual imports of guano from the UK Parliamentary Papers, in particular *An account of all guano imported into the United Kingdom in each of the years 1841 to 1850, inclusive, distinguishing the quantities imported from each country respectively*, PP 1851 (204) LIII, 309 and the annual *Accounts relating to trade and navigation, customs duties and tonnage of vessels* cf. PP 1851 (21) LIII, 1.

Agricultural Periodicals. To track the early diffusion of guano across space, we digitize all mentions of fertilizer in *The Farmer's Magazine* (accessed via Hathi Trust) between 1840-44 and manually geolocate locations where possible. To account in part for the selection into being mentioned in the magazine at all, we geolocate *all* location mentions in the 1839 issue, before the introduction of guano fertilizer, using the Claude.ai API with the prompt "Provide a list of the English towns, villages, and estates mentioned in the text along with their latitude and longitude." Based on verifying several cases of the LLM automatic geolocating, the exercise was quite accurate. The raw data is plotted in Figure A1, with locations mentioning the use of guano in blue and locations mentioned in the 1839 issue in brown, both plotted against a C:N ratio choropleth. We define a parish as being "mentioned" if there is at least one mention based on the relevant variable; it is possible for a parish to both have a recorded use of guano and a mention in 1839 and as such we cannot run a conventional balance test.

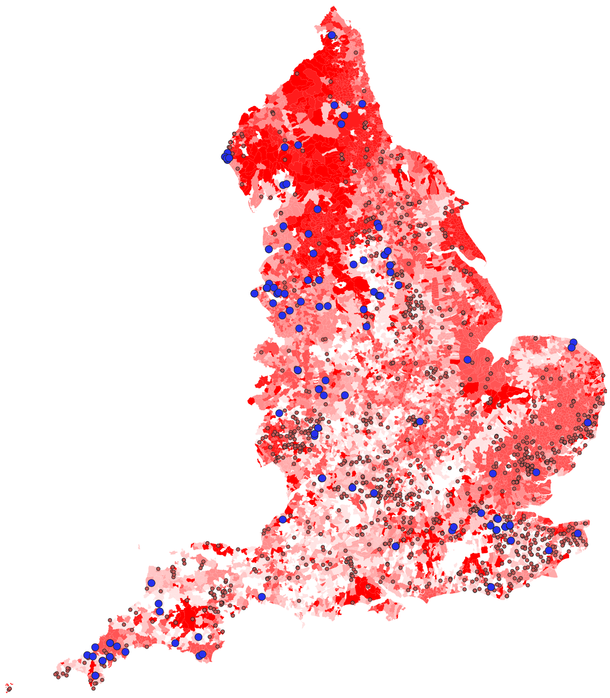


Figure A1. Guano vs. general mentions in *The Farmer's Magazine*

Rateable Values. As part of assessing the goodness-of-fit of our structural trade model, we rely on data from the UK Parliamentary Papers which reports the rateable or annual value of parishes for tax purposes in various years during the 19th century. Specifically, we digitize *Poor rates, &c. Return to an address of the Honourable the House of Commons, dated 21 February 1854*, PP 1854 (509) LVI, 1, which reports each parish's Annual Value of Real Property Assessed to the Property Tax in April 1815 and April 1843; and each parish's Rateable Value of Property Assessed to the Poor's Rate for the Year ended 25 March 1852. Overall, we match around 90% of the sample of parishes we use in the structural model estimation to their data on land values.

According to Stamp (1927), annual values outside the Metropolis (i.e. London) were defined as follows:

> The annual value of lands, tenements, hereditaments or heritages charged under Schedule A shall be understood to be the rent by the year at which the same are let at rackrent ... fixed by agreement withint ... seven years, or if not let at rackrent, then at the rackrent at which the same are worth to be let by the year.

That is, the annual value of a property represents the rackrent (market rent without any special dispensations) if the property was leased within the past seven years, or an imputed value otherwise.

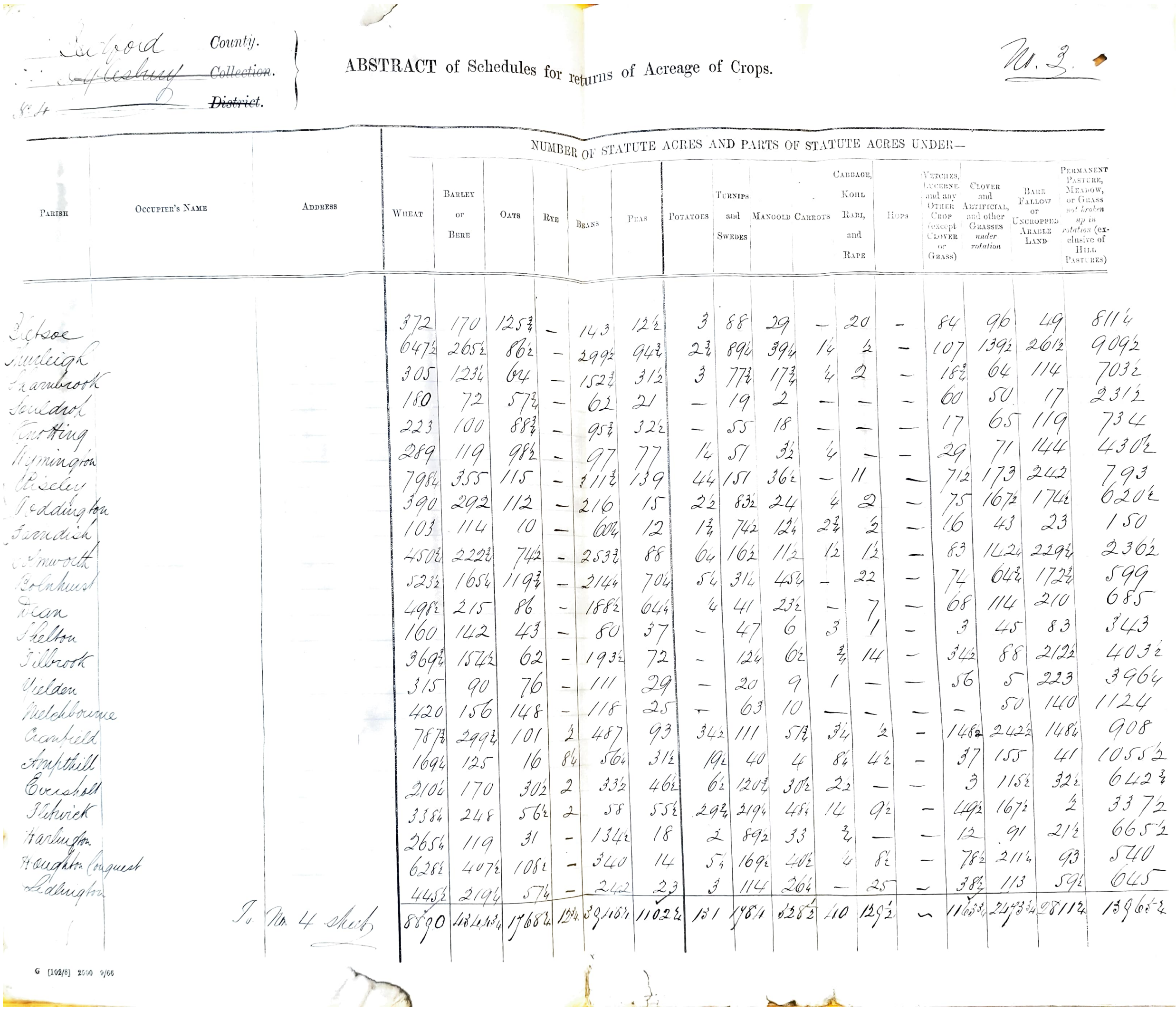
To derive the variable we use in the goodness-of-fit regression, we divide the annual value in 1843 by the area in acres listed as part of the return in the Parliamentary Papers.

