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Agrarian transformations, climate change and energy. A study of the impact of 17th and 18th century climate change on the Agricultural Revolution and the onset of economic growth in England

Transformaciones agrarias, cambio climático y energía. Un estudio sobre el impacto del cambio climático de los siglos XVII y XVIII en la Revolución Agrícola y los inicios del crecimiento económico de Inglaterra

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Agrarian transformations, climate change and energy. A study of the impact of 17th and 18th century climate change on the Agricultural Revolution and the onset of economic growth in England

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Martínez-González, J.L. & Francisco J. Beltrán Tapia (2019). Revisiting Allen's nitrogen hypothesis from a climate perspective (1645-1740). *Documentos de Trabajo de la Sociedad Española de Historia Agraria 1902*, Sociedad Española de Historia Agraria. http://repositori.uji.es/xmlui/bitstream/handle/10234/182881/DT-SEHA%201902.pdf?sequence=1&isAllowed=y

Martínez González, J.L. (2019). High Wages or Wages for Energy? An Alternative View of The British Case (1645-1700). *Working Papers 0158*, *European Historical Economics Society* (EHES). http://www.ehes.org/EHES_158.pdf

Another working paper (1) was the basis for a journal publication:

Martínez-González, J.L. (2016). Building an English wheat annual series in an intriguing era (1645-1761): Methodology, Challenges and Opportunities. A first assessment from the relationship between Landrace seeds and the Agrarian Revolution. *Documentos de Trabajo núm. 1613* (DT-AEHE), Asociación Española de Historia Económica, https://EconPapers.repec.org/RePEc:ahe:dtaehe:1613.

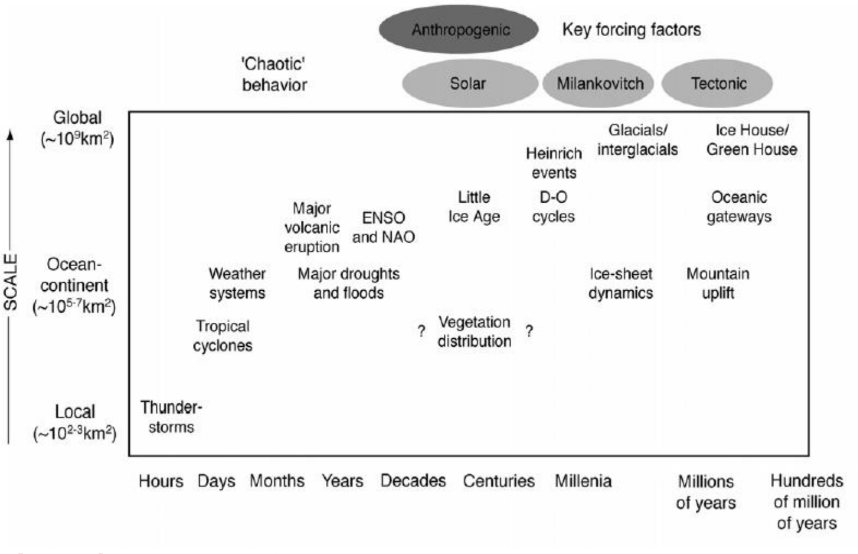
Chapter 0. Introduction.

1. Objetivo y motivación.

Durante los siglos XVII y XVIII tuvieron lugar en Inglaterra cambios decisivos para comprender los orígenes de uno de los hitos del desarrollo económico contemporáneo: la Revolución Industrial. La primera transición de una economía orgánica (basada en la captación de energía solar a través de la fotosíntesis), a otra centrada en el consumo de combustibles fósiles (Wrigley, 1991; Allen, 2009), puso en marcha un crecimiento continuado del producto por habitante, origen de la actual crisis climática global (Malm, 2016).

El propósito de esta Tesis Doctoral es precisamente estudiar los vínculos económicos y sociales entre el clima, la energía y la economía de Inglaterra en las etapas iniciales de aquellos trascendentales cambios acaecidos durante el período conocido como el "Mínimo de Maunder" (1645-1715), que fue el más frío de la Pequeña Edad de Hielo (*Little Ice Age* o LIA; Fig. 0), y la etapa inmediatamente posterior de ascenso de la temperatura (1715-1750)[1]. Este estudio propone considerar los factores climáticos como actores presentes en aquellos procesos, y en particular los efectos, directos e indirectos sobre la economía agraria, y la economía en general. También se exploran los diversos procesos evolutivos de adaptación que tuvieron lugar en esa etapa, dado que algunas de las respuestas sociales y técnicas que emergieron entonces (p.e. la Revolución Agrícola) marcarían las diferencias de Inglaterra respecto a los demás países y regiones competidoras de la Europa continental.

Figura 0. Dimensión temporal y espacial de la LIA dentro de los distintos cambios del clima habidos en la Tierra.



Fuente: Maslin & Christensen (2007).

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[1] Este trabajo no pretende hacer del Mínimo de Maunder la gran causa del enfriamiento. No está claro que la actividad solar fuera el factor decisivo en aquel endurecimiento del clima. Otras fuerzas como la actividad volcánica podrían haber sido especialmente importantes (Henry, 2020).

Realizar una Tesis Doctoral en Historia Económica sobre Inglaterra desde la Universidad de Barcelona con el formato de publicaciones no ha sido una tarea fácil. En cierto sentido, podría considerarse una temeridad. La bibliografía es inmensa, el nivel de exigencia es muy elevado, y todavía más para un aspirante a investigador "extranjero" cuya lengua nativa no es el inglés y su ocupación principal se sitúa, por ahora, fuera del ámbito académico (aunque sea profesor asociado). A ello debemos añadir la dificultad de publicar artículos en las revistas de referencia sobre un país y un tema tan estudiado y debatido, y con los máximos especialistas en liza. Por último, a los estudiantes de doctorado se nos aconseja, con muy buen criterio, acotar al máximo nuestro objeto de estudio, una estrategia que me ha costado seguir en algunas ocasiones, dada la transversalidad del cambio climático, que no entiende de ciencias estancas ni convencionalismos. Todas estas circunstancias, unidas al hecho de tener que realizar mi investigación a tiempo parcial compatibilizando el doctorado con trabajos precarios y responsabilidades añadidas, explican que el proceso de maduración y redacción se haya alargado más de lo inicialmente previsto.

Siempre ha estado presente en mí una fuerza interior que me impulsaba a conocer y comprender la historia bajo diferentes perspectivas. Una energía rebelde, bastante inmune a las convenciones de mi educación, formación y experiencias personales. Desde muy joven me preguntaba que había detrás de los fenómenos de largo alcance. ¿Cómo aparecían, se desarrollaban y declinaban? Quería entender la evolución de la sociedad y, dentro de ésta, comprender los ciclos económicos desde un punto de vista evolutivo, pero que también integrara la historia de la Tierra. ¿Por qué ocurrían esas trayectorias? ¿Qué las hacía diferentes o similares? ¿Había elementos comunes con independencia de su cronología o geografía? ¿Qué podemos aprender de todo eso para nuestro presente? Uno de los motores de esta curiosidad era la angustia personal de saber que todas las personas tenemos un final. El hecho de saber que todas formamos parte no solo de la historia humana, sino también de la evolución de la Tierra, daba sentido a mi vida.

En los años noventa del siglo XX, mientras estudiaba por la mañana en la Facultad de Economía de la Universidad de Barcelona, trabajaba por la tarde en una empresa de alimentos orgánicos. Era entonces un sector muy nuevo y pionero, de gente muy implicada con la Naturaleza y el Medio Ambiente. Como contrapartida, en la Universidad encontré un enfoque más racional y científico, aunque algo alejado del mundo real. En la asignatura de Historia del Pensamiento Económico y en una visita al Trinity College de Dublín, me llamó la atención la teoría de los ciclos solares y los precios del trigo de Stanley Jevons. Por la misma época, estudiando modelos econométricos con un nuevo profesor llamado Jordi Suriñach –quien es ahora Director del Departamento de Econometría y nos acompaña como coautor en uno de los capítulos—, cayó también en mis manos un artículo que utilizaba una serie de manchas solares y la relacionaba con series del PIB, como un ejemplo de relación espuria entre variables. El artículo me produjo un cierto desasosiego. Me quedé con la pregunta de si, una vez más, no se estaría negando a la Naturaleza el papel que le correspondía, y que, debido a la compartimentación académica de las diversas áreas de conocimiento, las ciencias sociales se estaban convirtiendo en algo poco práctico y lejano de la realidad de nuestro planeta entendida en clave biológica y ambiental.

En 1993 me matriculé en el Doctorado de Historia Económica de la Universidad de Barcelona. En aquel entonces tenía a Jordi Nadal como referente, que nos reunía en una pequeña sala de investigación de la biblioteca de la facultad. Recuerdo también a los profesores Carles Sudrià (UB) y Ramon Garrabou (UAB), el segundo dando alguna clase en un sindicato de Barcelona, o a Alfonso Herranz como compañero. Empecé a trabajar sobre ciclos de innovación, para lo cual establecí relación con un becario llamado Patricio Saiz, que estaba poniendo en orden las reales cédulas de invención del siglo XIX. Sin embargo, en aquel momento aplacé el doctorado por varias razones, algunas de ellas personales. También tuvo cierto peso el hecho de que en aquel entonces el Departamento de Historia Económica estaba muy centrado en la Historia Industrial. Aún había poco espacio para estudiar la dinámica de los ciclos histórico-económicos, el crecimiento económico a largo plazo, o para proyectos que conectaran economía y naturaleza. Mientras la vida iba pasando, seguía leyendo por libre lo que me apasionaba. Finalmente, en 2011 encontré que las cosas habían evolucionado. Había grupos que estudiaban la historia ambiental y su relación con el crecimiento económico a largo plazo, como los profesores Enric Tello, Gabriel Jover o Alfonso Herranz, y muchos más. Sentí que había llegado la hora de hacer algo, poner en movimiento mis intuiciones, y ver hasta dónde podía llegar. Así que hice el Máster de Historia Económica, una gran y recomendable experiencia, y ahora este doctorado.

2. Cambio climático, adaptación y energía.

El cambio climático se define como “la variación del estado del clima identificable en las variaciones del valor medio y/o en la variabilidad de sus propiedades, que persiste durante largos períodos de tiempo, generalmente decenios o períodos más largos”[2]. En el planeta Tierra se han producido variaciones climáticas mucho más intensas que las reflejadas en los escenarios más pesimistas del “calentamiento global” actual (en los últimos tres millones de años ha habido 41 glaciaciones). Es ya un hecho irrebatible que la actividad humana ha contribuido a modificar de forma creciente los ciclos autorregulados de la Naturaleza. La evolución del nivel de concentración de gases de efecto invernadero en la atmósfera, estimada por los paleoclimatólogos, muestra que entre 10.000 y 8.000 años atrás el clima ya comenzó a recibir una influencia antrópica con la aparición de la agricultura y la ganadería. Es probable que las grandes catástrofes demográficas (como la Peste Negra del siglo XIV en Europa o la brutal mortalidad en las comunidades indígenas americanas al tomar contacto con la civilización europea en el siglo XVI), fueran factores causales de la Pequeña Edad de Hielo (1350-1850), junto con otros como

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[2] IPCC, 2013: Glosario [Planton, S. (ed.)]. En: *Cambio Climático 2013. Bases físicas. Contribución del Grupo de trabajo I al Quinto Informe de Evaluación del Grupo Intergubernamental de Expertos sobre el Cambio Climático* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex y P.M. Midgley (eds.)]. Cambridge University Press, Cambridge.

la variación de la actividad solar y volcánica (Camenisch & Rohr, 2018; Koch et al., 2019).

En este punto, es importante distinguir entre clima (variaciones de los indicadores climáticos a largo plazo) y tiempo atmosférico (*weather*, variaciones de los indicadores meteorológicos a corto plazo). En años recientes ha aparecido un buen número de investigaciones que estiman el impacto del *weather* a través de una serie de variables socioeconómicas (Dell et al. 2014). La ventaja de analizar los impactos del *weather* es que éste es aleatorio desde una perspectiva económica y, por tanto, se pueden identificar muy bien. Los efectos de un *weather shock* no son iguales a los derivados del cambio climático. Los primeros son más grandes porque sólo permiten una adaptación inmediata, por lo que ésta es mucho más limitada[3]. En otras palabras, los *weather shocks* estiman la elasticidad a corto plazo y el cambio climático la elasticidad a largo plazo. Esto hace poco recomendable extrapolar los efectos de la meteorología a los del cambio climático, porque es muy poco probable que lleve a resultados con cierta permanencia. Esta distinción la aplicamos en nuestros modelos econométricos, como se podrá comprobar en los capítulos siguientes.

Aquí entra en juego un segundo concepto, el de las adaptaciones. Son éstas (o su ausencia) las que suavizan o intensifican los efectos permanentes de un cambio climático. Como se podrá observar en los próximos capítulos, este concepto tiene un carácter central en esta Tesis Doctoral. Este argumento entronca con toda una tradición científica en la historia de nuestra especie. La capacidad adaptativa humana (o su ausencia) puede entenderse como una respuesta social cooperativa a la presión climático-ambiental y a las necesidades de energía (Bowles & Gintis, 2011; Sigaut, 2013; Gilliagan, 2018). Por ejemplo, las variaciones climáticas han sido utilizadas para explicar por qué y cuándo evolucionaron las especies de homínidos y finalmente migraron fuera de África Oriental (Maslin & Christensen, 2007; Maslin et al., 2014; Potts & Faith, 2015), o para comprender el tránsito de la sociedad recolectora-cazadora a la primera agricultura neolítica Natufiana (Belfer-Cohen, 1991; Bar-Yosef, 1998). En esta cuestión hay una dificultad añadida. Si las adaptaciones tienen éxito, los resultados econométricos dejan de percibir estos impactos y es difícil demostrar de forma directa que tengan que ver con un cambio del clima.

Los procesos adaptativos humanos, y el ingenio que requirieron y desarrollaron, estaban intrínsecamente ligados con la necesidad de conservar o incrementar la dotación de energía disponible. Precisamente por eso la energía es el tercer concepto clave de esta Tesis Doctoral. Desde un punto de vista físico, la energía es “el potencial de realizar trabajo o proporcionar calor, y el trabajo es lo que se obtiene cuando algo se mueve, y la cantidad de trabajo es el producto de la fuerza aplicada y la distancia recorrida” (Common & Stagl, 2005). En economía, “energía es la capacidad de realizar un trabajo útil para el

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[3] Aunque también cabe decir que si el cambio climático es intenso puede a la larga ser todavía peor, entendiendo el concepto de “peor” desde una perspectiva utilitarista humana.

ser humano, gracias a los cambios introducidos con cierto coste o esfuerzo en la estructura de la materia o en su ubicación en el espacio” (Malanima, 2014).

Las leyes de la termodinámica afirman que la energía y materia no se destruyen, solo se transforman, y que cada acción de transformación genera una entropía (o un desorden) creciente. En este sentido, la Economía Ecológica considera que el flujo circular de la renta tiene una alta entropía (Georgescu-Roegen, 1971). Dado que los recursos son finitos, su visión del futuro es pesimista (¿pesimista para quién?) incluso reconociendo el importantísimo papel del ingenio humano para incrementar la eficiencia en el uso de energía exosomática. Por contra, la Economía Neoclásica, más optimista, considera que la innovación y el avance tecnológico tienen las llaves del crecimiento económico a largo plazo. Por tanto, en la explicación de las adaptaciones humanas, entendidas como adquisición de conocimiento útil para aumentar la eficiencia en el uso de recursos naturales, sea mediante prueba y error o por métodos científicos, subyace una “tierra de nadie”.

¿Qué es el conocimiento desde el punto de vista de la energía? ¿No es acaso energía potencial acumulada en información, que se convierte en efectiva cuando se moviliza siendo capaz de generar más conocimiento, o bien que se desecha cuando no se utiliza? El gran ecólogo Ramon Margalef nos enseña que “*Historia es tiempo, e historia es termodinámica. No es posible concebir la información y la predicción fuera del contexto de las restricciones de la termodinámica*.” Y añadía: “*De la segunda ley de la termodinámica se sigue que la entropía siempre aumenta en cualquier proceso irreversible que ocurra espontáneamente en cualquier sistema aislado*”. […] Sin embargo, en todo sistema complejo esa misma entropía “*no debe considerarse como algo totalmente perdido. Más bien parece como si la energía gastada, con la entropía asociada, se hubieran colocado en una «cuenta de ahorro termodinámico», y se reflejaron luego en la mayor economía en la producción posterior de las copias de objetos, cualesquiera que sean* […]. *La analogía de la «cuenta de ahorro» resulta apropiada, también porque la energía que se cambia y se degrada en un punto, puede aparecer y recuperarse como información en otro lugar. Ésta es una particularidad muy notoria en los sistemas vivos* […]. *Seguramente ocurre lo mismo en toda organización complicada y uno se sentiría tentado a hablar, en cada caso, de una «cuerda» tendida entre el centro de gravedad en el aumento de entropía y el centro de gravedad en el aumento de información*. […] *La información asociada con una estructura puede luego canalizar el uso de la energía en una dirección que se nos antoja particularmente eficiente*.”. Margalef infería de todo ello que “*Este concepto puede resultar útil en economía, pero en ecología basta recordar que la información no es gratuita y se ha pagado de algún modo y por alguien*” (Margalef, 1993: 88-95).