A.2 Data Collection and Digitization

Handwritten Data. We systematically collect and digitize three agricultural census from the UK National Archives (series MAF 68). These data come in wide, consistently formatted tables, as the ones shown in Figures A2 and A3. The table entries are handwritten: therefore, we use a new software developed for automated recognition of such data, `Transkribus`. Our workflow proceeds in three steps: (i) table recognition, (ii) layout analysis, (iii) and text recognition. We trained the software with ground-truth data that we manually digitized until we reach a Character Error Rate of 5%. For 1866, we compile a large amount of effective "ground truth" data due to the use of antiquated ARP system for recording crop levels, which turned difficult to fully automate. For 1884, water damage for some counties (e.g., Figure A3) meant that we hand-corrected data at the National Archives.

Typewritten Data. We use `Amazon Textract`, a commonly-used machine learning service that automatically extracts text and layout elements. While training for particular use case is not available, Amazon Textract is very effective when tables are well formatted.

Figure A2. Sample 1866 Crops Return for Bedfordshire



Bedford County.
~~Aylesbury~~ ~~Collection~~.
No. 4 ~~District~~.

ABSTRACT of Schedules for returns of Acreage of Crops.

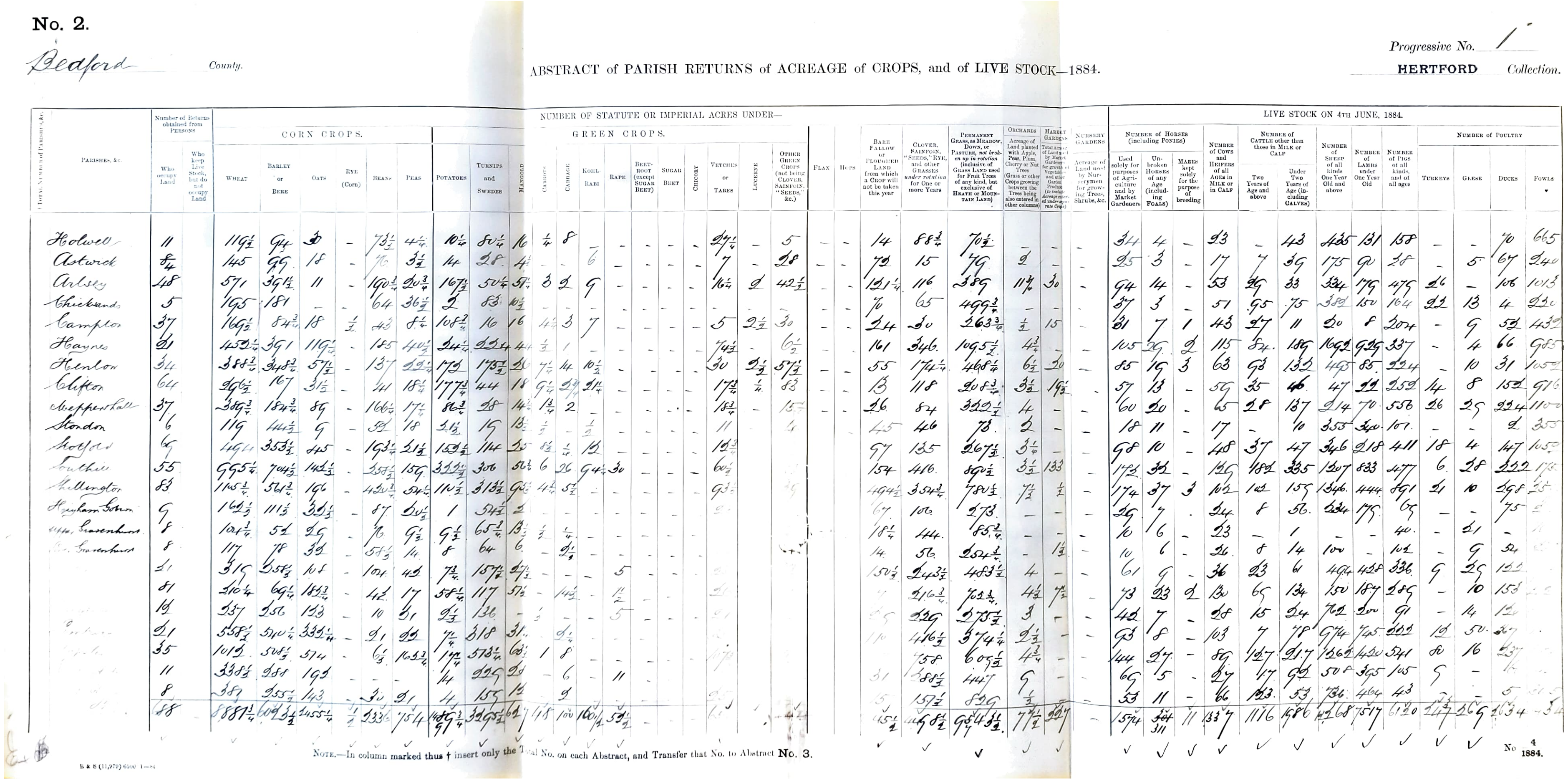
U. 3.

NUMBER OF STATUTE ACRES AND PARTS OF STATUTE ACRES UNDER—

Parish	Occupier's Name	Address	Wheat	Barley or Bere	Oats	Rye	Beans	Peas	Potatoes	Turnips and Swedes	Mangold	Carrots	Cabbage, Kohl Rabi, and Rape	Hops	Vetches, Lucerne, and any other Crop (except Clover or Grass)	Clover and Artificial, and other Grasses under rotation	Bare Fallow or Uncropped Arable Land	Permanent Pasture, Meadow, or Grass not broken up in rotation (exclusive of Hill Pastures)
Keysoe			372	170	125¾	–	143	12½	3	88	29	–	20	–	84	96	49	811¼
Thurleigh			647½	265½	86½	–	299½	94¾	2¾	89¼	39¼	1¼	½	–	107	139½	261½	909½
Sharnbrook			305	123¼	64	–	152¾	31½	3	77¾	17¾	¼	2	–	18¾	64	114	703½
Souldrop			180	72	57¾	–	62	21	–	19	2	–	–	–	60	50	17	231½
Knotting			223	100	88¾	–	95¾	32½	–	55	18	–	–	–	17	65	119	734
Wymington			289	119	98½	–	97	77	1¼	51	3½	¼	–	–	29	71	144	430½
Riseley			798¼	355	115	–	311¾	139	44	151	36½	–	11	–	71½	173	242	793
Podington			390	292	112	–	216	15	2½	83½	24	4	2	–	75	167½	174½	620½
Farndish			103	114	10	–	60¼	12	1¾	74½	12¼	2¾	½	–	16	43	23	150
Colmworth			450¼	222¾	74½	–	253¾	88	6¼	16½	11½	1½	1½	–	83	142¼	229¾	236½
Bolnhurst			523½	165¼	119¾	–	214¼	70¼	5¼	31¼	45¼	–	22	–	74	64¾	172¾	599
Dean			498½	215	86	–	188½	64¼	¼	41	23½	–	7	–	68	114	210	685
Shelton			160	142	43	–	80	37	–	47	6	3	1	–	3	45	83	343
Tilbrook			369¾	154½	62	–	193½	72	–	12¼	6½	¾	14	–	34½	88	212½	403½
Yielden			315	90	76	–	111	29	–	20	9	1	–	–	56	5	223	396¼
Melchbourne			420	156	148	–	118	25	–	63	10	–	–	–	–	50	140	1124
Cranfield			787¾	299¾	101	½	487	93	34½	111	57¾	3¼	½	–	148½	242½	148¼	908
Ampthill			169¼	125	16	8¼	56¼	31½	19½	40	4	8¼	4½	–	37	155	41	1055½
Eversholt			210¼	170	30½	2	33½	46½	6½	120¾	30½	2½	–	–	3	115½	32½	642¾
Flitwick			338¼	248	56½	2	58	55½	29¾	219¼	48¼	14	9½	–	49½	167½	½	337½
Harlington			265¼	119	31	–	134½	18	2	89½	33	¾	–	–	12	91	21½	665½
Houghton Conquest			628½	407½	108½	–	340	14	5¼	169½	40½	¼	8½	–	78½	211¼	93	540
Lidlington			445½	219¼	57¼	–	242	23	3	114	26¼	–	25	–	38½	113	59½	645
		To No. 4 sheet	8890	4341¾	1768¾	12¾	3916¼	1102¼	131	1784	528½	40	129½	–	1165¾	2473¾	2811¼	13965¼

G [102/8] 2500 9/66

Figure A3. Sample 1884 Census Return for Bedfordshire



No. 2.

Bedford County.

ABSTRACT of PARISH RETURNS of ACREAGE of CROPS, and of LIVE STOCK—1884.

Progressive No. 1

HERTFORD Collection.

Parishes, &c.	Who occupy Land	Wheat	Barley or Bere	Oats
Holwell	11	119½	94	30
Astwick	8	145	99	18
Arlsey	48	571	391½	11
Chicksands	5	195	181	
Campton	37	169½	84¾	18
Haynes	21	452½	391	119½
Henlow	34	388½	348¾	57½
Clifton	64	296½	167	31½
Meppershall	37	389¾	184¾	89
Stondon	6	119	44½	9
Shefford	69	49½	353½	45
Southill	55	995¼	704½	142½
Shillington	83	1145½	561½	196
Higham Gobion	9	162½	111½	32½
Upper Gravenhurst	8	104¾	51	29
Lower Gravenhurst	8	117	78	32

Note.—In column marked thus † insert only the Total No. on each Abstract, and Transfer that No. to Abstract No. 3.

No. 4 1884.

Notes: This is an example of a return that has been water-damaged; we supplement with additional close-up photos in these cases.

A.3 Variable Construction and Sample Selection

Variables based on geographic data.

Variables based on agricultural censuses.

- *Nitrogen-intensive crop acreage*: sum of acreage under wheat, barley, turnips, and potatoes
- *Nitrogen-fixing crop acreage*: sum of acreage under oats, peas, and beans
- *Total acreage*: sum of acreage under wheat, barley, turnips, and potatoes
- *Cows*: sum of cows and cattle of all ages
- *Horses*: sum of all types of horses (mares, foals, etc.)
- *Sheep*: sum of sheep and lambs

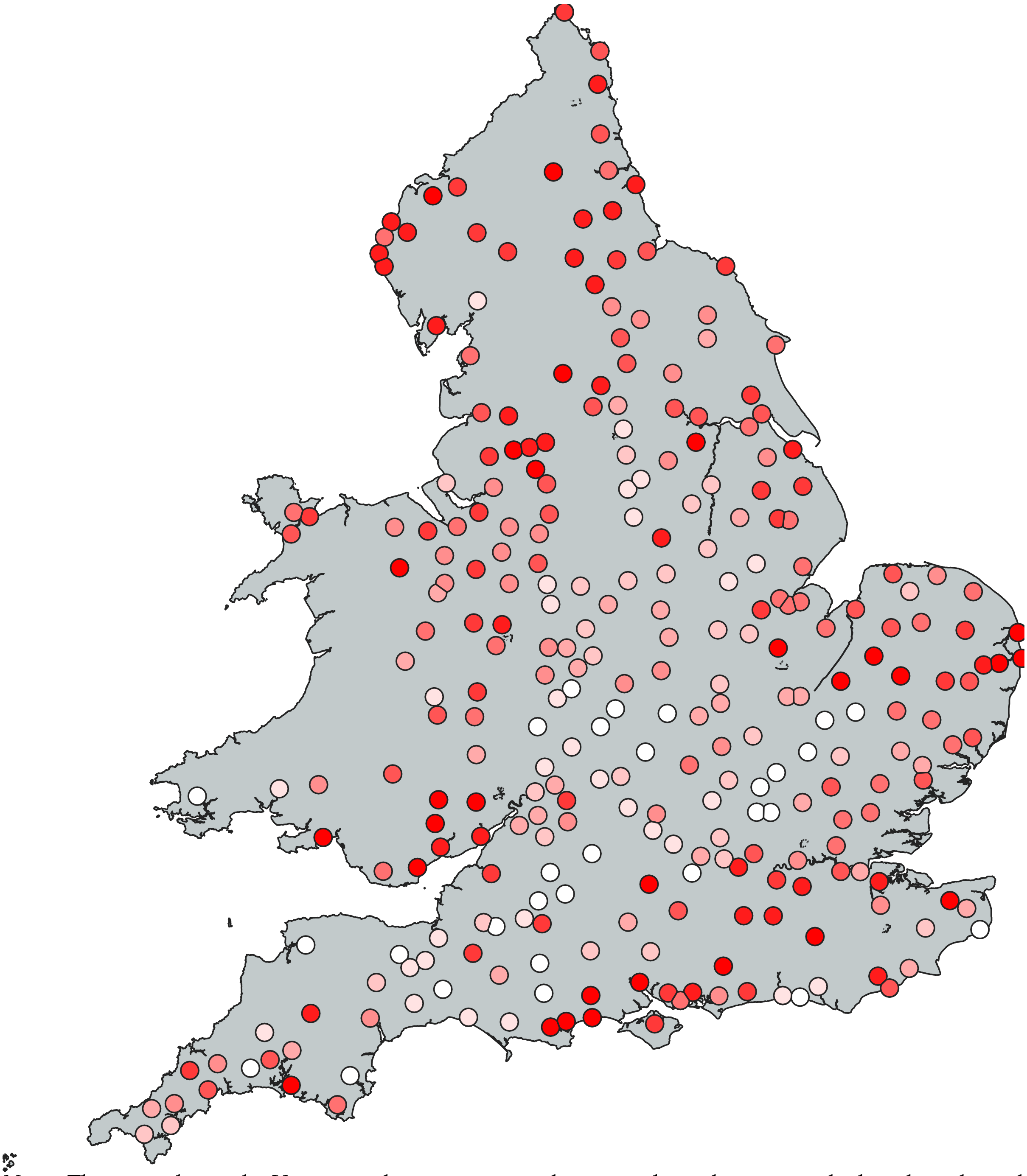
The overlap between crop and livestock data in 1866 is not perfect, because they were reported in separate sheets in the archival source. We drop parishes that only reported grass in 1836 as we do not consistently use grassland as part of our acreage variable as it is missing in 1801. We cap total acreage using the area of the I-CeM consistent parish.

Variables based on gain market data.

- *Sales Volumes of Nitrogen-Intensive Crops*: sum of sales of wheat, barley, and rye

We define the C:N ratio at the market town level as the average C:N ratio of cells within a Voronoi polygon around the city, which is capped at 5km, as shown in Figure A4.