Esa energía transformada en información se transmite de generación a generación gracias al cerebro y al lenguaje, y se incorpora a las herramientas o los bienes de capital de todo tipo creados por el hombre que se pueden activar, desarrollar y transformar por razones ecológicas adaptativas u otros mecanismos más comúnmente estudiados por la Historia

Económica. Dicho en estos términos, las adaptaciones a un cambio del clima de la Tierra no son más que la activación de esta energía potencial contenida en la información heredada y la nuevamente generada. Aunque todavía no somos capaces de almacenar muy bien la energía solar, desde hace unos cuantos centenares de milenios tenemos la capacidad única de almacenar la energía potencial como información socialmente acumulada a través del conocimiento (Ho & Ulanowicz, 2005; Toledo & Barrera-Bassols, 2008).

Desde una concepción económica de la energía, si por un cambio en las condiciones ambientales aumenta la necesidad endo/exosomática de energía, esto requiere un mayor coste o esfuerzo, sea mediante trabajo físico o mental. Esta idea es fundamental para entender mi Tesis Doctoral: un enfriamiento del clima aumenta los esfuerzos y los costes para mantener los requerimientos de energía. En este punto, una enorme dificultad radica en que no disponemos ni de buenas fuentes ni de una metodología clara y sencilla para contar los flujos de energía empleados por las sociedades humanas en el período 1650-1750. Ni tampoco ahora las tenemos aún para contar la energía acumulada en forma de conocimiento.

3. Efectos de primer nivel: el sistema ecológico.

Hasta la fecha, las investigaciones realizadas sobre los efectos del último cambio climático que ha afectado a nuestras sociedades muestran que sabemos bastante poco sobre las relaciones entre clima y economía. Los avances del conocimiento sobre esa cuestión están más focalizados en un primer nivel (donde actúan las ciencias naturales del cambio climático) que en un segundo nivel (las ciencias sociales y las humanidades). En el primer nivel, la ciencia está ahora avanzando a marchas forzadas, estudiando los impactos del clima en los sistemas físicos y biológicos, los fenómenos ambientales y meteorológicos. Los resultados sugieren que se ha incrementado la variabilidad de temperaturas, los regímenes de lluvias, nubosidad, dirección y velocidad del viento, y acidificación de las aguas (IPCC, 2019a). Estos cambios, en parte no predictibles, afectan de un modo integral a los ecosistemas, los agroecosistemas y la biodiversidad (IPCC, 2019b). Asimismo, esos estudios sugieren que una mejora en la gestión de los agroecosistemas y de los sistemas socioeconómicos puede mitigar los efectos del cambio climático, mientras que el mantenimiento del actual modelo de consumo y producción podría agravarlos (Stern, 2006; Steffen, Richardson, Rockström et al., 2015; Lade, Steffen, de Vries et al., 2019).

El cambio climático afecta pues a gran parte de la esfera física y biológica de la Tierra, y en un segundo nivel, al sistema social creado por el hombre. Esta característica holística, que une en una “totalidad” las dimensiones biofísicas y socioeconómicas ha desarmado a las ciencias parcelarias heredadas del siglo XX (y algunos de los revisores anónimos que hemos tenido), que hasta ahora se han visto bastante incapaces de comprender que para abordar esa clase de problemas relacionados con la sostenibilidad ambiental del desarrollo humano es necesaria una visión más integral y global, una nueva Ciencia de la

Sostenibilidad que vaya más allá de una simple suma de aportaciones parciales (Kates et al., 2001; Clark & Dickson, 2003; Kates, 2011). Que unas disciplinas se impongan a otras, sean cual sean los motivos (históricos, políticos, institucionales, geográficos) es un problema serio para abordar tales asuntos porque genera una visión incompleta y sesgada del problema, cuando el alto grado de incertidumbre del cambio climático ahora en curso exige un buen nivel de precisión en los diagnósticos y las políticas. Una prueba de los peligros de esa parcialidad de visión de las ciencias parceladas heredadas del siglo pasado es su más que problemático traspaso a las políticas públicas (aparte de frenar la publicación de buenos trabajos de investigación).

4. Efectos de segundo nivel y sus implicaciones: el subsistema económico.

Uno de los ámbitos a valorar del segundo nivel de impacto del clima sobre la sociedad es el económico. Aquí los estudios se podrían clasificar en dos tipos, los que se quedan en la esfera de las políticas públicas y sectores productivos, y los desarrollados en el entorno académico que suelen ser base imprescindible de los anteriores. A diferencia del primer nivel, los estudios económicos son por regla general insuficientes en cantidad y algunos incluso en calidad. Por ahora, las estimaciones del impacto económico global del cambio climático muestran que un aumento de 2,5 grados implicaría un descenso de la renta (*income*) del orden del 1,3 por 100 en promedio, aunque esos resultados están en revisión constante y parece que infravaloran las consecuencias del cambio climático actualmente en marcha al ignorar las interacciones entre las múltiples dimensiones en juego (Stern, 2006; Lade, Steffen, de Vries et al., 2019).

Las estimaciones de impacto se suelen obtener de diferentes formas (modelos de proceso, modelos de optimización, de equilibrio, estadísticos, espaciales o temporales). A partir de los efectos naturales y físicos se hace una valoración (usando precios de mercado u otros métodos de valoración como preferencias reveladas, preferencias declaradas, beneficio transferido, WTP o *willingness to pay*, WTAC o *willingness to accept compensation*), multiplicando precios por cantidades y agregando los resultados. Es preocupante observar que muchos de estos métodos son demasiado "ingenuos", a pesar de ser muy caros, dado que presuponen que los agentes no actúan adaptándose ante los cambios del clima. Además, sus metodologías se basan en valoraciones del coste directo sin tener en cuenta los cambios de los precios relativos ni las interacciones entre la oferta y la demanda de distintos sectores (Tol, 2019)[4].

Esta Tesis Doctoral parte justamente de una visión crítica hacia los modelos comúnmente empleados hasta ahora para tratar los impactos económicos de las variaciones climáticas. Se propone mostrar que, combinando historia económica, métodos cuantitativos y una visión transdisciplinar, podemos empezar a analizar mejor aquellos impactos con modelos que permitan capturar las adaptaciones y que, a través de su desarrollo futuro, permitan simular escenarios dinámicos más próximos a la realidad. Más concretamente,

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[4] Preocupa en especial que se apliquen en estudios gubernamentales sin tenerse en cuenta sus importantes limitaciones y defectos.

nos marcamos como objetivo desvelar algunos de los cambios que el enfriamiento producido durante el Mínimo de Maunder indujo sobre la trayectoria de la economía inglesa a través de la adaptación, la innovación y el cambio agrario.

Nuestra investigación se aparta de los modelos de valoración del impacto económico directo del cambio climático, como también de otros estudios que abordan esa temática desde la perspectiva de un modelo de equilibrio general, incluyendo cambios de precios e interacciones entre mercados, sea en output, bienes intermedios o finales, y entre las diversas economías entrelazadas por redes comerciales. También difiere de otras estimaciones que emplean regresiones de algún tipo de medida de bienestar en el clima. Por ejemplo, la aproximación ricardiana toma como referencia clave los precios de la tierra agraria, suponiendo que reflejan la productividad del suelo y por tanto el valor de la tierra. También se ha trabajado con las relaciones estimadas entre clima y patrones de gastos familiares, usando como aproximación el cambio en el excedente del consumidor debido al cambio climático, un enfoque interesante pero difícil de aplicar en un período histórico tan escaso en datos y estimaciones.

Dicho de una forma general, la principal ventaja del método estadístico es que se basa en el consumo efectivo (lo que es más robusto que el comportamiento modelado en el método enumerativo anteriormente expuesto). La desventaja es que las variaciones climáticas en el espacio se usan para derivar el impacto del cambio climático en el tiempo, como ocurre en la aproximación ricardiana. Otros problemas del método ricardiano son que 1) el clima varía en el tiempo, pero la identificación de los efectos del cambio climático viene de variaciones *cross section*, y como el clima varía lentamente sobre el espacio, los datos *cross section* necesitaran cubrir períodos muy largos; y 2) que existen otras variables que también varían en el tiempo y en el espacio, por ejemplo, la política comercial, y afectan simultáneamente al funcionamiento económico. Asimismo, el método ricardiano es vulnerable también a asociaciones espurias, o puede estar sesgado porque podría haber variables no observadas determinantes de la productividad agraria y correlacionadas con el clima (Deschenes & Greenstone, 2009). Algunos de estos problemas pueden arreglarse parcialmente con la técnica estadística de datos de panel, pero nada nos dice este método cuando hay factores de confusión que no cambian mucho en el tiempo, como por ejemplo preferencias culturales por el pastoreo extensivo en zonas áridas (Tol, 2019).

Siguiendo con el estudio de impactos, existe también una creciente literatura que estudia los efectos económicos del clima, los *weather shocks* y los fenómenos extremos. En este contexto, los principales temas investigados son: producción agregada, composición de la agricultura, productividad del trabajo, industria y servicios, salud y mortalidad, energía, conflictos y estabilidad política, crimen y agresión, comercio internacional, integración del mercado, e innovación (Dell et al., 2014). Casi todos estos ítems son analizados en el capítulo II de nuestra investigación.

Es importante resaltar también que la incertidumbre es cada vez mayor acerca de la prospectiva futura del cambio climático ahora en marcha. La probabilidad de que aparezcan factores aceleradores del cambio climático está creciendo. Los impactos del cambio climático no son lineales, sino de tipo exponencial. Si las temperaturas aumentan el doble, los impactos son mayores en proporción, incluso sin tener en cuenta el problema de los *tipping points:* es decir, que hay un punto de no-retorno a partir del cual los efectos biofísicos se disparan. Por otro lado, casi todos los estudios se paran por debajo de los tres grados de aumento de la temperatura media global. Nadie sabe que pasa después.

Los países pobres son mucho más vulnerables que los ricos porque gran parte de su economía está más expuesta al cambio climático. El sector primario y el agua son más importantes en proporción que en los países más desarrollados, más centrados en industria y servicios. Muchos de los países pobres acostumbran a estar en zonas más cálidas. Tienen una capacidad adaptativa más limitada, por falta de tecnología, recursos o instituciones inclusivas y protectoras. Como la pobreza implica vulnerabilidad, el crecimiento económico sigue siendo visto por muchos como una vía para reducir el impacto del cambio climático (Ayers & Dodman, 2010, Lenton & Ciscar, 2013). Pero también existen modelos de signo contrario, que muestran un fuerte impacto del cambio climático sobre una tendencia general al decrecimiento económico (Nieto, Carpintero, Miguel et al., 2019).

Tal como se explica en detalle en los capítulos de esta Tesis Doctoral, si el cambio climático reduce el crecimiento, las sociedades pueden ser más vulnerables, lo que a su vez minora aún más el crecimiento económico. El bienestar se ve afectado a través de la utilidad, la oferta de trabajo, la productividad, la depreciación del capital, siendo las tres últimas variables las que tienen efectos para el crecimiento (Tol, 2019). El cambio climático afecta la productividad del trabajo mediante cambios en la mortalidad o morbilidad. El trabajo manual es más complicado de ejecutar con mucho calor o mucho frío y humedad, lo que lleva a impactar en el output total, y por tanto en la inversión y la producción futura, pero también puede afectar la productividad de otros inputs. Estos efectos son directos, pero los hay también de tipo indirecto, sobre la productividad de otros inputs. Por ejemplo, junto a peores cosechas, el transporte también puede verse afectado por fenómenos meteorológicos extremos, lo que a su vez afectaría tanto la producción total como la inversión futura. Estas cuestiones han sido observadas en nuestro trabajo de investigación en los siglos XVII y XVIII: un clima adverso a corto plazo empeoraba las cosechas y el transporte a Londres, así como también la productividad agraria.

También hay efectos indirectos que pueden ser de igual o mayor impacto que los directos (por la ya comentada transversalidad de los efectos del cambio climático). Por ejemplo, el aumento de la temperatura puede incrementar la demanda de aire acondicionado, lo que permite a la fuerza laboral de las oficinas seguir trabajando, pero aumenta los costes y la entropía sin incrementar el output (pérdida de productividad). Esto modifica la composición del capital hacia la generación de energía. Como la productividad cambia, también lo hace el output y la inversión. Finalmente, también afecta la tasa de depreciación del capital. Las inundaciones destruyen o deterioran puentes, diques, carreteras, construcciones. Esto implica menos capital productivo y por tanto menos output e inversión, porque se tiende a reemplazar capital y no a expandir el stock per cápita disponible para nuevas actividades o fortalecer otras con futuro. En el modelo canónico de Robert Solow, solo el 25 por 100 de crecimiento viene explicado por la acumulación del capital, y un 75 por 100 por el cambio tecnológico, que no está incluido en ese tipo de modelos (Solow, 1978). Si incluimos el progreso tecnológico en el modelo (lo que se llama el nuevo modelo de crecimiento), entonces las inversiones en capital humano pueden caer igual que lo hacen las inversiones en capital físico, por lo que el crecimiento económico se vería afectado todavía más (Tol, 2019).

En el capítulo IV de la Tesis Doctoral realizamos un ejercicio de inclusión del factor climático a través del retorno de nitrógeno a los suelos fértiles cultivados, en un modelo de crecimiento donde se valora su rol de freno o acelerador del producto agrario, y por tanto también del producto total en una economía de tipo orgánico. Nuestro modesto intento se inscribe en el esfuerzo colectivo en marcha para reconectar la teoría y la contabilidad del crecimiento económico con su base biofísica (Victor, 2008; Ayres & Warr, 2010; Jackson, Victor & Naqvi, 2016; Nieto, Carpintero, Miguel et al., 2019).

5. Efectos económicos de segundo nivel en perspectiva histórica.

Si buscamos estudios históricos del impacto económico de la variabilidad climática, encontramos que éstos no son frecuentes, y menos aún desde una perspectiva transdisciplinar combinando análisis estadístico con métodos cuantitativos e históricos. El repaso de la historiografía del cambio climático en clave de historia económica se puede enfocar de varias formas. En primer lugar, bajo una perspectiva sectorial. Aquí observamos que apenas hay estudios de impacto económico global (todos los sectores a la vez) ocasionados por la variabilidad climática. Existen unos cuantos más que estudian sectores concretos (agricultura o población, por ejemplo, que ahora no citaremos aquí ya que están enumerados en cada capítulo). En segundo lugar, desde un punto de vista geográfico, los estudios históricos de los impactos económicos se centran solo en algunos países europeos (Inglaterra, Francia, Alemania, Países Escandinavos). En tercer lugar, bajo una perspectiva de tipo cronológico aún es más difícil realizar una catalogación, porque hay muchos trabajos de impactos económicos sectoriales ya desde el Neolítico hacia adelante.

En cualquier caso, puede asegurarse que en la historia económica de los últimos siglos el papel del cambio climático es un tema que permanece en gran medida como un territorio por estudiar. Por contra, hay toda una larga tradición en la historia misma del clima, y en la reconstrucción de series temporales con variables climáticas. En suma, hay un fuerte contraste entre el dinamismo investigador de la historia climática respecto la historia económica de los impactos del clima, cuyos trabajos escasean.

6. Preguntas de investigación y relevancia del estudio.

Las preguntas principales

Las principales preguntas de investigación que se plantea esta Tesis Doctoral son las siguientes: ¿El clima importa en la historia económica? ¿Podemos considerar la variación del clima ocurrida en Gran Bretaña entre los siglos XVII y XVIII como un factor influyente en los inicios del notable despegue económico acontecido justo en aquel periodo? La coincidencia en el tiempo de ambos fenómenos ¿guarda alguna relación significativa, con independencia de su relevancia? Si esta última pregunta obtuviera una respuesta afirmativa, ¿cuáles fueron los mecanismos de interacción entre el cambio climático y el sistema económico? ¿Cuál fue el rol del aumento del Nitrógeno incorporado en el suelo como materia orgánica? ¿Puede una economía despegar y romper la restricción malthusiana en el marco de una economía orgánica, sin necesidad de una revolución tecnológica basada en combustibles fósiles?

Las preguntas secundarias

A partir de estas cuestiones, se derivan otras preguntas más específicas. Dado el carácter transversal del factor climático-ambiental, los temas tratados en esta tesis doctoral adquieren valor en el marco de algunos de los debates más relevantes de la historia económica. En primer lugar, en la controversia sobre *cuando* se inició el crecimiento económico moderno, lo que podríamos llamar el punto cero. Tenemos una primera posición, digamos clásica, que sitúa este salto entre finales del XVIII y comienzos del XIX (desde el prometeico *take-off* industrial de Walt Whitman Rostow a visiones más modernas como las de Gregory Clark o Ken Pomeranz y la escuela de California en el debate sobre la Gran Divergencia), a otras posiciones más recientes que lo sitúan más atrás, hasta el siglo XVII y aún en el marco de una economía orgánica (Pomeranz, 2000; Wallis, Colson & Chilosi, 2018).