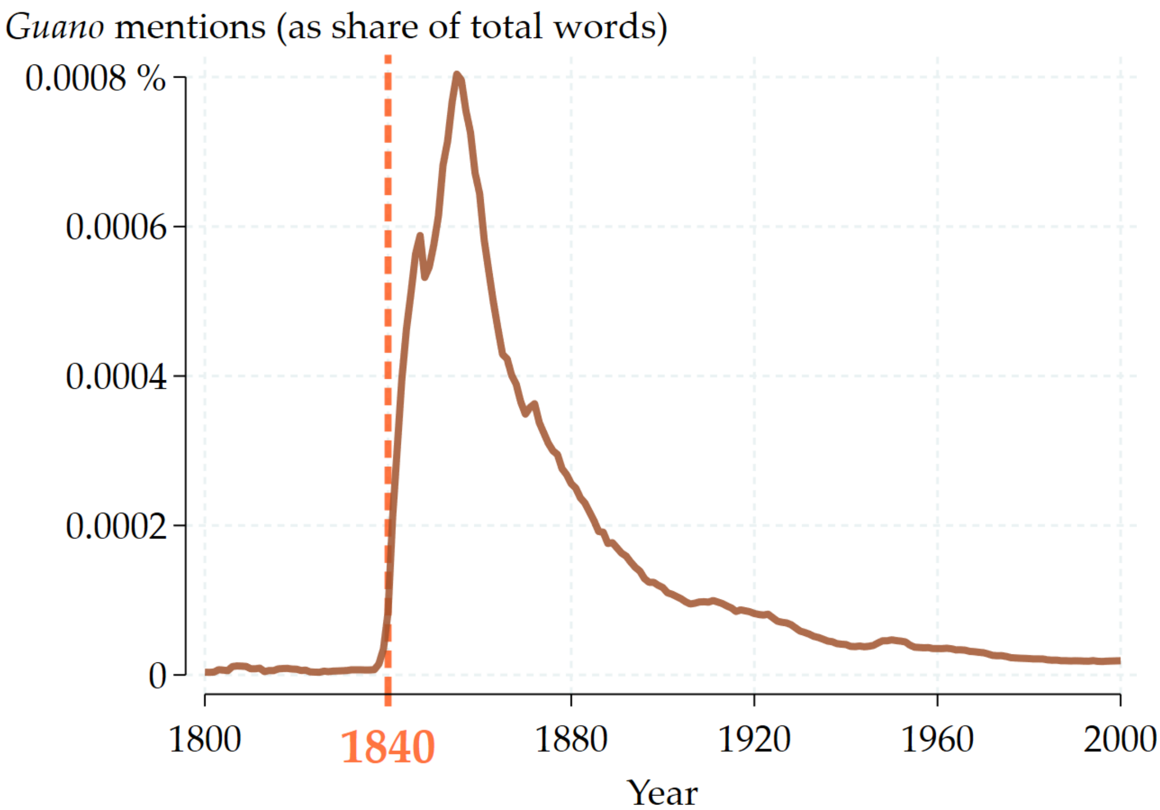
Figure A4. Voronoi Polygons for Market Towns



Notes: This map shows the Voronoi polygon corresponding to each market town, which is then clipped at 5km of distance. The average C:N ratio of the town's catchment area is represented by the shaded colour, with darker colours indicating higher values.

B Additional Results and Robustness

Figure B1. Frequency of "Guano" Mentions Since 1800



Notes: The brown line plots the number of times the word "guano" appeared in a given year relative to the entire body of words in the corpus of books (in English) published in that year, as available in *Google Books*. Data extracted from *Google Books Ngram Viewer* (generated in February 2020 – version 3).

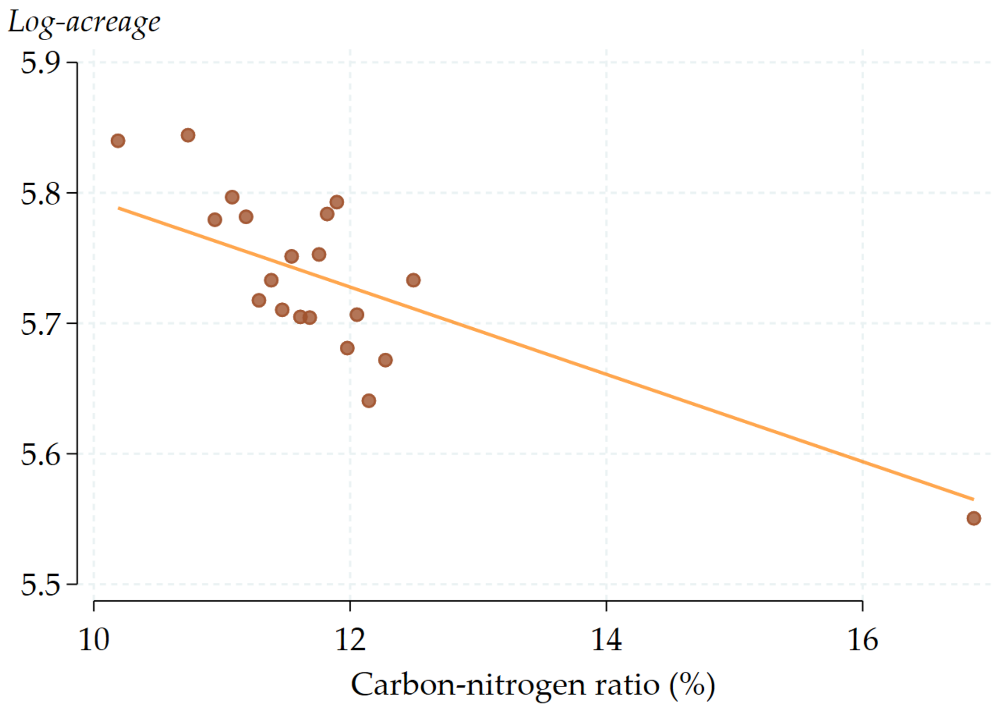
Table B1. Linear relationship between *median* nitrogen deficiency and crop acreage prior to the introduction of guano

	(1)	(2)	(3)	(4)	(5)
Log-acreage under nitrogen-intensive crops					
Carbon:**N**itrogen ratio (%)	-0.073***	-0.085***	-0.089***	-0.071***	
	(0.015)	(0.016)	(0.016)	(0.016)	
Carbon:**N**itrogen ratio above the sample median (0/1)					-0.143***
					(0.030)
Number of observations	7,305	7,304	7,304	7,304	7,304
Number of parishes	6,330	6,329	6,329	6,329	6,329
Adjusted R-squared	0.009	0.173	0.179	0.198	0.195
Log-acreage under nitrogen-light crops					
Carbon:**N**itrogen ratio (%)	0.137***	0.019	0.029*	0.020	
	(0.016)	(0.016)	(0.016)	(0.017)	
Carbon:**N**itrogen ratio above the sample median (0/1)					0.157***
					(0.046)
Number of observations	7,320	7,319	7,319	7,319	7,319
Number of parishes	6,347	6,346	6,346	6,346	6,346
Adjusted R-squared	0.192	0.295	0.301	0.305	0.305
County fixed effects		✓	✓	✓	✓
Soil heaviness fixed effects			✓	✓	✓
Crop suitability controls				✓	✓

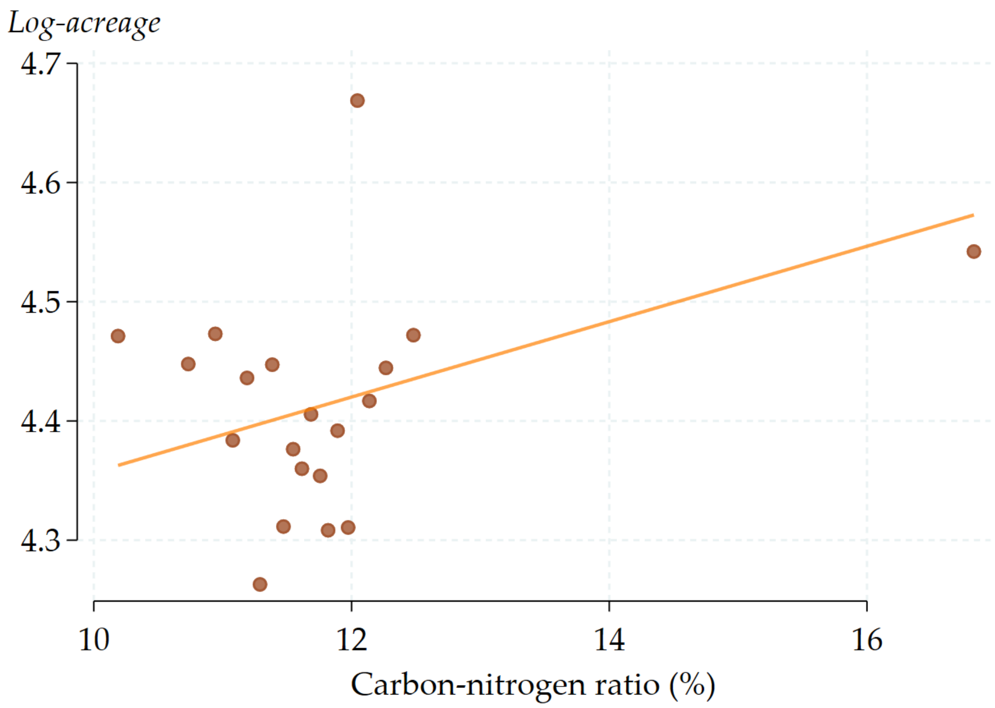
Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Sample: 1801 and 1836. All regressions are least squares with fixed effects and controls (indicated in the last three rows of the table) and standard errors clustered at the parish level (in parentheses).