Una segunda discusión, muy relevante también, versa sobre la génesis de la "pequeña" divergencia europea. De todo lo anterior se deriva además un tercer debate sobre la evolución de los salarios anuales y jornales diarios en el que aportamos en esta Tesis Doctoral un modelo teórico y empírico que esperamos sea de interés del lector, para intentar comprender por qué y cuándo los salarios no agrícolas comienzan a desviarse de los agrícolas. El cuarto debate es acerca de cuándo dejó de tener efecto el freno malthusiano al crecimiento económico británico. Hay autores y autoras que defienden su vigencia hasta el siglo XIX (Nicholas F. R. Crafts, Gregory Clark), mientras otros dicen que como máximo tuvo relevancia hasta el período 1650-1750 (Stephen Broadberry y otros).

Un quinto debate, muy fructífero y todavía en evolución a pesar de su larga trayectoria, es el de los campos abiertos y cerrados. Encontramos que hay un vacío importante en el debate sobre los cerramientos (*enclosures*) y los campos abiertos en lo que se refiere a los salarios y los ingresos, cuando justamente ahí sospechamos que pueden estar parte de las respuestas. Si pudiéramos disponer de datos y estudios en este punto, los resultados podrían ser reveladores. Por el momento, en este trabajo intentamos comprender la lógica de esta relación a través de una primera aproximación. Y finalmente, el cambio climático también tiene relevancia en el asunto que se refiere al debate sobre el nivel de vida y su tendencia durante el período 1650-1750, habida cuenta que las últimas tendencias de investigación para la primera fase de la industrialización (1760-1840) arrojan la idea de que los niveles de vida empeoraron (Comín et al., 2005; Allen, 2009).

7. Aportaciones de esta Tesis Doctoral a la Historia Económica.

En resumen, podemos sintetizar en cuatro las aportaciones más importantes de esta Tesis Doctoral. En primer lugar, el intento de armonizar historia económica con historia del clima. En segundo lugar, el hecho de realizar un esfuerzo de conexión analítica y empírica entre la esfera física (primer nivel) y la esfera económica y social (segundo nivel), así como la puesta en marcha de un enfoque multidisciplinar que nos permita avanzar en la comprensión de los problemas tratados. Tercero, poner en el centro del debate el rol central de las adaptaciones, que de acuerdo con nuestros resultados habrían facilitado la puesta en marcha de la Revolución Agrícola inglesa. Cuarto, el papel crucial de la energía, entendida no solo como materia prima (alimentos, madera o carbón) si no también –y muy importante— como necesidad calórica metabólica humana que permite la realización de todo tipo de trabajos. Un enfoque basado en la energía nos ayuda a comprender mejor el comportamiento microeconómico de cada uno de los actores sociales.

8. Aportaciones al problema del cambio climático actual.

En nuestra opinión, el valor de esta Tesis Doctoral no se limita únicamente al ámbito de la Historia Económica como disciplina. También es útil como modelo de estudio del desafío climático actual, a través de una verdadera “prueba de laboratorio social” basada en los hechos históricos entendidos como un experimento natural. Nuestra investigación presenta modelos y resultados econométricos que nos permiten una mejor comprensión de las causas y los efectos de la variabilidad climática sobre el funcionamiento económico, así como métodos para evaluar sus impactos y las respuestas adaptativas que se pueden producir. Reúne ciencia natural (climatología), ciencia social (economía) y humanidades (historia). Ante la elevada incertidumbre de las predicciones actuales, propone una mirada alternativa a través de la revisión de un caso histórico paradigmático: la Inglaterra de los siglos XVII y XVIII durante el período de enfriamiento y posterior recuperación de las temperaturas.

Estos aspectos están cobrando mucha importancia. La Comisión Europea destina cada vez más recursos para avanzar en la comprensión de los efectos del cambio climático y las posibilidades de adaptación. La estrategia de investigación Horizon 2020 plantea un enfoque “basado en los desafíos sociales”, reuniendo conocimientos de diferentes campos y disciplinas, incluidas las ciencias sociales y las humanidades. De los siete retos planteados, el 35 por 100 del presupuesto está destinado a la "acción climática, medio ambiente, eficiencia de recursos y materias primas". La Comisión admite que Europa y el resto del mundo "*tienen que adaptarse a los cambios actuales y futuros del clima*", y que "*las medidas de adaptación aumentarán la resiliencia de la sociedad ante el cambio climático y reducirán sus impactos y costos*". Las acciones que impulsa la Comisión Europea tienen por objeto "*seguir mejorando la comprensión de las causas y los efectos del cambio climático y coordinar mejor los esfuerzos para hacerles frente*". Así pues, se prioriza "*el desarrollo de mejores herramientas, métodos y normas que ayuden a evaluar el impacto del cambio climático y las respuestas de adaptación*", "*mejorar la comprensión de la economía del cambio climático*", o "*crear redes sobre el cambio climático para facilitar el diálogo entre las comunidades científicas pertinentes, los organismos de financiación y las comunidades de usuarios de la UE*"[5].

9. Sistema de publicación y secuencia de los capítulos.

El método seguido por esta Tesis Doctoral es el sistema de publicaciones. Consiste en tres artículos publicados en revistas científicas de impacto, y cuatro más publicados en forma de documentos de trabajo por sociedades científicas importantes como la SEHA y la AEHE en España (2) y la EHES en Europa (2). Están repartidos en cinco capítulos, más el apéndice final. Este último documento, *Did Climate Change Influence English Agricultural Development? (1645-1740)",* publicado en abril de 2015 en la *European Historical Economics Society*, podría considerarse como el documento seminal de esta investigación o una especie de "Capítulo 0". Al ser utilizado para elaborar parte de algunos capítulos, no lo incluyo en el cuerpo de la tesis, sino de forma complementaria. Considero un acto de justicia hacerlo así, ya que todo comienza en él y es el resultado de muchísimas horas de trabajo. Aunque algunas secciones sean o bien complementarias, o bien el punto de partida a los capítulos de esta Tesis Doctoral, puede ser interesante leerlo en paralelo, ya que es una primera presentación de la idea que vincula la variación climática con las respuestas de los agricultores ingleses a través del aumento de la reposición de nitrógeno en el suelo por vías orgánicas.

De esos cinco capítulos y el apéndice final, dos se han publicado con mi única autoría. Los otros cuatro son en coautoría con diversos especialistas en econometría (Jordi Suriñach), climatología histórica (Javier Martin-Vide y Mariano Barriendos-Vallbé), historia agraria de la Edad Moderna (Gabriel Jover-Avellà), historia ambiental (Enric Tello, Verena Winiwarter), edafología (José Ramon Olarieta), nutrición vegetal (Roberto García-Ruiz), agroecología histórica (Manuel González de Molina) y métodos cuantitativos en historia económica (Nikola Koepke, Marc Badia-Miró, F. J. Beltrán Tapia). En tres de estos cuatro, soy el primer firmante y *corresponding author* (dos publicados en revistas JCR y un documento de trabajo) y en el otro soy el segundo

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[5] Más información sobre Horizon 2020 en https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges y https://ec.europa.eu/programmes/horizon2020/en/h2020-section/fighting-and-adapting-climate-change-1.

firmante (publicado también revista JCR). Tal como plantea la Comisión Europea en su claro mensaje sobre *Integration of social sciences and humanities in Horizon 202*, ha llegado la hora "*to begin to break the classic boundaries between disciplines, sectors and policy areas*". Esa interdisciplinariedad "*stems from the realization that our societal challenges are far too complex for only one discipline or a group of disciplines to deliver on. In general terms, SSH [Social Sciences and Humanities] play a key role in analysing and influencing behavioural and societal choices so that better policies can be devised in the future with a direct societal impact. In this context, the fostering of SSH integration offers almost endless opportunities*." Eso comporta trabajar en equipo y, congruentemente, publicar en coautoría rompiendo una inveterada inercia académica por desgracia aún predominante en las Humanidades y la Ciencias Sociales (incluidas la Economía y la Historia Económica). La interdisciplinariedad requerida para investigar abordando los Retos Sociales definidos por la Unión Europea, y no según los viejos cánones de cada disciplina, implica que la publicación en coautoría nunca puede considerarse un demérito. Pues sólo investigando y publicando en equipo es posible abordar científicamente esa clase de problemas que son los más importantes a los que se enfrenta nuestra sociedad en el siglo XXI.

El *background* historiográfico específico se presenta en cada capítulo, por lo que no lo repetimos en esta introducción. El capítulo I (*Building an annual series of English wheat production in an intriguing era (1645-1761): methodology, challenges and results*, publicado en *Revista de Historia Agraria* en 2019[6]), presenta por primera vez una serie de producción de trigo en términos físicos que llega a enlazar con las series estadísticas de Mitchell de finales del siglo XIX y principios del XX, y que ha sido enviada al Banco de Inglaterra al ser solicitada por éste a su autor. El trigo se ha considerado, en Inglaterra, el cereal clave en la transición de una economía agraria a otra de tipo industrial (Allen, 1999). Esta estimación de las cantidades de trigo anualmente producidas nos permitirá hacer diversos ejercicios en los capítulos siguientes, que no habrían sido posibles partiendo solo de los precios. Otras posibilidades que aporta esta nueva serie histórica de rendimientos físicos de la tierra en Inglaterra entre 1645 y 1761 son una mayor comprensión cuantitativa de la cronología de las cosechas anuales, los rendimientos, la productividad, o ahondar en cuestiones de demanda y oferta. Permite visibilizar mejor la llamada Revolución Agrícola inglesa, en un sentido que confirma la interpretación de Robert Allen y otros autores de que hubo dos "revoluciones", la primera entre 1650 y 1750 protagonizada por el campesinado *yeomen*, y la segunda en la que se impusieron los terratenientes, cuyos inicios se solaparon con la primera y cuyo despliegue completo se prolongó durante el siglo XIX. A nivel metodológico, abre las puertas a desarrollar en el

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[6] **Martínez-González, J. L.** (*corresponding autor*), Jover-Avellà, G., Tello, E. (2019). *Historia Agraria*, 79, 1-29. DOI: 10.26882/histagrar.079e01m. La revista *Historia Agraria* está incluida en el JCR con in Factor de Impacto en 2019 de 0.634, y en el Cuartil 2 en Historia. Accesible en abierto en: https://www.researchgate.net/profile/Jose_Martinez281/publication/334114143_Building_an_annual_series_of_English_wheat_production_in_an_intriguing_era_1645-1761_methodology_challenges_and_results/links/5d17a5cfa6fdcc2462b0cc5c/Building-an-annual-series-of-English-wheat-production-in-an-intriguing-era-1645-1761-methodology-challenges-and-results.pdf

futuro series similares de output en la cebada, centeno y avena, o a mejorar las estimaciones del PIB agrícola británico.

El capítulo II se centra en valorar si el factor climático fue estadísticamente significativo como determinante del comportamiento económico de Inglaterra durante el Mínimo de Maunder (*Assessing Climate Impacts on English Economic Growth (1645 1740): an Econometric Approach*, recientemente publicado en *Climatic Change* en el 2020[7]). Con el aporte de una metodología econométrica rigurosa, presentamos en este trabajo estimaciones de impacto total y marginal de las temperaturas y precipitaciones en la producción agrícola (trigo y cebada), población, consumo de energía, productividad, salarios y PIB.

En los siguientes capítulos se entra más a fondo en los nexos causales existentes entre las variables previamente correlacionadas. Los capítulos III y IV detallan los impactos de la variabilidad climática en la agricultura desde una óptica multidisciplinar, ofreciéndose una valoración de las respuestas adaptativas de los agricultores. Más concretamente, en el capítulo III (*The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients*, publicado en *Journal of Interdisciplinary History*, 2017[8]), se combina ciencia del suelo, agronomía e historia económica para explicar por qué las oscilaciones climáticas importaban, tomando como referencia algunos de los trabajos sobre el tema, en especial los de Robert Allen en relación con la hipótesis del papel del nitrógeno disponible en los suelos cultivados para los inicios de la Revolución Agrícola inglesa.

El capítulo IV (*Revisiting Allen's Nitrogen Hyphotesis from a Climate perspective*, publicado en *Documentos de Trabajo de la SEHA*, 2019[9]), que tiene como origen el artículo publicado como *Working Paper* en 2015 por la *European Historical Economic Society*, titulado "*Did Climate Change Influence English Agricultural Development?*

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[7] **Martínez-González, J. L**. (*corresponding autor*), Suriñach, J., Jover-Avellà, G., Martín-Vide, J., Barriendos-Vallvé, M., Tello, E. (2020). Assessing climate impacts on English economic growth (1645-1740): an econometric approach, *Climatic Change* 160, 233–249; https://doi.org/10.1007/s10584-019-02633-0. Esta revista está incluida en el JCR con un Factor de Impacto en 2019 de 4.134, y en el Cuartil 1 en Ciencias Ambientales, Meteorología y Ciencias de la Atmósfera. Disponible en abierto como *postprint* en https://www.researchgate.net/profile/Jose_Martinez281/publication/338037994_Assessing_climate_impacts_on_English_economic_growth_1645-1740_an_econometric_approach/links/5dfb4f40299bf10bc36654e1/Assessing-climate-impacts-on-English-economic-growth-1645-1740-an-econometric-approach.pdf

[8] Tello, E. (*corresponding autor*), **Martínez-González, J. L**., Jover-Avellà, Olarieta, J. R., García-Ruiz, R., González de Molina, M., Badia-Miró, M., Verena Winiwarter, Koepke, K. (2017). The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients. *Journal of Interdisciplinary History*, 47(4), 445-474; https://doi.org/10.1162/JINH_a_01050. Esta revista, publicada por The MIT Press, está incluida en el JCR con un Factor de Impacto en 2017 de 0.563, y en el Cuartil 2 en Historia (en 2018 ha subido a 0.909 y al primer cuartil). Disponible en acceso abierto en el repositorio de la UB: http://diposit.ub.edu/dspace/bitstream/2445/107786/1/667412.pdf.

[9] **Martínez-González, J. L**. (*corresponding autor*), Beltrán Tapia, F. J. (2019). Revisiting Allen's nitrogen hyphotesis from a climate perspective (1645-1740). *Sociedad de Estudios de Historia Agraria DT-SEHA 1902*. Disponible en abierto en: http://repositori.uji.es/xmlui/bitstream/handle/10234/182881/DT-SEHA%201902.pdf?sequence=1&isAllowed=y

(1645-1740)", completa la idea del capítulo III, pero integrando ciencia física (nivel uno) y social (nivel dos). A partir de una revisión crítica, flexibiliza y refuerza la ecuación matemática del nitrógeno de Allen mediante la inclusión de variables climáticas, pero también transforma un modelo agronómico estático en otro de tipo cuantitativo, dinámico y con variables retardadas, así como también incorpora el factor climático en un modelo de crecimiento.

En el capítulo V (*High Wages or Wages For Energy? An Alternative View of The British Case (1645-1700)*, publicado como *Working Paper* por la *European Historical Economics Society*, 2019[10]), proponemos una doble visión física y económica, bajo una perspectiva energética, con un modelo (simplificado) de los efectos del enfriamiento climático en la productividad del trabajo, los salarios de subsistencia, y el mercado de trabajo en el campo y la ciudad. Analizamos las diferentes respuestas en función del tipo de fincas (capitalistas o comunales), o qué incidencia pudo haber tenido el cambio climático den la desigualdad, el desempleo o el subempleo.

Finalmente, presentamos la conclusión de la Tesis Doctoral.

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[10] **Martínez-González, J. L.** (2019). High Wages or Wages For Energy? An Alternative View of The British Case (1645-1700). *Working Paper 158 of the European Historical Economics Society (EHES)*. Disponible en acceso abierto en el repositorio de la EHES: https://econpapers.repec.org/paper/heswpaper/0158.htm.

Chapter 1. Building an annual series of English wheat production in an intriguing era (1645-1761): methodology, challenges, and results[11].

1. Introduction.

One of the most widely discussed aspects regarding the English Agricultural Revolution has been quantifying the magnitude of the agricultural product and GDP and GDP per capita. The Agrarian Reform (1536) and Social Revolutions (1640 and 1688) disrupted one of the most useful sources used as a proxy for crop production in continental Europe in pre-capitalist times: tithes (Kain & Prince, 2006). This lack of data has led to estimations being made from indirect methods and other sources. From a demand-side approach, agricultural production has been calculated on the basis of consumption per head, population, prices and elasticities. From a supply-side approach, on the other hand, the sources have been a growing set of non-randomly selected site-specific probate inventories and farm accounts. This methodological diversity has produced widely varying estimates due to the differing temporal and spatial features and sources used in each case. For instance, Morgan Kelly and Cormac Ó Gráda (2013) have called for an upward adjustment of the recent agricultural production estimated by Stephen Broadberry, Alexander Klein, Mark Overton and Bas van Leeuwen (2015). There is also an ongoing debate over the dating of the English Agricultural Revolution, raised by Mark Overton (1996a) and Robert C. Allen (1991, 2008, 2009). Another open question is whether waves in agricultural output and productivity might have been responsible for the slow progress of English economic growth between 1760 and 1815, and for its later acceleration. To help determine the answers to these questions, Robert Allen has called for new methods to be developed that allow a better inference of changes in production and yields (Allen, 1999: 209-211).