Figure B2. Non-parametric relationship between crop acreage and *at-centroid* nitrogen deficiency prior to the introduction of guano

(a) Nitrogen-intensive crops



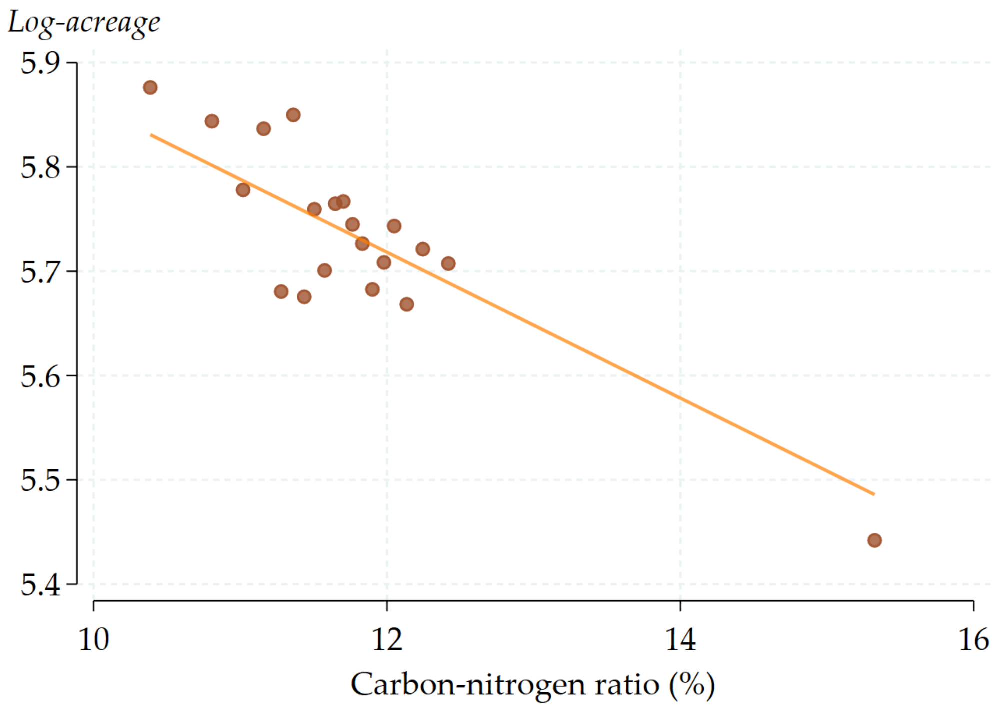
(b) Nitrogen-light crops



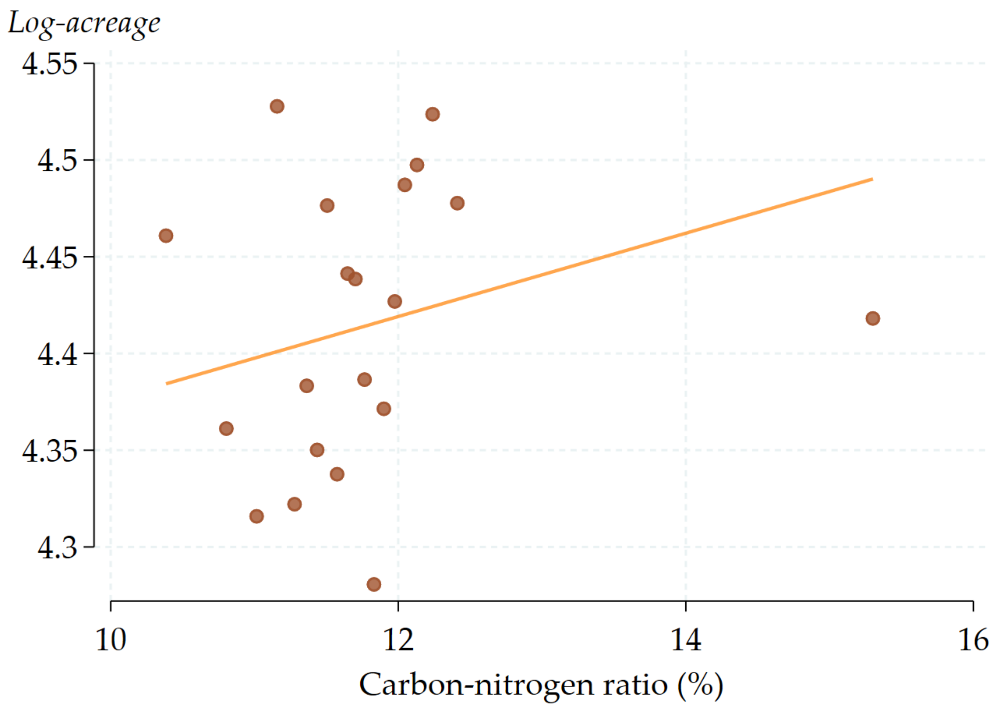
Notes: Binned scatterplots are obtained by grouping log-acreage (on the y-axis) and carbon-to-nitrogen ratio (on the x-axis) into twenty equal-sized bins. Binning is performed after residualizing both variables for county and soil heaviness fixed effects as well as potential yields of wheat, barley, peas and beans. The orange line plots a linear fit, i.e., the prediction for log-acreage on carbon-to-nitrogen ratio, estimated from a linear regression controlling for fixed effects and covariates.

Figure B3. Non-parametric relationship between crop acreage and *median* nitrogen deficiency prior to the introduction of guano