In partial response to Allen's request, the aim of this paper is to estimate an annual series of wheat output in England between 1645 and 1761. A new method is presented based on Davenant's Law (1699). Charles Davenant was a contemporary author from that intriguing period and the first to propose estimating the inverse variations of wheat harvests from the variations of their prices. He did this using data previously collected by Gregory King. The usefulness and accuracy of this method has been highlighted by historians such as Edward Anthony Wrigley (1987) and economists such as Anthony M. Endres (1987) and Jean-Pascal Simonin (1996). The method is also currently being used to estimate production from prices when facing unreliable statistical output data (Nielsen, Smith & Guillén, 2012). We will use it for the same purpose, adding other assumptions,

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[11] Martínez-González, J.L., Jover-Avellà, G., Tello, E. (2019). Building an annual series of English wheat production in an intriguing era (1645-1761): methodology, challenges and results. *Historia Agraria* 79, 41-69. https://doi.org/10.26882/histagrar.079e01m [JCR IF 2019: 0.634; Q2 in History]. Martínez-González is the main author. The contributions of Jover-Avellà and Tello have consisted of a review of the written expression, the bibliography, and the introductory part. They have taken care of the academic quality of the text.

i.e. to estimate a final aggregate gross and net production of wheat —meaning gross output minus seeds, animal feeding and losses— from a demand-side approach, to then compare the outcome with the supply data assembled by other historians who have considered yields, population growth and long-term income growth.

Notwithstanding the importance of wheat it is worth stressing other grains, such as barley, rye and oats, as well as pulses, turnips and clover, potatoes and livestock. However, as Robert Allen stated, during the transition from subsistence to market agriculture and urban development *wheat dominates the history of crop yields, and the history of wheat shows the importance of the pre-1750 agricultural revolution* (Allen, 1999: 225).
This paper is structured as follows. The first section summarizes the current debates in agricultural historiography. The second explains the methodology used to build the new series. The third assesses the results obtained comparing them with current estimates, and justifies their accuracy. And the fourth concludes.

2. The problem with assessing the economic performance of English agriculture prior to 1884.

There are no statistical data on the annual physical wheat production in Britain prior to 1884 (Mitchell, 1988). Neither can we count on any proxy such as tithes, traditionally used as sources in continental Europe. Thus, over the last thirty years economic and agricultural historians have had to use other indicators to assess the performance of English agriculture: total physical output, yields, agricultural production, consumption and elasticities. As can be seen in Table 1.1, physical output estimates are scarce and never annual. One of the earliest was contributed by Phyllis Deane and W. A. Cole (1967: 62-8) and showed a rise in wheat production during the 18th century from 29 to 50 million bushels (73%), substantially larger than the growth in other grains (43%). Gross production can be calculated using the acreage estimates and Allen's yields (2005: 28, 32) put forward for the period 1300 to 1850, and this highlights a dramatic increase in production between 1800 and 1850.

Based on some assumptions regarding the consumption of bread and flour by labourers, Robert Allen also presented an estimate to support his idea that the volume of wheat demand was bigger than that put forward by Gregory Clark (2007), according to which wheat demand would have gradually risen from 40 million bushels in 1770 to 170 or more in 1850, with a rapid increase from 1820 onwards. Allen multiplies the share of bread and flour in the average wages by the employed population (manual labour). He obtains the total income spent on bread and flour, which he divides by their respective prices, deducting their volume. Applying a 2:1 relationship between bread and flour, he calculates the total wheat demanded in bushels. To do this, he supposes an income elasticity of bread and flour demand equal to zero at the upper average income levels of manual labourers. The latest estimates have been presented in Broadberry *et al.* (2015), with decennial averages of net physical output and cultivated area taken from a Manorial Accounts Database, a Probate Inventories Database and a Modern Farm Accounts

Database following a supply-side approach. All of these estimates are summarized in Table 1.1.

Table 1.1.
Physical output and demand of wheat in millions of bushels, according to different authors, 1650-1884

Years	Estimate	Type of estimate	Author
1650-59	27.01	Net output	Broadberry *et al.* (2015)
1700-09	27.94	Net output	Broadberry *et al.* (2015)
1700	30.00	Gross output	Deane and Cole (1967)
1700	26.60	Gross output	Allen (2005)
1750-59	31.48	Net output	Broadberry *et al.* (2015)
1750	42.00	Gross output	Allen (2005)
1770	40.00	Demand	Allen (2007)
1800-09	46.32	Net output	Broadberry *et al.* (2015)
1800	50.00	Gross output	Deane and Cole (1967)
1800	50.00	Demand	Allen (2005)
1850-59	73.69	Net output	Broadberry *et al.* (2015)
1850	100.80	Gross output	Allen (2005)
1850	170.00	Demand	Allen (2007)
1860-69	86.07	Net output	Broadberry *et al.* (2015)
1884	80.20	Gross output	British Statistics (1988)

Source: our own calculation. Calculation from the references given in the table.

A second and much more frequent approach is that related to land productivity (yields), measured in bushels per acre. Although we can find abundant information on the Middle Ages, and again in the 19th century, estimates on the early modern era are scarce. This has led researchers to use intermediate methods, with estimates being elaborated from site-specific primary sources, mainly local probate inventories (Overton, 1979, 1991, 1996a, 1996b; Allen, 1988, 1989, 1991, 1999; Glennie, 1991; Turner, 1982, 1986; Theobald, 2002; Yelling, 1970, 1973) and farm accounts (Turner, Becket & Afton, 2001). For the second half of the 18th century and the beginning of the 19th century, there is the well-known work by Arthur Young (see John, 1986). There are also some public statistics, such as the Harvest Inquiries of 1794, 1795 and 1800, Crop Returns in 1801 (Turner, 1982), and the Board of Agriculture Surveys in 1816 (see John, 1986). The works of James Caird in 1852, Mark Lane Express in 1860 and 1861 (John, 1986), or those by John B. Lawes and Joseph H. Gilbert (1893) regarding the results of the Rothampsted experiments between 1852 and 1884. A summary of all these contributions can be found in a chapter on the wheat question published by Turner, Beckett and Afton (2001: 116-149). The figures proposed by M. J. R. Healy and Eric L. Jones (1962) are also available, based on market studies of Liverpool grain merchants, and from data published by B. A. Holderness (1989), which reported 16 Net bu/acre in 1750, 19.5 in 1800, 20.5 in 1810, and 26 in 1850.

Liam Brunt (2004, 2015) used another different approach from the supply-side perspective. This author analysed the production of wheat and its yields. To control for variability, he used climatic variables (temperatures and rainfall), which he related to output data registered by the cereal traders of Liverpool between 1815 and 1859 by means of a regression model (Healy & Jones, 1962). He then predicted crop movements backwards before introducing technological variables to establish the trend.

All of these data have created a difficult puzzle to fit together. Some basic facts do seem quite clear, however. Agricultural output per head increased between 1700 and 1760 (Crafts, 1980). Yet, there is a long debate on what happened before 1700 and after 1760. Mark Overton (1996a) argued that it was between 1750 and 1850 that the Agricultural Revolution took place, whereas Allen pointed out that output grew slowly, and yields fell during the second half of the 18th century. The first wave of innovations (clover, turnips, new Leicester sheep, convertible husbandry) did not seem to contribute much to economic growth from 1760 onwards, and Nicholas Crafts even talked about a *Malthusian shadow* threatening England at the end of the 18th century (Crafts, 1980). It was not until the first half of the 19th century that agricultural output started to rise significantly. Assuming this would help to explain the slow advance of the first stage of the Industrial Revolution and the faster next stage. Allen also suggested a three-stage general chronology: from 1520 to 1739, from 1740 to 1800, and from 1800 onwards. During the first stage, there would have been significant agricultural growth, also pointed out by Jones (1965) and Kerridge (1967) and other authors. During the second stage, output only increased 10% (and yields also began to decline), whereas from 1800 to 1850, agricultural production grew by 65% (Allen, 1999: 210-25).

According to Gregory Clark (2002: 16-25), population growth during the Industrial Revolution was largely supported by food imports. Rather than a productive revolution, there would have been a reorientation of agriculture towards human feeding. Before 1869, improvements in land yields would have been much more relevant than in labour productivity. In this author's opinion, it was a long period of modest but constant advance in crop yields (1600-1750). After that period, a 50-year pause would have followed, when both yields and labour productivity decreased. And then, after 1800, land and labour productivities would start to grow slowly but steadily.

Finally, under another perspective related to consumption, food demand and elasticities, E. J. T. Collins (1975) claimed that it was not until at least 1745 that the increase of income made wheat the most consumed cereal by the English population. During the 17th and 18th centuries rye bread, and that made by mixing other cereals, were basic foods. *Maslin* (wheat and rye bread) and *muncorn* (barley and oat bread) predominated in the

Lowlands. Barley, rye, oat, beans and pulses marked the prevailing consumption pattern. High substitution elasticity would explain why England avoided famine (Appleby, 1979; Hoyle, 2013). Even during the Tudor period, and that of the first Stuarts, Malthusian pressure reduced wheat consumption. Something similar was claimed by chroniclers of the time. Gregory King described wheat consumption as being in the minority at the end of the 17th century. According to Tooke and Newmarch (1838), the increase of wheat bread consumption was slow. In south-west England, the working classes (including agricultural labourers and small farmers) consumed barley. In 1795 less than 45% ate wheat bread, while barley still prevailed in the peninsular counties (55%). In Wales, staple food consisted of barley and oats, whereas in the Midlands the consumption pattern was more diversified (Collins, 1975: 98-9).

Christian Petersen (1995) dated the beginning of the *golden age* of wheat bread between 1770 and 1870, not earlier. We know that between 1656 and 1704 wheat became more expensive than rye (its relative price increasing from 1.23 to 1.89). Although wheat prices decreased later, it was still more expensive than rye in 1739 (1.43), and from 1750 onwards its exchange rate worsened again according to our own calculation using Gregory Clark's prices (2004, 2005, 2007). Using the output estimates of Broadberry *et al*. (2015: 98, 112), we find that in 1650 wheat would have constituted 38.4% of grains (27.01 million of bushels on average), and 36.7% in 1750 (31.48 million bushels on average).

Another sign of increased wheat demand is international trade. It was not until the 1760s that Great Britain became a wheat importer (Ormrod, 1985). Government policies must also have had an influence on this fact: several regulations (*Assize of Wheat, Bounty Acts*) kept wheat prices high thereby affecting domestic consumption (even though it was decreasing in the long run), a fact harshly criticized by Adam Smith in his *Wealth of Nations* (1776). From the second half of the 17th century, export subsidies began to be applied, such as those implemented in 1663 and 1689, although they do seem to have been more effective in the first half of the 18th century. They were cancelled in periods of scarcity, as in the late nineties of the 17th century (Comber, 1808; Hipkin, 2012). Some econometric studies also confirm the influence of Corn Bounties on wheat supply (Tello *et al*., 2017). At the same time, however, it seems that wheat was the most integrated cereal in the different English counties as early as the 1690s (Chartres, 1985, 1995) - although this remains a controversial issue.

In summary, it would seem that cereal consumption was diverse in Britain during the 18th century and wheat did not start to stand out until at least after 1760. Consequently, it is acceptable to assume that the slow income per head rise was not initially a significant factor in wheat demand. Whereas farm management in relation to soil fertility, land yields and labour productivity, together with weather impacts and expectations, determined the evolution of supply, population growth was the main driver of wheat demand. This fact suggests an inverted U-shaped wheat income elasticity (ε_i) over time. In a first phase, it would be null or very low. As wheat bread (and other wheat products) increasingly started to be consumed and replaced other types of bread to become a basic product, ε_i increased. It only fell again when the standards of living improved, consumption diversified, people's preferences changed, and basic needs were better met at the end of the 19th century. We know that elasticities are not fixed over time. As recent research shows, while ε_i is currently low in both countries where wheat is secondary and well-developed countries, it is high in under-developed ones (Abler, 2010).

It has also been observed that price elasticity tends to fall when income elasticity does (Abler, 2010: 21). This trend has been confirmed by Campbell and Ó Gráda's work (2011), which showed that the price elasticity of wheat demand fell in the very long term. These authors analysed Robert Fogel's (2004) and Gunnar Persson's (1999) divergent positions on the issue. Fogel assumed a low price elasticity of demand throughout the Modern Age in England (-0.183). He also provided complementary reasons for product variation such as income distributed unequally and government passivity (Campbell & O'Grada, 2011: 875). Conversely, Gunnar Persson (1999) and Rafael Barquín (2005) proposed higher elasticities (-0.6 and -0.6/-0.8, respectively). This meant a significantly greater threat of famine, mortality outbreaks and dearth compared to Fogel's assumption. In light of these two positions, Campbell and Ó Gráda (2011) adopted a more dynamic vision: if the price elasticity of English grains fell between half and one third in the long term, harvest variability would have substantially decreased, leading to a new period of economic, political and biological progress.

Indeed, most of these pieces of research on agricultural price elasticities may be right in their own terms. The problem lies in the different sources and methods applied to different historical times, which makes it difficult to reach conclusive results. A great deal of these studies have been carried out on food products as a general category rather than wheat. It can be assumed that the absolute value of wheat income elasticity (ε_i) was much lower than that of other food items, such as meat. Nicholas F.R. Crafts (1980) quotes three old works that use cross-sectional data. The first, published by D. Davies (1795) estimated a food ε_i near to 1. The second, by F. M. Eden (1797), obtained similar income elasticity for a group of poor agricultural labourers. And the third, conducted by W. Neild (1841) for industrial workers in Lancashire between 1836 and 1841, established an ε_i of 0.853. Crafts ends up calculating an ε_i of 0.74 for the period from 1820 to 1840, and applying a similar value (0.7) to the period 1700-60 for food in general, though not for wheat (Crafts, 1980: 162). Clark (2002: 29) used similar values in his agricultural demand equation, with an ε_i of 0.6. In Clark, Cummings and Smith (2010), a value of 0.6 is still found for 1860. However, Clark considered the increase in income per head to be small between 1760-69 and 1860-69. Therefore, once more it is assumed that the role played by income elasticity of food demand would have been limited. Following Crafts and Clark, Allen (1999: 213) also suggested a food price elasticity of 0.6.

According to Robert Allen, Clark assumed income elasticity to be below 0.6 because his budget studies did not include high incomes. For the same reason, Crafts estimated an income elasticity for all food products rated at 0.5. That meant a small crossed elasticity of 0.1, and a price elasticity of -0.6. Some years later, Allen (2005) dealt with this subject again, obtaining an income elasticity of 0.5 in 1300, of 1 in 1500 and of 0.5 after 1500. Later, in 2007, he estimated wheat output from consumption per head by assuming demand income elasticity for bread and flour of 0 at those levels above the average income. On the other hand, applying Craft's food ε_i for wheat (0.5), Barquín (2005: 244-50) concluded that wheat price elasticity in England must have ranged between -0.6 and -0.8, questioning Fogel (-0.18) and King-Davenant's Law (-0.4), and agreeing with Parenti (1942) and Persson (1999). By way of conclusion, studies conducted on food price elasticity ε_p range from -0.18 to -0.80, and lately -0.6< ε_p< -0.8. For income elasticity ε_i, the range is between 0 and 1, and more precisely between 0.5 and 0.7. Campbell and Ó Gráda estimates with the available data provided by Turner, Becket and Afton (1997) would be a demand price elasticity of -0.73 (using net yields) in the period 1268-1480, or of -0.57/-0.55 (using gross yields), that would have been lowered to some -0.23/-0.35 from 1750 to 1850 (using gross wheat yields).

3. Methodology used to estimate a yearly series of physical wheat production in England (1640-1761).

If we wish to obtain an annual series of physical wheat output on the basis of probate inventories, there is little we can do. Doing the same thing based on consumption (like Clark or Allen), the results are so general that they do not allow much advance either. But by integrating the two approaches, the outcome is better than the sum of the parts. This is the holistic principle supported in this chapter following Allen's advice: since all methods are indirect (even the one created by Mark Overton relying on probate inventories), it is inevitable that we start from one or several theoretical assumptions. This means that historians must examine all these approaches without underestimating any position, testing all of them all equally against the scarce empirical evidence available (Allen, 1999: 211).