(a) Nitrogen-intensive crops

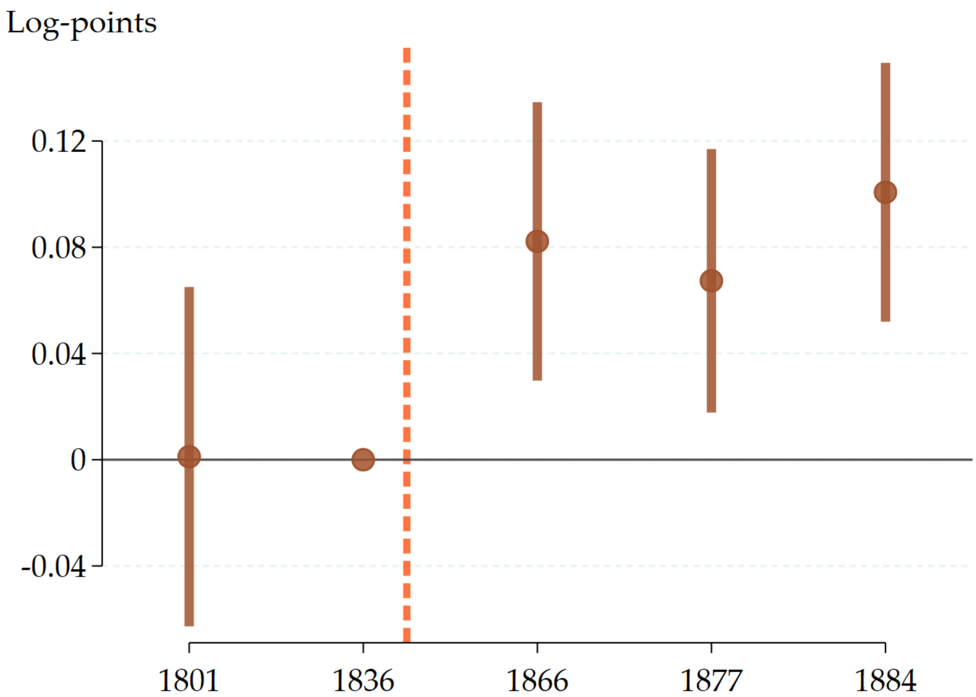


(b) Nitrogen-light crops



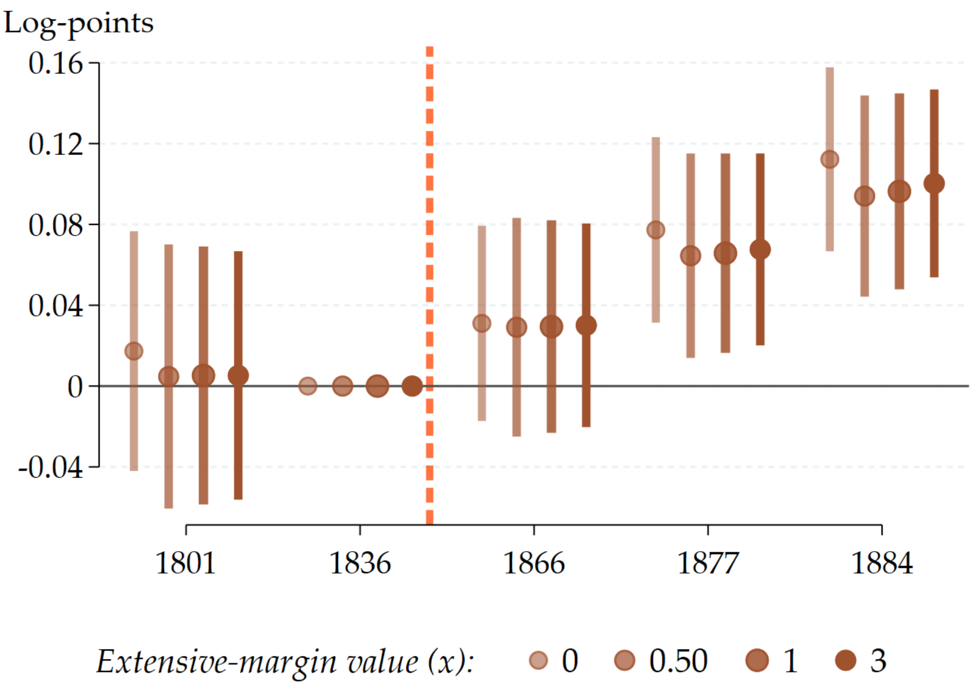
Notes: Binned scatterplots are obtained by grouping log-acreage (on the y-axis) and carbon-to-nitrogen ratio (on the x-axis) into twenty equal-sized bins. Binning is performed after residualizing both variables for county and soil heaviness fixed effects as well as potential yields of wheat, barley, peas and beans. The orange line plots a linear fit, i.e., the prediction for log-acreage on carbon-to-nitrogen ratio, estimated from a linear regression controlling for fixed effects and covariates.

Figure B4. Dynamic Effects on Nitrogen-Intensive Crop Acreage – Robustness to Exposure Measure



Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 2 with year and parish fixed effects. Standard errors clustered at the parish level. Unit of observation: parish $\times$ year. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Figure B5. Dynamic Effects on Nitrogen-Intensive Crop Acreage – Robustness to Explicit Calibration of Extensive Margin



Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 2 with year and parish fixed effects. Standard errors clustered at the parish level. Unit of observation: parish × year. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Table B2. Effect on crop allocation – Alternative estimation samples and spatial correlation

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
Whole sample (at least 3 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.010	0.061***	-0.117***	-0.332***
	(0.022)	(0.023)	(0.042)	(0.093)
p-values corrected for spatial correlation within				
25 km	0.745	0.032	0.049	0.003
50 km	0.811	0.126	0.109	0.005
100 km	0.838	0.126	0.152	0.003
200 km	0.079	0.000	.	0.000
400 km	0.000	0.000	0.000	0.000
Sample mean of the outcome variable	18,600	18,600	18,600	15,121
Sample mean of the explanatory variable	4,927	4,927	4,927	4,889
Number of observations	0.679	0.705	0.540	0.525
Almost-balanced panel (at least 4 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.047**	0.087***	-0.076*	-0.389***
	(0.021)	(0.023)	(0.046)	(0.101)
p-values corrected for spatial correlation within				
25 km	0.072	0.002	0.226	0.001
50 km	0.179	0.029	0.307	0.001
100 km	0.174	0.012	0.310	0.000
200 km	0.000	0.000	0.000	0.000
400 km	0.000	0.000	0.000	0.000
Sample mean of the outcome variable	15,250	15,250	15,250	12,566
Sample mean of the explanatory variable	3,780	3,780	3,780	3,774
Number of observations	0.699	0.710	0.558	0.534
Fully-balanced panel (5 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.082*	0.137***	-0.052	-0.319
	(0.046)	(0.050)	(0.092)	(0.194)
p-values corrected for spatial correlation within				
25 km	0.025	0.001	0.620	0.054
50 km	0.071	0.008	0.587	0.035
100 km	0.136	0.022	0.539	0.000
200 km	0.000	0.000	0.097	0.000
400 km	0.000	0.000	0.000	0.000
Sample mean of the outcome variable	2,529	2,529	2,529	2,020
Sample mean of the explanatory variable	514	514	514	514
Number of observations	0.707	0.698	0.468	0.486

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are Poisson pseudo maximum likelihood as in Equation 3 with year and county fixed effects. Standard errors (in parentheses) are clustered at the parish level. 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The coefficients approximate the percentage change in the count of the outcome variable.

Table B3. Effect on crop allocation – Median exposure

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
Whole sample (at least 3 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.016	0.083***	-0.125***	-0.334***
	(0.022)	(0.023)	(0.042)	(0.092)
Number of observations	18,600	18,600	18,600	15,121
Number of parishes	4,927	4,927	4,927	4,889
Adjusted R-squared	0.679	0.705	0.540	0.525
Almost-balanced panel (at least 4 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.058***	0.107***	-0.070	-0.344***
	(0.021)	(0.023)	(0.046)	(0.101)
Number of observations	15,250	15,250	15,250	12,566
Number of parishes	3,780	3,780	3,780	3,774
Adjusted R-squared	0.699	0.710	0.558	0.534
Fully-balanced panel (5 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.083*	0.130***	-0.144	-0.260
	(0.046)	(0.050)	(0.091)	(0.194)
Number of observations	2,529	2,529	2,529	2,020
Number of parishes	514	514	514	514
Adjusted R-squared	0.707	0.697	0.468	0.485

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are Poisson pseudo maximum likelihood as in Equation 3 with year and county fixed effects. Standard errors (in parentheses) are clustered at the parish level. 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The coefficients approximate the percentage change in the count of the outcome variable.

Table B4. Effect on crop allocation – Poisson pseudo maximum likelihood regression

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
Whole sample (at least 3 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.052**	0.117***	-0.066*	-0.156*
	(0.023)	(0.022)	(0.035)	(0.090)
Number of observations	18,600	18,597	18,592	14,194
Number of parishes	4,927	4,926	4,924	4,587
Pseudo R-squared	0.817	0.828	0.737	0.703
Almost-balanced panel (at least 4 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.060**	0.125***	-0.073*	-0.252***
	(0.024)	(0.024)	(0.038)	(0.088)
Number of observations	15,250	15,250	15,250	11,871
Number of parishes	3,780	3,780	3,780	3,570
Pseudo R-squared	0.825	0.830	0.745	0.694
Fully-balanced panel (5 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.060	0.133***	-0.101	-0.043
	(0.041)	(0.043)	(0.070)	(0.107)
Number of observations	2,529	2,529	2,529	1,950
Number of parishes	514	514	514	496
Pseudo R-squared	0.829	0.827	0.723	0.681

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are Poisson pseudo maximum likelihood as in Equation 3 with year and county fixed effects. Standard errors (in parentheses) are clustered at the parish level. 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The coefficients approximate the percentage change in the count of the outcome variable.

Table B5. Effect on crop allocation – Controlling for region × year dummies

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
Whole sample (at least 3 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.027	0.051**	-0.131***	-0.285***
	(0.021)	(0.023)	(0.041)	(0.093)
Number of observations	18,600	18,600	18,600	15,121
Number of parishes	4,927	4,927	4,927	4,889
Adjusted R-squared	0.700	0.722	0.569	0.559
Almost-balanced panel (at least 4 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.042**	0.056**	-0.114**	-0.348***
	(0.021)	(0.023)	(0.046)	(0.106)
Number of observations	15,250	15,250	15,250	12,566
Number of parishes	3,780	3,780	3,780	3,774
Adjusted R-squared	0.714	0.726	0.580	0.559
Fully-balanced panel (5 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.049	0.088*	-0.005	-0.275
	(0.047)	(0.050)	(0.096)	(0.202)
Number of observations	2,529	2,529	2,529	2,020
Number of parishes	514	514	514	514
Adjusted R-squared	0.732	0.725	0.475	0.499

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are least squares as in Equation 3 with year and county fixed effects as well as controlling for wheat suitability interacted with year dummies. Standard errors (in parentheses) are clustered at the parish level. 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Table B6. Effect on crop allocation – Controlling for wheat suitability × year dummies

	(1)	(2)	(3)	(4)
Outcome:	*Total acreage*	*Nitrogen-intensive crops*	*Nitrogen-light crops*	*Fallow land*
Whole sample (at least 3 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.020	0.064***	-0.097**	-0.329***
	(0.021)	(0.022)	(0.041)	(0.091)
Number of observations	18,600	18,600	18,600	15,121
Number of parishes	4,927	4,927	4,927	4,889
Adjusted R-squared	0.681	0.706	0.548	0.533
Almost-balanced panel (at least 4 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.048**	0.084***	-0.069	-0.395***
	(0.021)	(0.023)	(0.046)	(0.100)
Number of observations	15,250	15,250	15,250	12,566
Number of parishes	3,780	3,780	3,780	3,774
Adjusted R-squared	0.701	0.712	0.562	0.539
Fully-balanced panel (5 waves)				
High **C**arbon:**N**itrogen ratio × Post-1840	0.077*	0.127***	-0.046	-0.285
	(0.046)	(0.049)	(0.092)	(0.193)
Number of observations	2,529	2,529	2,529	2,020
Number of parishes	514	514	514	514
Adjusted R-squared	0.709	0.702	0.468	0.494

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are least squares as in Equation 3 with year and county fixed effects as well as controlling for wheat suitability interacted with year dummies. Standard errors (in parentheses) are clustered at the parish level. 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Table B7. Effect on livestock – Median exposure

	(1)	(2)	(3)
Outcome:	*Cows*	*Horses*	*Sheep*
Almost-balanced panel			
High **C**arbon:**N**itrogen ratio × Post-1840	0.217**	0.404***	0.101
	(0.096)	(0.149)	(0.149)
Number of observations	19,615	15,549	19,615
Number of parishes	6,391	7,501	6,391
Adjusted R-squared	0.632	0.566	0.489
Fully-balanced panel			
High **C**arbon:**N**itrogen ratio × Post-1840	0.170	0.395***	-0.056
	(0.113)	(0.153)	(0.175)
Number of observations	1,768	13,329	1,768
Number of parishes	442	6,391	442
Adjusted R-squared	0.599	0.559	0.416

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are least squares as in Equation 3 with fixed effects (indicated in the last three rows of the table) as well as All regressions are least squares as in Equation 3 with year and county fixed effects, controlling for wheat suitability interacted with year dummies, and standard errors clustered at the parish level (in parentheses). 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Table B8. Effect on livestock – Alternative estimation samples

	(1)	(2)	(3)
Outcome:	*Cows*	*Horses*	*Sheep*
Almost-balanced panel			
High **C**arbon:**N**itrogen ratio × Post-1840	0.169*	0.289**	0.023
	(0.089)	(0.131)	(0.132)
Number of observations	19,615	15,549	19,615
Number of parishes	6,391	7,501	6,391
Adjusted R-squared	0.632	0.565	0.489
Fully-balanced panel			
High **C**arbon:**N**itrogen ratio × Post-1840	0.187*	0.284**	0.041
	(0.107)	(0.133)	(0.157)
Number of observations	1,768	13,329	1,768
Number of parishes	442	6,391	442
Adjusted R-squared	0.599	0.558	0.416

Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are least squares as in Equation 3 with fixed effects (indicated in the last three rows of the table) as well as All regressions are least squares as in Equation 3 with year and county fixed effects, controlling for wheat suitability interacted with year dummies, and standard errors clustered at the parish level (in parentheses). 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

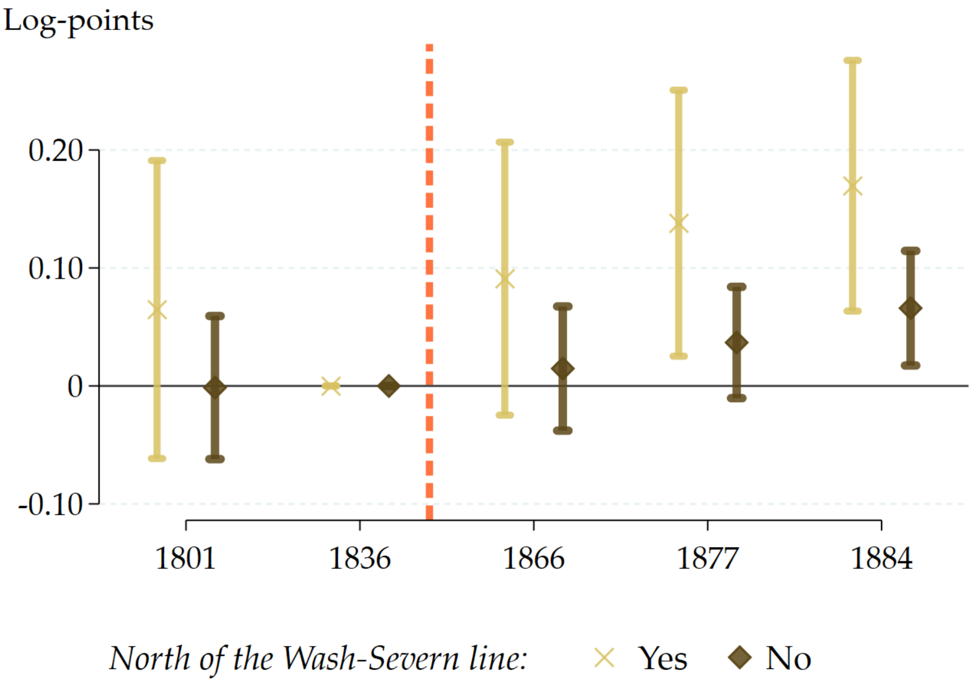
Table B9. Effect on livestock – Controlling for wheat suitability × year dummies