Accordingly, we propose the following estimation method. First, deduce the yearly variation of harvests from the variation of prices. To do this, we need a mathematical expression that relates prices and quantities. Taking the price and physical quantity for the year 1700 (a year of average production), and knowing the prices of other years, we can calculate the physical quantities of all years of the period with an equation based on a price elasticity assumption. We do not have any prior econometric equation for the period 1640-1761. For a standard regression model, we need the two variables of price and quantity, but we do not have the latter. We do, however, have the King-Davenant-Jevons-Bouniatian equation (Davenant, 1771 [1699]; Endres, 1987; Wrigley, 1987; Simonin, 1996). This expression was developed from observations made in the 17th century. There is no written proof that it was developed as such by Gregory King. For this reason, it is believed that it was some kind of "law" discovered by Charles Davenant, who was the first to quote it. According to this "law", the progressive reductions of one tenth of production generated successive price rises in the sequence of 1.3, 1.8, 2.6, 3.8, and 5.5. Compared to a normal harvest, one at 90% would increase the equilibrium price of wheat 130%. A harvest at 80% would increase the price 180%. This supposed "law" – or rather, empirical regularity corresponding to a given historical context— was formalized by Stanley Jevons through an algebraic expression, and later improved by Mentor Bouniatian as follows:

$$y = 0.757/(x - 0.13)^2 \quad (1)$$

Calculated by means of Davenant's Law, price elasticity is -0.403, although Barquín (2005: 244-50) corrected this value downward to 0.360. Generally speaking, Davenant's Law has been acknowledged by economic historians for a long time, from Tooke and Newmarch (1838) to Thorold Rogers (1877) and Bernard H. Slicher van Bath (1963). For example, Mentor Bouniatian proved its validity for American corn price elasticity between 1866-91, and Prussian rye around the middle of the 19th century. Anthony Wrigley accepted its prestige, although it was not clear for him whether Davenant talked about net or gross product, or whether it was also applicable to other places and times (Wrigley, 1987; Nielsen, Smit & Guillén, 2012). There are other authors who have disregarded the price elasticity resulting from Davenant's Law, either considering it to be too low or merely a speculative generalization with no real basis (Barquín, 2005; Persson, 1999; Parenti, 1942). However, Campbell and Ó Gráda's (2011) research on English wheat harvest variability suggests a decrease in price elasticity in the very long term from a value of -0.57 for 1268-1480 to -0.23 for 1750-1850. Surprisingly, Davenant's value is an average of both values that can only be applied to an intermediate stage. Another recent study on 19th century Saxony confirms the validity of this (Uebele, Grünebaum & Kopsidis, 2013).

Furthermore, it seems that this "law" also formed part of English traders' practical oral knowledge. According to William Petty, a good trader had to possess certain abilities: he had to be good at arithmetic and accounting, intelligent, a connoisseur of trading practices and the weights used at every commercial site, and of all the currencies, interest rates and exchange rates. He needed to know about the seasons in which agricultural raw materials were sowed in different places, the shipping points and routes, the relationship between volumes and transaction prices, transport costs, customs duties and wages (1927: 192). Charles Davenant (1656-1714) was himself one of these well informed English traders and extremely knowledgeable about all such 17th-century practices and rules. Taking advantage of his privileged high-ranking position, he published in 1699 *An Essay upon the Probable Methods of Making a People Gainers in the Balance of Trade* (Davenant, 1771 [1699]). Interestingly, this is a work about policy to be applied to fight the fluctuation of harvests, about the prices of grain, and how to profit from trade. Davenant calculated that in a period of good harvests, England could count on five months of grain stock. By estimating the price rise resulting from bad harvests and the observation of Dutch barns management, he suggested that England should take similar stock measures to avoid famine for the poor (Hutchison, 1988: 51-2).

We therefore assume the implicit price elasticity of Davenant's "law" to have been a knowledgeable observation of the time, a very good historical source in itself. The method deriving from this assumption is as follows. In equation (1), y is an index number of the wheat price. Assuming that Clark's price of 1700 is equals to 1 ($y = 1$), we calculate the values for the other years: x represents the proportion (or quotient) between the actual quantity (the numerator) and the "usual" average quantity (the denominator). We assume that this quotient is equal to 1 for 1700, that is, the numerator and the denominator are the same (real quantity = usual quantity), which means considering this an average harvest of a "usual" year according to Broadberry *et al.* (2015) and Deane and Cole (1967) (see also Table 1.1 below). Then, for the other years the numerator (the real quantity of the market) is the unknown variable whose value is to be determined.

It should be noted that in this way we obtain a series in millions of bushels according to the implicit price elasticity of Davenant's Law, but without revealing a trend. We have inferred variations of quantities from variations of prices without considering that both demand (the population to be fed) and supply (wheat acreage and produce) also changed. Ignoring this would mean assuming a completely unrealistic stationary state where only harvests and prices changed yearly. Therefore, we have incorporated a population index to obtain a *second series*, which registers short-term movements (based on King-Davenant's Law) plus the trend derived from population change. The following step is to add another trend factor, income variation, together with an average factor (*n)* greater than 0, which attenuates the effect of income on wheat demand (e.g. 0.4), providing us with a *third series*. The final output in the second and third series depends on the figure that we take as "usual" in 1700 (the denominator). If the output is net, the calculated series is for net production. If the output is gross, the calculated series is for gross production.

Finally, we estimate market demand. If the series obtained shows a net output, we have the supply of domestic produced wheat. If we deduct the net foreign balance (the difference between imports and exports), we obtain the demand for wheat. If the series obtained is for gross output, the part devoted to seeds and other uses must be deducted from the resulting series and the foreign balance added (everything depending on the starting value as the "usual" average quantity).

By means of this method we obtain four output series: in the first one (series I), we take the physical net output provided by Broadberry *et al.* (2015: 398) to be the "usual" quantity in 1700 and we add demographic pressure using the estimates provided by Wrigley. Series II incorporates income growth accumulated in the long term, calculated using the real GDP index taken from Broadberry *et al.* (2015) and corrected with a factor of 0.4. For series III, we take the value provided by Deane and Cole in 1700 (1967) as an alternative "usual" quantity. Unlike the former series, this value is of gross output and we apply the same former population index to it. As a result, it also shows a gross series of wheat production. The fourth series (IV) is obtained by including the same income growth as in series III. To infer total demand in the English market, when necessary, we add the net foreign balance to the net series of each of the series (Mitchell, 1988; Ormrod, 1985).

The aim of estimating four series is to verify two issues. Firstly, whether using net data or gross data is more accurate as a starting point. Secondly, to consider whether it is better to add only population growth as a trend factor, or to add national income as well. We use a physical datum of 1700 as the starting point because it was a regular or "usual" average year. The annual average income from the real GDP is one of the few we have and, according to Broadberry *et al*. (2015), it was obtained independently from the other values (Clark's prices, and Wrigley's population estimated from parish records). We must be aware that GDP and population are statistically related. The series of GDP and wheat prices must also be correlated, given that agricultural GDP forms part of total GDP, and wheat was in turn an important component of agricultural output. Otherwise we would suspect that the series are not derived correctly. Upon performing the independence test, all of the above applies, a correlation coefficient of -0.36 between wheat prices and real GDP, of 0.58 between population and real GDP, and -0.0428 between wheat prices and population, with a critical value at 5% to two tails equal to 0.20 for n = 91 (1650-1740).

The second part of the method used compares the four series obtained, to the available database of land yields, labour productivities and prices at a site-specific micro-level (probate inventories and farm accounts), as well as with other output estimations and total demand accounts at a macro-level. For the net series I and II we carried out an estimation of the gross yield per acre, dividing these series by the surface area of land cultivated with wheat –2 million acres if we follow Broadberry *et al.* (2015) for 1650, 1700, 1750 or Allen for 1750— and adding 2.5 bu/acre as the part devoted to seeds and other uses. For the gross series III and IV, the yield is calculated directly by dividing them by 2 million acres. Following that, we compared the average yields per acre for series I, II, III and IV to those taken from probate inventories and farm accounts. We analysed the deviations to determine which series is closer to current site-specific knowledge. We then performed the opposite procedure to determine what the average surface area should be in order for each of the series to better fit the available yield database we have.

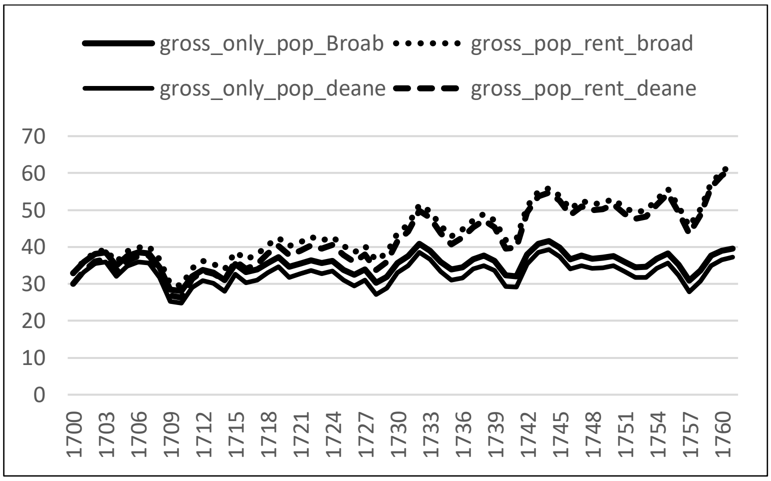
Next, we compared the four series with all of the output estimates available, both net and gross, and with demand figures to again observe which has a lower deviation. Finally, we applied a Cobb-Douglas regression model to the period 1640 to 1761 for the four logarithmical demand series through the non-linear equation $D_{wheat} = P_{wheat}^{\propto} I^{\beta}$, where D_{wheat} stands for the national annual wheat demand in bushels, $P_{wheat}^{\propto}$ stands for annual wheat prices, I is the annual English GDP as a measure of national income (Broadberry *et al.*, 2015), $\propto$ stands for an approximation of price elasticity, and β represents income elasticity. In addition, we also calculated the price elasticity of each of the four series by means of the method proposed by Campbell and Ó Gráda (2011), that is, by differentiating the price and quantity series to eliminate the trend and developing a simple regression model.

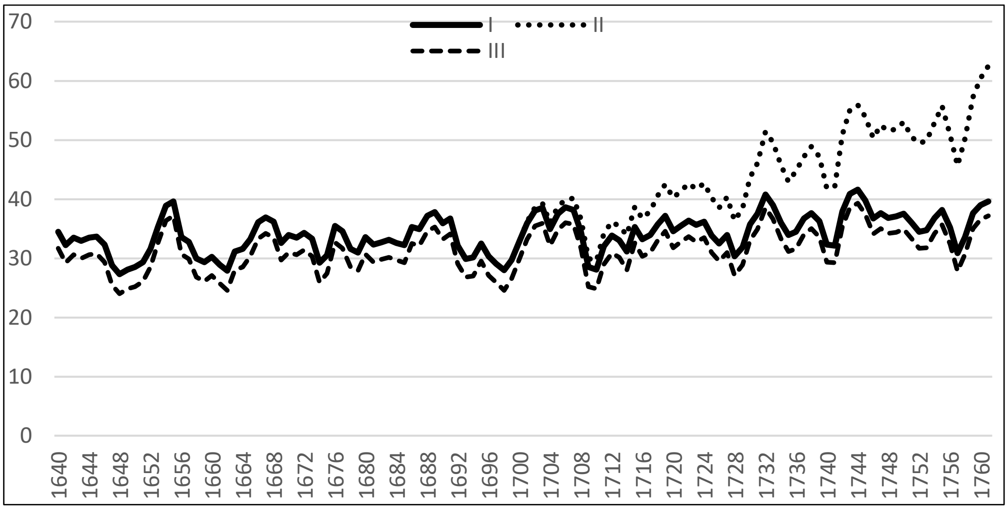
Accordingly, we chose the series with least deviation and tested whether the short-term movements were coherent. To do this, we examined the historiography and verified its correspondence with the movements of the series. Additionally, we linked the chosen series with the first statistics available from 1884 onwards by gradually incorporating a growing income-effect from 1761 onwards (obtaining a new series of net national production, series V) and then adding the net external balance (obtaining a new demand series, series VI). The aim of making this connection was to verify whether the series fits the current long-term historiographical perspective, acknowledging that the price elasticity implicit in Davenant's Law put forward in 1699 gradually lost accuracy and relevance with economic growth in the long run. As Campbell and Ó Gráda (2011) demonstrated, during the process of change from subsistence farming to a market economy prices were increasingly conditioned by international trade and other factors.

4. Discussion.

The four English gross-production series of wheat from 1640 to 1761 (I, II, III and IV) are presented in Figures 1.1 and 1.2. They show a range between the most optimistic (II) and the most pessimistic (III) series. To determine which comes closest to existing evidence, we compared them with the database provided by probate inventories and farm accounts (Tables 1.2 to 1.6).

Figures 1.1. and 1.2.
English gross production of wheat in millions of bushels, 1640-1761





Sources: our own calculation, from the following sources and methods. Series I (gross_only_pop_broad) is obtained with 27.94 million net bushels provided by Broadberry *et al*. (2015) c.1700, applying Davenant's Law with Clark (2004, 2005, 2007) prices, and adding population (Wrigley & Schofield, 1981), as well as 2.5 bu/acre of seeds and other uses. Series II (gross_pop_rent_broad) also adds income variation (based on British GDP by Broadberry *et al*., 2015) corrected with the average value 0.4, adding 2.5 bu/acre of seeds and other uses. Series III (gross_only_pop_deane) takes the gross datum provided by Deane and Cole (1967) for 1700 as a starting point, applying Davenant's Law and adding population. Series IV (gross_pop_rent_deane) adds the income evolution corrected with 0.4 to series III.

According to these results, between 1640 and 1761 average wheat yields were 18.1 bu/acre. The first thing we observe is that the four series correlate well with this baseline and that their implicit yields range from 15.9 to 19.9 bu/acre. Series I and IV present a lower deviation (-4.5% and +3.4%). If we adjust the surface area of land cultivated with wheat for each series to the yields obtained on the farms, we also observe that I and IV have the best fit to the available estimates, and especially series I with a deviation of only 1%. The feeling that series I is the best fit is confirmed by comparing the total outputs estimated by other authors, where the deviation is only 4%.

Table 1.2.
Comparison with English wheat series estimated from probate inventories and farm accounts, 1640-1761

SERIES	Estimated yield	Deviation	Correlation
BROAD_POP (I)	17.3 bu/acre	-4.5%	0.66
BROAD_POP_RENT (II)	19.9 bu/acre	10.2%	0.75
DEANE_POP (III)	15.9 bu/acre	-12.3%	0.65
DEANE_POP_RENT (IV)	18.7 bu/acre	3.4%	0.74

Source: our own calculation. Between 1640 and 1761 average wheat yields from probate inventories and farm accounts were 18.1 bu/acre.

Table 1.3.
English Land surface cultivated with wheat (millions of acres) necessary to fit the yields of the four estimated series to those obtained from probate inventories and farm accounts, 1640-1761

SERIES	**Cultivated area required, in millions of acres**	**Deviation**
BROAD_POP (I)	2.01	1%
BROAD_POP_RENT (II)	2.27	14%
DEANE_POP (III)	1.85	-7%
DEANE_POP_RENT (IV)	2.12	6%

Source: our own calculation. Average surface stated by Broadberry *et al.* (2015) between 1650 and 1750 = 2 million acres.

Table 1.4.
Comparison of our English series of wheat production with outputs estimated by other authors, 1645-1761

SERIES	**Average estimated output**	**Deviation**	**Correlation coefficient**
BROAD_POP (I)	32.1	4.0%	0.80
BROAD_POP_RENT (II)	37.5	21.6%	0.89
DEANE_POP (III)	29.3	-5.1%	0.82
DEANE_POP_RENT (IV)	35.0	13.6%	0.89

Source: our own calculation from the sources and methods explained in Table 1.

The conclusion is simple. Series I, that is, the one calculated from physical estimates originating in Broadberry *et al*. (2015) with Davenant's price elasticity and the population trend (using 1700 as a year of average harvest throughout the period) is the one with the best fit. This is based on two main facts. The first is that the wheat component of the agricultural GDP estimated by Broadberry *et al*. (2015) seems very reliable. The second is about the elasticities. The price elasticities of the different demand curves are -0.39/-0.38 in I, -0.33/-0.39 in II, -0.47/-0.46 in III, and -0.40/-0.47 in IV (Tables 1.5 and 1.6). On the other hand, income elasticity is nearly zero in I and III, and 0.6/0.7 in II and IV.

Table 1.5.
Price and income elasticities of English wheat consumption calculated through the Cobb-Douglas method, 1645-1761

SERIES	Price elasticity	Income elasticity
BROAD_POP (I)	-0.39	0
BROAD_POP_RENT (II)	-0.33	0.59
DEANE_POP (III)	-0.47	0
DEANE_POP_RENT (IV)	-0.40	0.68

Source: our own calculation. Cobb-Douglas method has been applied.

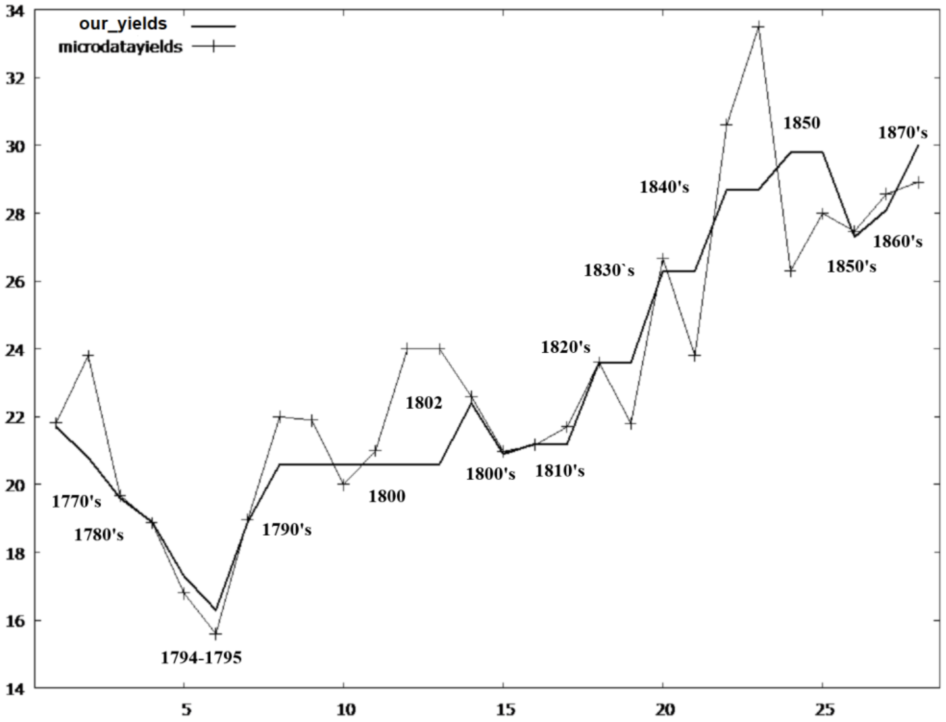
Table 1.6.
Price elasticity of English wheat consumption obtained through differences and logarithms, 1645-1761

SERIES	Price elasticity
BROAD_POP (I)	−0.38
BROAD_POP_RENT (II)	−0.39
DEANE_POP (III)	−0.46
DEANE_POP_RENT (IV)	−0.47

Source: our own calculation. Price and production series differentiation method has been applied.