	(1)	(2)	(3)
Outcome:	*Cows*	*Horses*	*Sheep*
Whole sample			
High **C**arbon:**N**itrogen ratio × Post-1840	0.170**	0.291**	0.092
	(0.086)	(0.131)	(0.131)
Number of observations	24,911	15,549	24,911
Number of parishes	9,039	7,501	9,039
Adjusted R-squared	0.624	0.567	0.529
Whole sample			
High **C**arbon:**N**itrogen ratio × Post-1840	0.169*	0.291**	0.021
	(0.088)	(0.131)	(0.132)
Number of observations	19,615	15,549	19,615
Number of parishes	6,391	7,501	6,391
Adjusted R-squared	0.634	0.567	0.492
Balanced panel			
High **C**arbon:**N**itrogen ratio × Post-1840	0.196*	0.284**	0.038
	(0.106)	(0.133)	(0.159)
Number of observations	1,768	13,329	1,768
Number of parishes	442	6,391	442
Adjusted R-squared	0.600	0.560	0.416

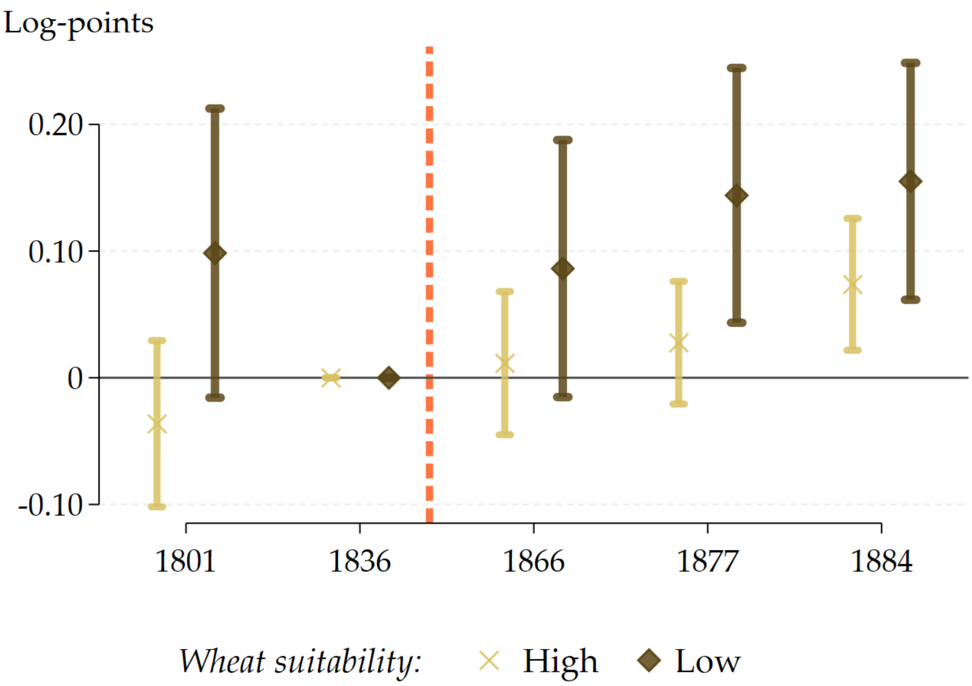
Notes: *Significant at 10%. **Significant at 5%. ***Significant at 1%. Unit of observation: parish × year. Estimation sample specified in the panel header. 'Fully-balanced panel' contains all parishes that are consistently observed in all the five waves of data. All regressions are least squares as in Equation 3 with fixed effects (indicated in the last three rows of the table) as well as All regressions are least squares as in Equation 3 with year and county fixed effects, controlling for wheat suitability interacted with year dummies, and standard errors clustered at the parish level (in parentheses). 'High carbon-to-nitrogen ratio' is a binary variable equal to one if the carbon-to-nitrogen ratio of the parish is above the sample median. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

Figure B6. Heterogeneous Dynamic Effects on Nitrogen-Intensive Crop Acreage

(a) By North-South Separation



(b) By Wheat Suitability



Notes: Event-study estimates with 90 percent confidence interval based on least squares regressions as in Equation 2 with year and parish fixed effects. Standard errors clustered at the parish level. Unit of observation: parish $\times$ year. The outcomes are expressed in natural logarithm so that coefficients can be interpreted in terms of percentage change.

C Model Calculations and Robustness

Consumption Shares. The structure of the Eaton-Kortum model makes it such that consumption shares do not have a large impact on the model solution, as in the aggregate equal land is devoted to each crop in equilibrium (i.e., in a model with six crops, each parish will on average devote 1/6 of its land to each crop, regardless of the consumption weight). For example, the consumption share has no impact on any model fundamentals in a symmetric 2×2 economy with frictionless trade, which is solved with the single market clearing equation:

$$rL_o = (\pi^1_{oo}\mu_1 + \pi^2_{oo}\mu_2)rL_o + (\pi^1_{od}\mu_1 + \pi^2_{od}\mu_2)L_d$$

Noting that $\pi^k_{oo} = \pi^k_{od} = \pi$ due to frictionless trade and symmetry, μ_k is completely eliminated from the expression. One corollary of this is that it is impossible to generate *aggregate specialization* in the EK model; if one location specializes in a certain crop, then that means the other location must specialize in a different crop–they cannot both "specialize" in a crop that is in relatively high demand. Consumption shares have a much more direct impact on welfare, however, as they determine the relative weight that is placed on the different crops in the real income calculation.

We estimate consumption shares from the data as follows. For the crops of wheat, barley, oats, and peas/beans, we are able to use data from the *London Gazette*. Using a random sample of consumption shares for London in the pre-period (i.e. before 1840), we obtain that out of the four crops the average consumption share is: wheat=0.335, barley=0.154, oats=0.426, beans=0.083. It remains to estimate the consumption shares of turnips and potatoes, the two other major crops we consistently include in our analysis. In 1841, the mayor of Manchester, William Neild, read a paper to the Statistical Section of the British Association which shows the household expenditures of a set of 19 families living in Manchester and its suburb of Dukinfield (Neild, 1842). On average, the expenditure shares on food items (out of total expenditure) were as follows:

Variable	Obs	Mean	Std. Dev.	Min	Max
Flour & bread	19	25.19	8.51	12.4	39.1
Meat	19	12.61	6.60	0	31.2
Bacon	19	2.77	3.11	0	10
Ham	19	0.09	0.39	0	1.7
Oatmeal	19	4.37	10.20	0	45.3
Butter	19	7.51	2.75	0	11.4
Eggs	19	0.69	1.03	0	3
Milk	19	6.18	3.41	1.1	15.2
Potatoes	19	5.71	3.11	1.7	13
Cheese	19	2.12	1.75	0	5.3

Table B10. Summary statistics on expenditure shares

Taking the flour & bread line item as roughly correlating to wheat and barley consumption, we obtain that the potato expenditure share should be around 22.7% of the expenditure share of wheat and barley from the *London Gazette*. We assume that turnips were used as an input into the production of dairy and beef products, as they were primarily fed to cattle but not other livestock (Trow-Smith, 2013). However, the challenge in this case is that cattle could also be raised on grassland; turnips were not the only crop they could be fed on. The consumption of dairy and beef products is given by the sum of Meat, Butter, Milk, and Cheese, which totals 28.4% (and thus is slightly more than the amount spent on Flour & bread). Our baseline assumption is that half of this total reflects the effective consumption share on turnips (and half on grass), although we show robustness to different assumptions.

The vector μ for our primary specification therefore is: Wheat (0.242), Barley (0.111), Oats (0.308), Beans (0.060), Potatoes (0.080), Turnips (0.199).