If series I is the closest to the estimates obtained from farm accounts and probate inventories, it means that Davenant's equation and its elasticity are not mere idle speculation. The equation fits with Campbell and Ó Gráda's (2011) estimates, since it is halfway along the decreasing trend of harvest variability from the Middle Ages to the 19th century. Income elasticity has little significance between 1645 and 1761, proving this to be an age when rent was not a relevant component of consumption decisions. If we tried instead a 0.5 to 0.7 income elasticity of wheat consumption, as has sometimes been claimed, we would move away from the estimates obtained from a large set of farm accounts and probate inventories accumulated during the last forty years. In fact, this would involve an unreliable national wheat yield of 31.2 bu/acre (according to our series II), much higher than the 22.4 provided by Michael Turner *et al.* (2001) for the years 1750-59, the 20 provided by Robert Allen (2005) for 1750, and the 20.1 by Jonathan Theobald (2002) also for 1750. The only way to consider income a significant demand factor throughout the period from 1640 to 1761 in a way that might fit the available estimates, and our own results, would be to assume a higher average of wheat cultivated area of around 10%, or the part allocated to seeds and other uses being 50% lower than the ones considered here — something that would require significant advances in empirical studies based on local sources to allow a profound change in current assumptions.

Figure 1.3.
Gross yields in bu/acre of our series V of English wheat production, compared to those resulting from other site-specific sources indicated in the previous tables, 1760-1870



Source: our own calculation.

The above does not preclude the existence of a structural change during the second half of the 18th century, through which income elasticity would have gained momentum along with the growing income per capita. If we try to incorporate this ascending effect in series I, lengthening it until 1850 with an average income elasticity of 0.6 (that is, close to 0 until the mid-18th century and growing to 1 in the 19th century), we see how the evolution of the wheat output, demand and yields obtained fit the trends observed by economic historians so far (series V and VI, Figures 1.3 and 1.5, Table 1.7). The correlation coefficient between our gross yield estimations of wheat per acre and those observed in the main sources is 90%, and average deviation between them is only 1%. These results have been obtained through a logarithmic regression model of the series between 1640 and 1870: we obtain a non-linear equation of $D_{wheat} = P_{wheat}^{-0,65}\, P_{agric}^{0,8}\, I^{0,6}$, where D_{wheat} stands for the national demand of wheat in bushels, P_{wheat} stands for wheat prices, P_{agric} is the centennial index of agricultural prices and I stands for the British centennial GDP (Broadberry *et al*., 2015). The addition of the three elasticities is not equal to zero, since we are not in perfect competition.

However, the accuracy of these results depends to a high degree on two variables: the wheat cultivated area and the difference between the gross and net outputs; that is, the resulting quantity after deducting the part allocated to seeds, personal consumption, payments in kind, animal feeding or losses. This stands true for the whole period analysed here. The number of acres of land used in wheat cultivation is unknown, but there is evidence that demographic pressure, together with prices and income changes, strongly affected its evolution in the long term. All published researches assume that from the second half of the 17th century on, the wheat cultivated area grew steadily until soon after the massive introduction of the American grain imports during the 1870s and 1880s. Robert Allen (2005) provided the estimates of 1.4 million of acres in 1700, 2.1 in 1750, 2.5 in 1800, and 3.6 in 1850. The statistical series of wheat cropland surface began in 1867 with 3.37 million acres.

Regarding the difference between net and gross yields per acre, what we can say on the whole is that this difference must have been between 2 and 2.5. Peter J. Bowden (1985) provided some site-specific estimates on wheat harvest detraction of seeds for sowing and animal feeding ranging from 2.25 to 3.37 bushels/acre between 1670 and 1745. Mark Overton (1984) quoted Bennet (2-2.5 bu/acre) and King (who estimated a range of seed-yield ratios from 1:4 to 1:8). Anthony Wrigley (1987) suggested a reference value of 2.5 (quoting Bowden and Slicher van Bath), plus 1 in other cereals for cattle-feeding. In some passages in their writings on agriculture, Robert Plot and John Mortimer claimed that farmers sowed between 2 and 2.5 bu/acre of wheat, or 2 bu/acre in poor soils and 3 in the most productive, respectively (Plot, 1705: 250; Mortimer, 1712: 95). All of these estimates exclude personal consumption, payments in kind or simply losses within farms.

Our series can also be compared with the crop estimates provided by English agricultural historiography. William G. Hoskins (1968: 20-2) described as deficient those crops from the years 1646, 1657, 1710, and 1711; as bad or very bad crops those from the years 1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728 and 1729; as “average” crops those from the years 1699, 1700, 1718, 1719 and 1720; and as good crop years those from 1652, 1653, 1654, 1655,

Table 1.7.

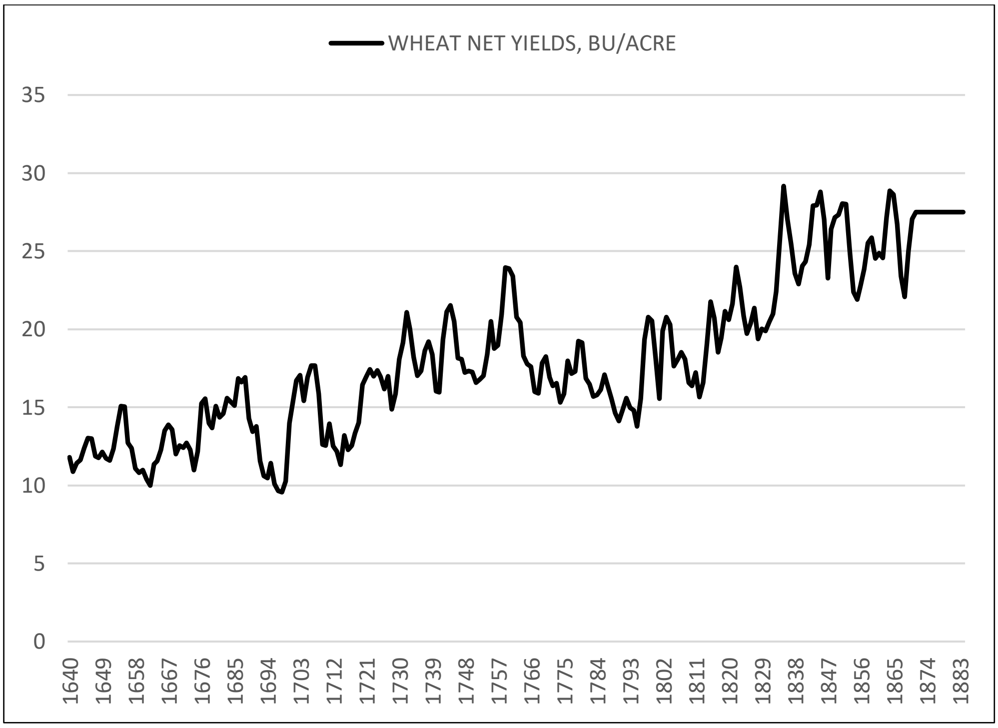
Comparison of different estimates of English wheat yields, 1760-1879

Years	Our estimates (gross, bu/acre)	Other authors (gross, bu/acre)	Deviation	Authors
1760-69	21.7	21.82	0.5%	Turner *et al.* (2001)
1770	20.8	23.80	12.6%	Artur Young (John, 1986)
1770-79	19.6	19.68	0.4%	Turner *et al.* (2001)
1780-89	18.9	18.88	-0.1%	Turner *et al.* (2001)
1794	17.3	16.8	-3.0%	Harvest inquiry (John. 1986)
1795	16.3	15.6	-4.5%	Harvest inquiry (John, 1986)
1790-99	18.9	18.97	0.4%	Turner *et al.* (2001)
1800	20.6	22	6.4%	Oxon (Allen, 2005)
1800	20.6	21.9	5.9%	Harvest inquiry (John, 1986)
1800	20.6	20	-3.0%	England (Allen, 2005)
1800	20.6	21	1.9%	Hants (Glennie, 1989)
1800	20.6	24	14.2%	Herts (Glennie, 1989)
1800	20.6	24	14.2%	Holderness (1989)
1802	22.4	22.6	0.9%	Crop Ret. (Turner *et al.*, 2001)
1800-09	20.9	20.98	0.4%	Turner *et al.* (2001)
1810-19	21.2	21.17	-0.1%	Turner *et al.* (2001)
1810-19	21.2	21.7	2.3%	Healy and Jones (1962)
1820-29	23.6	23.6	0.0%	Turner *et al.* (2001)
1820-29	23.6	21.8	-8.3%	Healy and Jones (1962)
1830-39	26.3	26.67	1.4%	Turner *et al.* (2001)
1830-39	26.3	23.8	-10.5%	Healy and Jones (1962)
1840-49	28.7	30.6	6.2%	Turner *et al.* (2001)
1840-49	28.7	33.5	14.3%	Healy and Jones (1962)
1850	29.8	26.3	-13.3%	Craigie (1883; from Turner *et al.*, 2001) 1982(1982)]
1850	29.8	28	-6.4%	Allen (2005)
1850-59	27.3	27.47	0.6%	Turner *et al.* (2001)
1860-69	28.1	28.57	1.6%	Turner *et al.* (2001)
1870-79	30	28.92	-3.7%	Turner *et al.* (2001)
Mean	23.03	23.36	1.1%	
Median	21.2	22.3	0.5%	
Minimum	16.3	15.6	-13.3%	
Maximum	30	33.5	14.3%	
Standard deviation	4.07	4.160	0.07	
C.V.	0.177	0.178	6.23	

Source: our own calculation. The correlation coefficient between the two columns is 0.9.

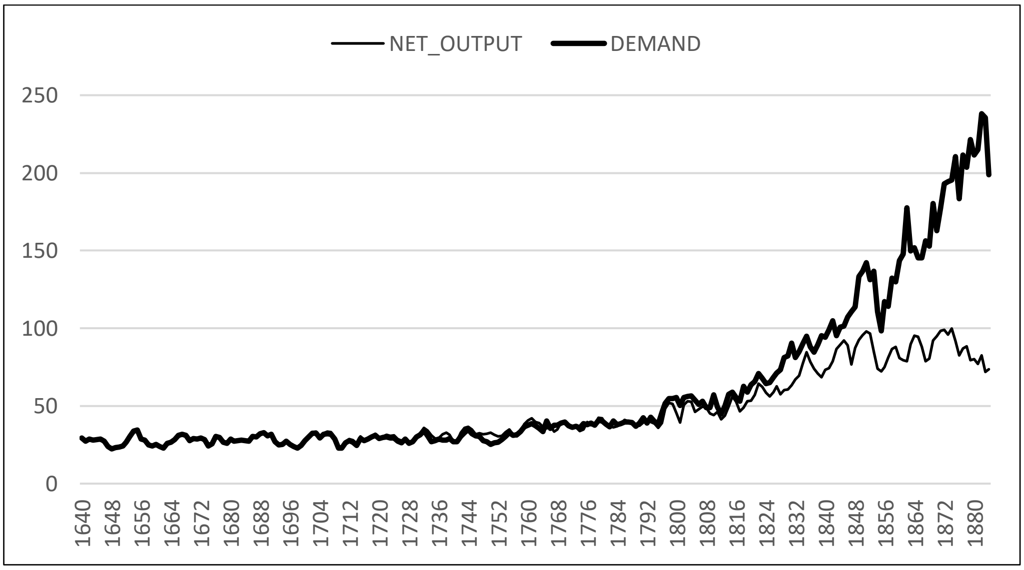
1665-72, together with the 1680s, generally good, as well as the periods 1700-07 and 1721-23. Peter Bowden (1985: 56) suggested the existence of bad crops in the second half of the 17th century in the periods 1645-51, 1656-63, 1695-99 and good crops in the periods 1664-72, 1685-91, 1714-24, and 1741-49. Our series fits the period 1640-1750 quite well (Table 1.8).

Figure 1.4.
Long-term evolution of English wheat yields in bu/acre, from 1645 to 1850



Source: our own calculation.

Figure 1.5.
Long-term comparison of our estimates of English wheat output and demand in millions of bushels (series V and VI)



Source: our own calculation.

Table 1.8.
Comparison of the variation of our English series of gross wheat output with the available chronology of the character of harvests, 1645-1749

Hoskins	**Years**	**Wheat gross output (bushels)**
Deficient crops	1646, 1657, 1710, 1711	31,306,518 (-8.8%)
Bad and very bad crops	1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728, 1729	30,330,181 (-11.6%)
Average crops	1699, 1700, 1718, 1719, 1720	34,302,075
Good years	1652, 1653, 1654, 1655, 1665-72, 1680s generally good, 1700-07 and 1721-23	35,332,446 (+3%)
Bowden	**Years**	**Wheat gross output (bushels)**
Bad crops	1645-51 1656-63 1695-99	29,696,256 30,491,192 29,886,137
Good crops	1664-72 1685-91 1714-24 1741-49	34,251,154 35,718,380 34,976,126 37,842,623

Source: our own calculation.

This verification can be completed by comparing Table 1.8 with the sequence of food riots studied by John Bohstedt (2010), a clear coincidence being observed with the worst production years. Furthermore, our annual series of wheat production also allows us to clear up some discrepancies. For example, Hoskins claimed that 1699 was an average year, whereas Bowden considered it bad. Who was right? Our results are 29.7 million bushels, a low figure. Therefore, it would appear that Bowden was closer to reality.

5. Conclusions.

This chapter presents the first estimation of the English annual series of wheat production, yields (considering acreage) and demand (adding foreign net trade balance) for a period for which these data are unknown: 1645-1761. The methodology applied is based on the price elasticity in England calculated by Charles Davenant in 1699, anchoring the series on the "usual" average harvest of 1700 and setting a long-term trend based on population and income growth in a way that allows supply and demand to be integrated by considering a slow increase in income elasticity from 1750 onwards. The results match the available estimates on yields and harvests gathered from site-specific farm accounts and probate inventories from that period, and also indicate that the starting points used by Broadberry *et al.* (2015) to build up the agricultural GDP in 1700 are reliable, at least in the case of wheat.

Through this exercise, Davenant's Law has been revealed to be much more accurate than just guesswork, probably because it was based on well-grounded empirical knowledge of British traders at the time. The series generated fits well with the independent sources available and confirms both the decreasing trend of price elasticity in the very long term (Campbell & Ó Gráda, 2011) and historiography on the variability of wheat crops (Hoskins, 1968; Bowden, 1985; Bohstedt, 2010).

The estimates carried out in the chapter suggest that income elasticity had little significant effect on consumption decisions, at least until the mid-18th century, increasing in importance at a later date. If we lengthen the series to the year when official statistics began in 1884, assuming an income elasticity of 0.6 for the whole period 1645-1884, the trend fits the available estimates on yields and output. The series confirms that wheat production and yields evolved negatively during the second half of the 18th century, and took off dramatically in the 19th century. Accordingly, seen from a production and yields perspective, the Agricultural Revolution seems to have taken place in two very different periods, before 1750 and after 1800.

However, many questions remain open. The change in surface area cultivated with wheat must be better studied. It is necessary to consider possible changes in the percentage allocated to seeds in more detail, as well as their uses other than market sale. The new estimates should also be extended to other cereals until 1884. The reasons behind the structural breakpoint found around 1761 must also be found, when wheat yields started to fall, total wheat production slowed down, England became a net importer, prices rocketed, and physical wheat consumption per head fell, despite bread intake remaining more stable thanks to substitution among grains.

6. Acknowledgements.

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7. Appendix.

Table 1.9. Wheat Gross Output

YEAR	WHEAT GROSS OUTPUT (BROAD_POP, SERIES I) Million bushels
1640	34,5
1641	32,2
1642	33,5
1643	32,9
1644	33,5
1645	33,7
1646	32,3
1647	28,8
1648	27,3
1649	28,1
1650	28,5
1651	29,3
1652	31,6
1653	35,3
1654	38,9
1655	39,6
1656	33,6
1657	32,8
1658	30,0
1659	29,3
1660	30,2
1661	28,9
1662	27,9
1663	31,1
1664	31,6
1665	33,2
1666	36,1
1667	36,9
1668	36,2
1669	32,6
1670	33,9
1671	33,5
1672	34,3
1673	33,3
1674	29,2
1675	30,5
1676	35,5
1677	34,6
1678	31,6
1679	31,0
1680	33,6
1681	32,3

1682	32,7
1683	33,1
1684	32,6
1685	32,2
1686	35,3
1687	34,9
1688	37,2
1689	37,8
1690	35,9
1691	36,7
1692	32,1
1693	29,9
1694	30,1
1695	32,5
1696	30,3
1697	29,1
1698	28,0
1699	29,7
1700	32,9
1701	35,9
1702	38,1
1703	38,5
1704	34,9
1705	37,5
1706	38,6
1707	38,2
1708	34,5
1709	28,5
1710	28,1
1711	32,0
1712	33,8
1713	33,0
1714	31,1
1715	35,3
1716	33,2
1717	33,9
1718	35,7
1719	37,2
1720	34,6
1721	35,5
1722	36,4
1723	35,6
1724	36,2
1725	33,8
1726	32,5
1727	33,9
1728	30,3
1729	31,9

1730	35,7
1731	37,5
1732	40,8
1733	39,0
1734	36,0
1735	33,9
1736	34,5
1737	36,7
1738	37,6
1739	36,3
1740	32,3
1741	32,1
1742	37,9
1743	40,9
1744	41,6
1745	39,8
1746	36,7
1747	37,6
1748	36,8
1749	37,1
1750	37,5
1751	36,0
1752	34,5
1753	34,7
1754	36,8
1755	38,2
1756	35,2
1757	30,9
1758	33,6
1759	37,6
1760	39,0
1761	39,6

Chapter 2. Assessing climate impacts on English economic growth (1645-1740): an econometric approach[12]

1. Introduction.

The threat and challenges climate change pose to the current model of social and economic development have aroused growing interest among social science researchers and public institutions, as well as some convergence in its diagnosis and future consequences (Dell et al. 2014). As these same studies recognize, the only laboratory available to perceive humanity's capacity to adapt to these changes is historical research (Parry 1978). Within this framework, one of the historical climate episodes that has aroused greatest interest among climatologists and historians has been the Little Ice Age (LIA, 1350-1850), as recently summarized by Camenisch and Rohr (2018), and in particular the period known as the Maunder Minimum (1645-1715). Some historians have argued that the marked worsening of climatic conditions in the medieval period (Campbell 2010, 2016) and in the seventeenth century (Parker 2013; White 2014) had a significant impact on the world's population and economy. However, there is no unanimous scientific agreement regarding the intensity of these climate disturbances or their impact on human activities. Even more, Kelly and O'Gráda (2014) have questioned these effects: in the very long term, the series of temperatures are stationary and do not have drastic breakpoints, although a correspondence has been observed between temperatures and volcanic activity, to which some relevance is attributed when explaining the decrease in temperatures (Owens et al. 2017) among other hypotheses (Koch et al. 2019).

This work is based on well-established assumptions in the socio-ecological literature, namely that in pre-industrial societies almost all of the energy that was consumed depended on the flow of solar radiation and on the management of organic converters that transformed that primary energy into food and fuel for rural and urban communities (Wrigley 2010; Smil 2017; Kander et al. 2013). Under these circumstances, we can expect that strong climatic fluctuations in the short and medium term may have played a relevant role in causing or hindering the changes that generally took place in the aforementioned communities (Overton 1989). In the same vein, we can assume that these impacts would have been particularly intense during extreme climatic periods (Cullen 2010; White 2014; Campbell 2016). Therefore, excluding climatic factors from the development models

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[12] Martínez-González, J.L., Suriñach, J., Jover, G., Martín-Vide, J., Barriendos-Vallvé, M., Tello, E. (2020). Assessing climate impacts on English economic growth (1645–1740): an econometric approach. *Climatic Change* 160, 233–249. https://doi.org/10.1007/s10584-019-02633-0 [JCR IF 2019: 4.134; Q1 in Environmental Science, Atmospheric Science and Global and Planetary Change, Multidisciplinary]. Martínez-González is the main author. Jordi Suriñach has supervised the robustness of the econometric models. Gabriel Jover-Avellà and Enric Tello have been careful to ensure that the text is in line with agricultural and environmental history. Javier Martin-Vide and Mariano Barriendos have reviewed the text to avoid inconsistencies from the climate history.

used to explain the historical paths of pre-industrial organic societies may reduce their explanatory capacity.

The aim of this chapter is to evaluate the effects of the climatic disturbances that took place during the Maunder Minimum on agriculture, the population, the energy transition, and the economy at large. The analysis will be focused on those socio-ecological processes in which climatic interferences on soil management (agriculture) and the well-being of individuals (energy availability) can be more easily approached from a logical and quantitative perspective. The study will distinguish between two periods: the first, from 1645 to 1700, that was especially cold and wet and climatic disturbances were more intense; and the second, warmer subsequent period (1700-1740). The study will focus on England for two reasons, firstly, because it has played a central role in the debates on the relationship between climate and economic changes during that period (Hoyle 2018), and secondly, because we can count on economic and climatic instrumental series to carry out this exercise.

The chapter is divided into the following sections. The first deals with the main historiographical and scientific discussions on the relationship between climate change and socioeconomic conditions. The second describes the sources, the model and methodology used. In the third, we present and discuss the results. And finally, the conclusion considers the strengths and weaknesses of the available econometric evidence on the relationship between climate and economic changes during the Maunder Minimum.

2. Climate and economic changes in England between 1650 and 1750: historical and current evidence.

The period 1650-1750 has been considered the starting point of the economic transformation towards the Industrial Revolution in England (Clark 2005; Broadberry et al. 2015; Crafts and Mills 2017). Several changes allowed that jump to be made: an increase in agricultural productivity, commercial expansion, and the growth of London urban population and those of other cities (Jones 1965; De Vries 1984; Wrigley 1985; Allen 2009). These transformations were achieved via the intensification of human work and energy consumption (De Vries 1994, 2008; Warde 2007; Malanima 2015). However, a whole historiographical tradition has stressed that these economic improvements took place in the second half of the seventeenth century under adverse climatic conditions. Climate studies have shown that in England, and all over Europe, average annual temperatures decreased and their interannual and seasonal variability increased throughout the period 1645-1715, while average rainfall also increased, particularly in the warmer months (Collins et al. 2002; Luterbacher et al. 2001; Brázdil et al. 2010; Parker 2013). These phenomena coincided with prolonged minimum solar activity, a period known as the Maunder Minimum (Eddy 1976), an increase in volcanic activity (Owens et al. 2017) and a decrease in the carbon global concentration in the atmosphere (Koch et al. 2019).

Studies on the relationship between climate and agriculture have yielded the most relevant results on the subject. They have shown that a cooler, wetter climate and a greater seasonal and interannual variability had relevant effects on crops and livestock production (Jones 1964; Appleby 1979, 1980; Overton 1989, 1996; Cullen 2010; Hoyle 2013). This involved not only direct impacts on crops deriving from extreme meteorological variations (frosts, storms and excess rainfall; see Jones 1965; Appleby 1979; Cullen 2010), but also agro-climatic changes that affected harvests in a longer term. On the one hand, less solar radiation and other atmospheric phenomena (such as a greater number of cloudy days reinforced by volcanic eruptions) combined with lower temperatures and led to a shortening of the plant growing season, and to a lower soil microbial activity. On the other hand, an increase in summer rainfall led to more leaching processes of soil nutrients (nitrogen, phosphorus and potassium), altered the acidity of soils, and increased pest infestation of crops (Camenisch et al. 2016; Tello et al. 2017). This type of relationships, of which there is some historical evidence for the period studied, has also been observed in modern advanced agriculture that is expected to be less weather dependent (Dell et al. 2012, 2014; Powell and Reinhard 2016).

However, a number of studies have also suggested that the worsening of the climate may have induced innovation in soil and plant management (Overton 1989; Hoyle 2013). Experimentation with drainage systems, manure fertilization and rotation of grains with legumes, as well as the introduction of new crops or species more resistant to cold or moisture have all been presented as evidences of adaptive behaviour. These studies have argued that although such practices had little effect on the increase on wheat yields during the second half of the seventeenth century (in contrast with other cereals such as barley), they did contribute to the further increase in yields when the climatic conditions improved in the first half of the eighteenth century (Michaelowa 2001; Tello et al. 2017). This impact of the hardening of the climate has been recorded in other Atlantic regions, particularly, the cultivation of cereals in Central Europe (Holopainen and Helama 2009; Pei et al. 2016; Zwiter 2015).

Climate change can also help explain one of the paradoxes of that age: the increase in the rate of urbanization in a period of decelerated population growth (Wrigley 1985). The effects of climate on demography were not necessarily direct, as they are mediated by other environmental and food factors, as numerous studies in today's advanced societies have highlighted. Outside the comfort zone of the human body (between 18 and 22 ºC) there are cardiovascular, respiratory and digestive effects and other physiological changes such as cerebrovascular problems, ergotism and fungal diseases that lead to increased mortality among the more vulnerable social groups (Deschênes and Greenstone 2012; Braga et al. 2001, 2002; Parsons 2014; Heal and Park 2016; Camenisch et al. 2016; Pillay and van den Bergh 2016). As current biomedical studies show, decreases in temperatures continue to have more drastic effects on health than increases (Keatinge et al. 2000; Martens 1998).

Historical research on England has also observed that a decrease in temperatures may have contributed to an increase in mortality, due to the increased presence of respiratory and cardiovascular diseases, a fertility decrease (due to increased mortality rate among pregnant women and foetal infections), and a drop in the nuptiality rate (Wrigley and Schofield 1981; Galloway 1985, 1986, 1994; Houston 1996). It has been observed in other geographical areas and periods that certain epidemics spread more easily when there is a decrease in temperature and an increase in humidity (Stenseth et al. 2006; Alfani and Murphy 2017; Campbell 2010). Thomas Sydenham (1676), considered the father of English medicine, linked weather and diseases, year per year. Recently, new anthropometric and biomedical studies have abounded in the same direction (Koepke and Baten 2005; Almond and Currie 2011; Graff Zivin and Shrader 2015; Heal and Park 2016).

Might this hardening of the climate have affected people's ability to work and comfort? The availability of work depended, in addition to economic and social factors, on the strength of the labour force in its most physical sense: the amount of energy that individuals should spend to work and reproduce, after discounting the energy required by the vital functions of the organism. Current studies show a 17 to 50% increase in energy expenditure with cold temperature (Mäkinen 2006; Claessens van Ooijen et al. 2006; Ocobock 2014, 2016). Thus, in order to maintain their work capacities during a period of colder temperatures in a wetter environment, people would have to consume more foods and heat (Malanima 2015).

Current researches have shown that, *ceteris paribus*, thermal stress during a temperature decrease can affect workers in at least two ways: through direct physical effects or through psychological discomfort, which cause a change in effort per hour and reduce short-term labour productivity (Graff Zivin and Neidell 2014; Seppänen et al. 2006; Heal and Park 2016; Pillay and van den Bergh 2016). These results allow us to recover the hypothesis raised by British historian Donald C. Coleman many years ago (Coleman 1956): might the decrease in temperatures have affected the labour force availability and labour productivity during the seventeenth century (Jones 1965; Finzi 1986, 1998)? Did this climate pressure end up affecting the remuneration of labour? In addition, recent studies have suggested that the decrease in temperatures may have played a role in the energy transition from firewood and charcoal to coal in England. All in all, the colder temperatures may have increase demand for endosomatic (food intake) as well as exosomatic (fuel) energy carriers (Flinn 1985; Hatcher 2003; Warde 2007; Kander et al. 2013; Malanima 2015).

Some authors have gone further by suggesting that the variation in aggregate production may have been due to the inclement weather. In areas where temperatures are persistently low, there is an increase in energy expenditure in both the agricultural and manufacturing sectors and at home. The hardening of climatic conditions can even induce an increase in wages or the substitution of labour for capital in the medium term (Park and Heal 2013;

Graff Zivin and Neidell 2014; Graff Zivin and Shrader 2015; Graff Zivin and Neidell 2016). Currently, robust evidence has been provided regarding the effect of an increase in temperatures on the reduction in economic growth rates due to decreased productivity in warmer countries (Dell et al. 2012). An opposite effect (increased productivity) has been found in temperate countries that experience significant drops in temperature (Heal and Park 2016). Many cross-sectional analyses have found strong evidence of a negative relationship between temperatures and economic activity in contemporary economies (Dell et al. 2014). We have good reason to assume that this relationship should have been much stronger in pre-industrial organic societies (Camenisch and Rohr 2018).

Based on these historical or current evidences, our aim is to explore this set of probable relationships between climate change and economic performance in England during the Maunder Minimum, using the available data to perform econometric tests.

3. Sources and methods.

The greatest problem facing empirical analysis is the scarcity and poor quality of data. Most available sources are estimates or indirect approximations from which relatively homogenous series of the relevant variables have been constructed by historians. Therefore, there is a high risk of error due to lack of reliable and independent exogenous variables to complete models, as well as possible endogeneity problems. In addition, when trends or variations in climatic series are studied in climatology, they must be homogeneous. That is, they should only reflect the natural behaviour of the observed variable, without external interferences to the phenomenon maintained over time.

Therefore, the results must be considered with caution, taking into consideration that this is only an empirical exploration using a multiple linear regression approach to the available metadata. Econometrics is used primarily to find evidence of short-term impacts. No panel techniques have been used, because there are not enough data (or of enough quality) to carry out a cross-sectional and dynamic analysis. It must also be taken into account that climate is an abstract and complex concept, in which the conjunction of elements is more important than their individual consideration. Climatic variables can be combined according to different functional relationships, and not necessarily linear ones, with different weights in different periods. This makes our econometric analysis even more difficult in a historical period without reliable statistics.

Although pre-instrumental climatic data are scarce, we do have series of temperatures and rainfall, as well as other exogenous indicators that affect climate and life, such as solar radiation and volcanic dust. There is a series of monthly temperatures for the Midlands that begin in 1659, known as ‘Central England Temperature’ or CET (Manley 1974). CET is a very valuable series of temperature, the longest in existence. For solar radiation and volcanic activity, we can refer to the series provided by Mann et al. (2000). Although there are no serial records of humidity or rainfall for the seventeenth century, some recent research is beginning to shed light on this issue through the reconstruction of historical series of rainfall between May and August (summer) in southern England (Rinne et al. 2013), between March and July (spring-summer) in the east of England (Cooper et al. 2012), and between March and July (spring-summer) in southern and central England (Wilson et al. 2012). At this point, it is important to highlight the interdependence between temperature and rainfall. The correlation between the CET temperatures and the series of rainfall in England and Wales during the summer varies according to the period analysed, but the warmer the climate, the drier it is. It is unlikely that a relationship that persists throughout the twentieth century does not apply to the seventeenth and eighteenth centuries. Although the multicollinearity statistics do not show any cause for concern it is reasonable to suggest that there will be some correlation between rainfall and temperature at the seasonal level and that this should be borne in mind.

A series of annual wheat production (in volume and weight) has been obtained for English and Wales from a new estimate of the physical product using the King-Davenant approach. The series fits very well with the trends and oscillations shown by other local and shorter series constructed from probate inventories and farm accounts (Martínez González 2016; Martínez González et al. 2019). Annual demographic indicators (population, births, marriages and deaths) are taken from Wrigley and Schofield (1981).

Real GDP at constant prices is taken from Broadberry et al. (2015), and GDP per capita is obtained by dividing the former by the population. Expenditure on coal consumption is calculated by multiplying the price of coal per tonne (Clark 2004, 2005, 2007) by its consumption (Warde 2007), after converting petajoules to equivalent tonnes of coal. Shipments of coal from Newcastle are taken from the mining accounts (Hatcher 1993), although the series only goes up to 1700. According to Hatcher, 75% of these shipments were to London. According to Broadberry et al. (2015), these shipments are also an excellent indicator of the increase in coal consumption in England. Corn bounties is a series of dummy variables with a value of 1 in the years when public export subsidies, and high import tariffs were applied, and a value of 0 when they were not applied during years of greatest scarcity (Ormrod 1985). The labour productivity for wheat cultivation is a physical value, which is obtained by dividing the gross production of wheat by the male labour force, calculated above. Total male agricultural productivity is the quotient between the real agricultural GDP (Broadberry et al. 2015) and the male labour force.

All the series of daily wages (for agricultural workers, craftsmen and construction workers) and grain prices (wheat, barley) are taken from Gregory Clark (2004, 2005, 2007). A proxy of real agricultural wages is obtained by relating daily agricultural wages to wheat prices. We use daily wages and not annual salaries, although it should be noted that the former only comprised part of the labour market. A significant proportion of agricultural workers received annual salaries, which included board and lodging (Kussmaul 1981). The demand for agricultural work shifted between both markets, and even required reserves of female and child labour during periods of intense demand, especially during agricultural labour intensification processes. However, temporary fluctuations are more likely to affect daily wages (the casual work market) than annual salaries.

The econometric method applied is presented in two parts: climate impacts on economic activity and society (*i*); and on the aggregate economic growth (*ii*). First, we try to find possible indications of biophysical effects on cropland production (agriculture), population growth (demography) and energy consumption (*i*); and then on wages and the economic growth as a whole (*ii*). We define 'climate impacts' in the following sense: *"climate change operates indirectly through multiple pathways, to affect economic activity and human well-being. These pathways include the biophysical effects of changes in temperature, precipitation on crop yields, human health, and plant pest and diseases*" (Feola et al. 2014).

We use the same impact equation that is presented in modern literature (Dell et al. 2014), with the following general formula:

$$\boldsymbol{Y_t = \alpha + \beta C_t + \gamma X_t} \qquad \textbf{(1)}$$

Where $\boldsymbol{Y_t}$ is the impact variable to be studied. In this paper, the series used are either in physical terms (output of wheat, physical labour productivity, population, birth rate, mortality rate, marriage rate) or in economic value (coal prices, coal expenditure, economic productivity, daily wages of agricultural workers, craftsmen and construction workers, GDP). In addition, $\boldsymbol{C_t}$ is the set of climatic variables (temperatures, rainfall) and other impact factors that affect the climate and all life processes (volcanic dust, solar radiation), and $\boldsymbol{X_t}$ could represent other possible explanatory variables that would come into play.

4. Results.

4.1 Impacts on agriculture, population growth, and energy consumption.

Table 2.1 (see supplementary material) shows two multiple regression models between production (dependent variable) and a group of independent variables (climatic and economic). On the whole, a statistically significant relationship is detected between climate and gross wheat production or barley price, which explains between 46 and 72% of the behaviour of the endogenous variable. The Ramsey reset test indicates that the linear relationship is the best specification of the model with respect to squared or cubed temperatures, or both exponents. In the first model, a 1° C drop in temperature and a 50 mm increase in summer rainfall generates an approximate average fall in wheat production of -3.5 million bushels. This combination of cold and wet weather was very common between 1659 and 1700: 38 years out of 41 had temperatures lower that the average ones in the first part of the twentieth century. That is, it was a much colder and wetter period than the contemporary one before the beginning of current global warming (Fig. 2.1). The impacts occurred during the year of the harvest considered, and in following ones. This suggests that the climate affected wheat harvests in two ways: through the direct effects of temperatures, rainfall, and storms, and through indirect effects on the rate of nitrogen (N) mineralisation and accumulation of organic matter (Tello et al. 2017). Although the lagged variables suggest the impacts had an interannual effect, the correlograms show that all of the series in model 1 are stationary, meaning that the observed shocks were short-term. The absence of very persistent effects could suggest the existence of adaptations, although this could also be due to a more statistical reason: since the variables are not cointegrated, we cannot establish an error correction model.

Unlike wheat, in barley, we do not have a series of annual production in bushels. According to Broadberry et al. (2015), barley production rose from 33.5 to 35.5 million bushels between 1650 and 1700. Barley had different characteristics from wheat. Firstly, it was a substitute for wheat in times of bad harvests (Appleby 1979, 1980; Hoyle, 2013), so its price also depended on how the wheat was produced. Secondly, barley was a spring cereal, which made it immune to the cold of winter, but it was sensitive to inclement weather during the harvest and summer rains (such as wheat, or a bit less). Excessive humidity also damaged the stored grain. Thirdly, demand for beer was a key factor in barley production. In 1700, 70% of the total was for brewing (Broadberry et al. 2015). Fourthly, it was also used to feed livestock. There is no doubt that the issue of barley deserves more research. However, in a first approximation (Table 2.1, model 2), we find that wheat production, temperature and the price of beer are very significant variables for the price of barley. The price of barley increased if wheat production declined (as it was a substitute cereal), if beer demand increased (as the main source of demand), if temperatures rose (implying that heat encouraged drinking), or if summer rains increased (damaging crops). According to these results, climate seems to have had significant impacts on agriculture. Although this impact was not necessarily prolonged, since adaptation strategies and agricultural improvements will have mitigated it, these results do corroborate those of other studies that have suggested similar interpretations (Jones 1964, 1965; Overton 1989, 1996; Michaelowa 2001; Waldinger 2014; Brunt 2004, 2015; Campbell 2010, 2016).

The regression models 3 and 4 present two stationary demographic variables (marriage and mortality), and climatic data are taken as explanatory variables. The minimum-quadratic regressions show a significant (positive) relationship with average annual temperatures and spring rainfall in the case of marriages, explaining 50% of the endogenous variable. The result suggests that good weather (which meant good harvests) was a factor that influenced decisions to get married. According to the literature, during this period in England, marriages were the key demographic indicators except in London, where there was a higher mortality and immigration (Beier and Finlay 1986).

The annual series of gross deaths shows a greater correlation with the increase in humidity (spring and summer rainfall), as well as winter and summer temperatures (colder winters and hotter summers being worse), together with an indicator of morbidity (deaths from sick people in the previous year). All other factors remaining constant, a one degree

Celsius increase in summer temperature caused 12,868 additional deaths, and a similar fall in winter temperatures caused around 4404 deaths. If spring and summer rainfall increased by 50 mm, the number of deaths increased by 16,600 and 8350 respectively. Thus, a year in which all of these changes occurred simultaneously meant an increase in the number of deaths by 42,222 people. Therefore, we again detect clear indications of the impact of climatic variables on population dynamics. These results are noteworthy and deserve further analysis beyond the scope of this chapter.

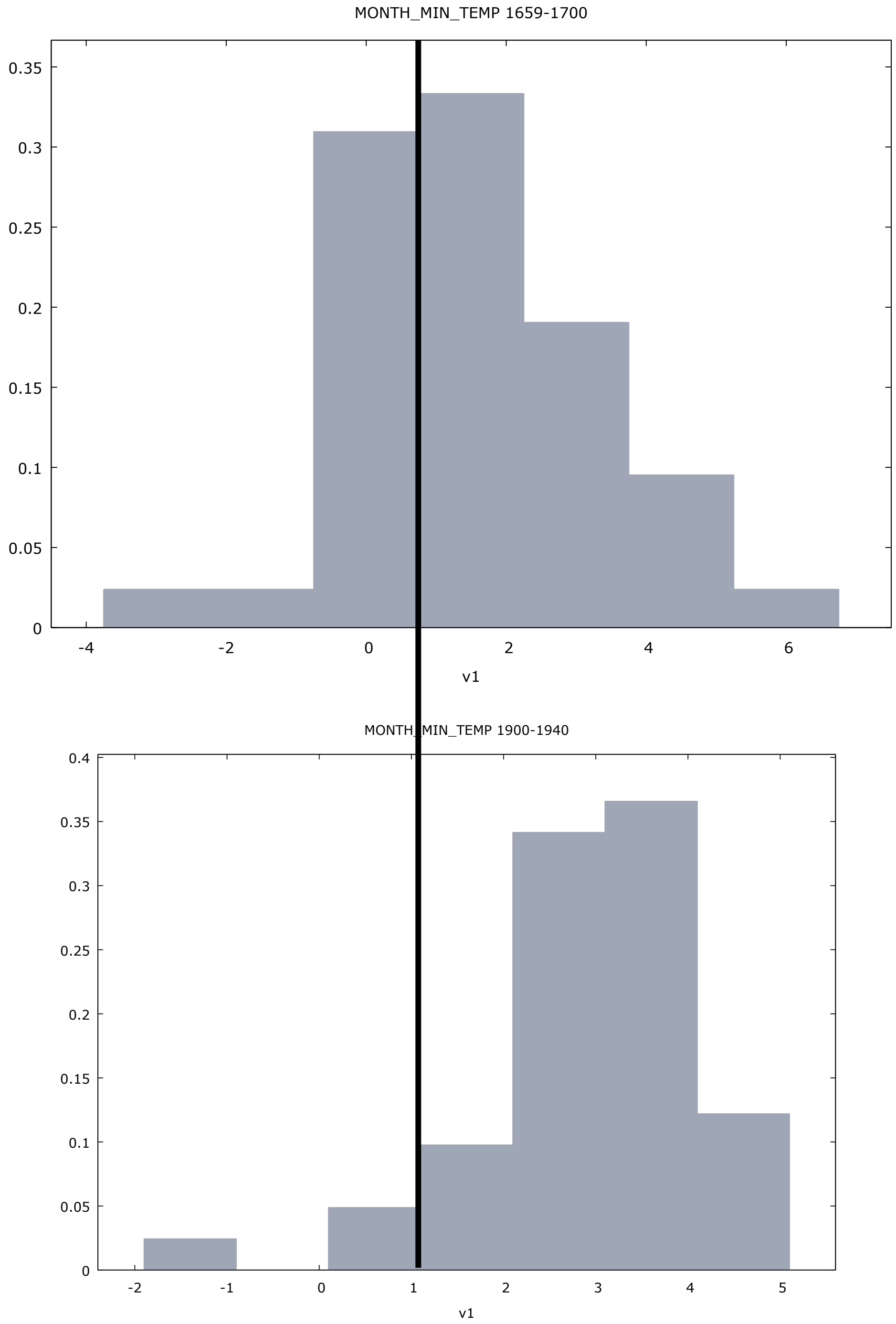

Fig. 2.1. Relative frequency of monthly minimum temperatures between the periods 1659-1700 and 1900-1940, England. Own elaboration from English CET temperatures. First, we calculate the distribution of the relative frequency of the monthly minimum temperatures in the periods 1900-1940 and 1659-1700. Then, we compared both distributions. We observe how in the twentieth century the minimum temperatures reached were much milder. The population did not have to endure so much cold, but it also had more resources.

Table 2.2 (see supplementary material) measures the relationship between climate and energy consumption. In model 1, 73% of the London coal price is explained by autumn and winter temperatures, and Newcastle coal shipments. The colder the temperature, more expensive the coal was, and vice versa. A 1° C reduction in temperature resulted in a price increase of 2.13 shillings, 15% in the average price of coal for the period studied. Knowing that the 1645-1700 period was especially cold, we understand that it was an important added stimulus to the demand of fuel per head. The lower the coal shipments, the more expensive it was. On the other hand, Hatcher (1993) has shown that shipments were radically reduced when the weather worsened, especially in autumn and winter. Therefore, the increase in prices reflects two things, an increase in the demand for heat, and an increase in the relative scarcity of coal. At that time, it was not easy to increase total winter energy consumption in proportion to low temperatures. According to this, total consumption could be more related to average temperatures based on forecasts and expectations.

Model 2 in Table 2.2 measures the relationship between the average fall in temperatures and an increase in coal consumption (total and per capita) between 1661 and 1700. A 1 ºC fall in temperatures caused an average 35% increase in coal consumption. This result can be benchmarked knowing that in a developed country like the USA between 1988 and 1994 poor families increased their monthly fuel expenditure by 32% in winter, having to reduce their food intake measured in calories by 10% (Bhattacharya et al. 2003). However, if the explanatory capacity is 60% up to 1700, it falls to 21% when the later warm period is included (model 3). All of this suggests that the Maunder Minimum accelerated the ongoing energy transition by increasing coal consumption during the fall in temperatures. According to Paolo Malanima, the energy divergence between England and Italy may have been accentuated during this period (Malanima 2015; Kander et al. 2013).

To expand model 2, we added two proxy variables for urbanization/proto-industry, specifically, the ratio of craftsmen wages/agricultural wages (a higher wage gap in favour of non-agricultural wages indicates urbanization) and population (the higher the population, the greater the demand). These last two variables do not seem significant in the cold period, whereas temperatures do (model 5). However, if we incorporate the later warm phase, it is the variables of urbanization and population and not temperatures that bear the main weight of the model (model 4). All of this suggests a very logical conclusion: colder temperatures would accelerate the consumption of coal, contrary to what happened in the warmer period, when temperatures would lose importance in favour of other demand factors (urbanization and population). This interesting idea doubtlessly requires further research: the coal consumption series is weakly stationary, and the climatic ones are stationary. Likewise, the population series is first-order integrated and the ratio of craftsman-agricultural wages is weakly stationary. Although there are those who do not appear to be a spurious relationship if we compare the adjusted determination coefficient and the DW statistic (Granger and Newbold 1974), we cannot know whether the possible impacts detected are short or long-term in nature, and even whether they are small or large. Nor do we have more exogenous annual explanatory variables of minimum sufficient quality. A much broader analysis is here required.

4.2. Economic impacts.

4.2.1 Productivity and wages.

Table 2.3 (see supplementary material) presents the relationships between climate, physical labour productivity and wages. The results of model 1 show climatic data to be associated with the average physical labour productivity (bushels/worker) by 58%. Lower winter temperatures and more intense summer rains have a negative impact on physical labour productivity, an effect that lasts for several years. Models 2 and 3 show the effects of climate on daily agricultural wages. First, the coefficients of determination indicate that these are not as sensitive to climatic variations as productivity, that is, changes in physical productivity do not translate into wage changes of the same order, implying that daily agricultural wages are not a good indicator of productivity. Second, despite the above, wages are more sensitive to cold weather (37%) than in the later warm period (19%). That is, when temperatures fell, so did daily agricultural wages, while in the warm period, when temperatures rose, the response was not the same, as if there were a ceiling difficult to overcome.

Models 4 and 5 show the relationship between climatic variables and daily wages of craftsmen. The explanatory capacity of the climate in the long period is much greater for craftsmen's daily wages than for those of agricultural workers (51% versus 19%). This could be a sign of the former being a more flexible market. The great surprise is that, although a positive direct relationship is found with temperatures throughout the period, the relationship is the opposite during the cold period, with higher daily wages during colder periods, although the sensitivity is lower. As regards daily wages of construction workers (models 6 and 7), the coefficient of determination during the cold period is 67%, and 43% for the entire period; that is, they were more sensitive during the cold period, and lower temperatures also pushed them upwards.

In summary, the most noteworthy facts here are, first, that there are indications of the impact of climate on physical labour productivity and daily wages, as expected according to the literature. We can also see that labour productivity accounted in energy terms moves in a similar way to temperatures, and the same happens with real daily wages, a trend verified in Fig. 2.2. Second, daily agricultural wages were more rigid than non-agricultural wages, while this should not be the case in an economic activity that depends much more on natural factors: the result suggests institutional differences between sectors. Third, a colder climate seemed to be a stimulus for non-agricultural daily wages, a finding which is fully consistent with the review of the literature. However, extreme caution is required when drawing conclusions here. All the data used is too aggregated and entails reliability problems to venture definitive conclusions. All series except for craftsmen's daily wages are stationary, which prevents us from studying a long-term relationship, even if we can detect that the possible impacts of the climate lasted several years.

Once again, it could be claimed that these results have been obtained omitting a fundamental force such as population which, in theory, conditions movements in wages and living standards according to Malthusian reasoning. However, in Table 2.4 (see supplementary material), we observe that agricultural daily wages (within their great rigidity) show a little short-term sensitivity only to climate (17%), but not to population or the other demographic variables (0%). Something similar occurs with real daily agricultural wages, with the climate having an apparent global effect of 34% whereas the effect of population is zero, and if we include other demographic variables their importance is similar, but no greater (Table 2.4). Furthermore, in the case of non-agricultural daily wages (craftsmen), their effects are similar, whether taken individually or jointly (61-60-68%). All of this indicates that we should not underestimate climate, and that the above conclusions are more than pure conjecture. As we saw in the previous section, there are reasons to think that population was also conditioned by changes in the climate.

4.2.2 Aggregated economic growth.

Current studies on the relationships between climate change and modern economies have already detected different degrees of relationship (Stern 2007; Dell et al. 2014). Therefore, in an economy much more dependent on climate and nature, relationships between the two spheres should be more intense. The models presented above suggest that agricultural production contributed to the increase in total and per capita output during the Maunder Minimum, while energy consumption accelerated and daily wages rose, which leads us to think of an increase in GDP. To do this exercise, in Table 2.5 (see supplementary material) we analyse the relationship between the variables for the whole period 1661-1740. The coefficients of the main climatic variables are significant, with an R^2 of 56%. Higher temperatures and spring rainfall resulted in a higher GDP, and the opposite was true when volcanic dust was present in the atmosphere or summer rains increased. One of the reasons for this impact on GDP is the increase in agricultural production, especially during the first part of the eighteenth century, thanks to the innovations introduced by farmers to cope with the previous cold phase (Tello et al. 2017). Higher temperatures and benign spring rains facilitated the plants' N uptake and growth. On the other hand, excessive storms and summer rainfall endangered crops.

Following the impacts on the agrarian sector, a temperature increase by 1 ºC, while keeping the rest of the variables constant, relates to a 4.73% rise in GDP. A 50-mm increase in spring rainfall led to a 6.78% rise in GDP (in the year 1700, GDP = 100). Conversely, during the cold period the worsening of the climate correlated with an acceleration of growth, following the same trend as observed in energy consumption (food and coal), as well as in the daily wages of craftsmen and construction. The 1 ºC drop in temperature relates to a GDP growth of 12.79 points. These results suggest that non-agricultural daily wages were a good qualitative indicator of the direction taken by GDP, and that some of the causes of the notable increase in GDP that occurred in the second half of the seventeenth century were due to a combination of the agricultural improvements started to tackle the colder conditions, energy consumption, and urban and proto-industrial development. Likewise, they would support the start of the English Agricultural Revolution as well as the theory of the Industrious Revolution proposed by De Vries (1994), both situated within the context of a worsening climate. In this sense, Allen and Weisdorf (2011) have suggested that it was the urban and craftsmen's families that were at the forefront of the modern consumer revolution (Broadberry et al. 2015).

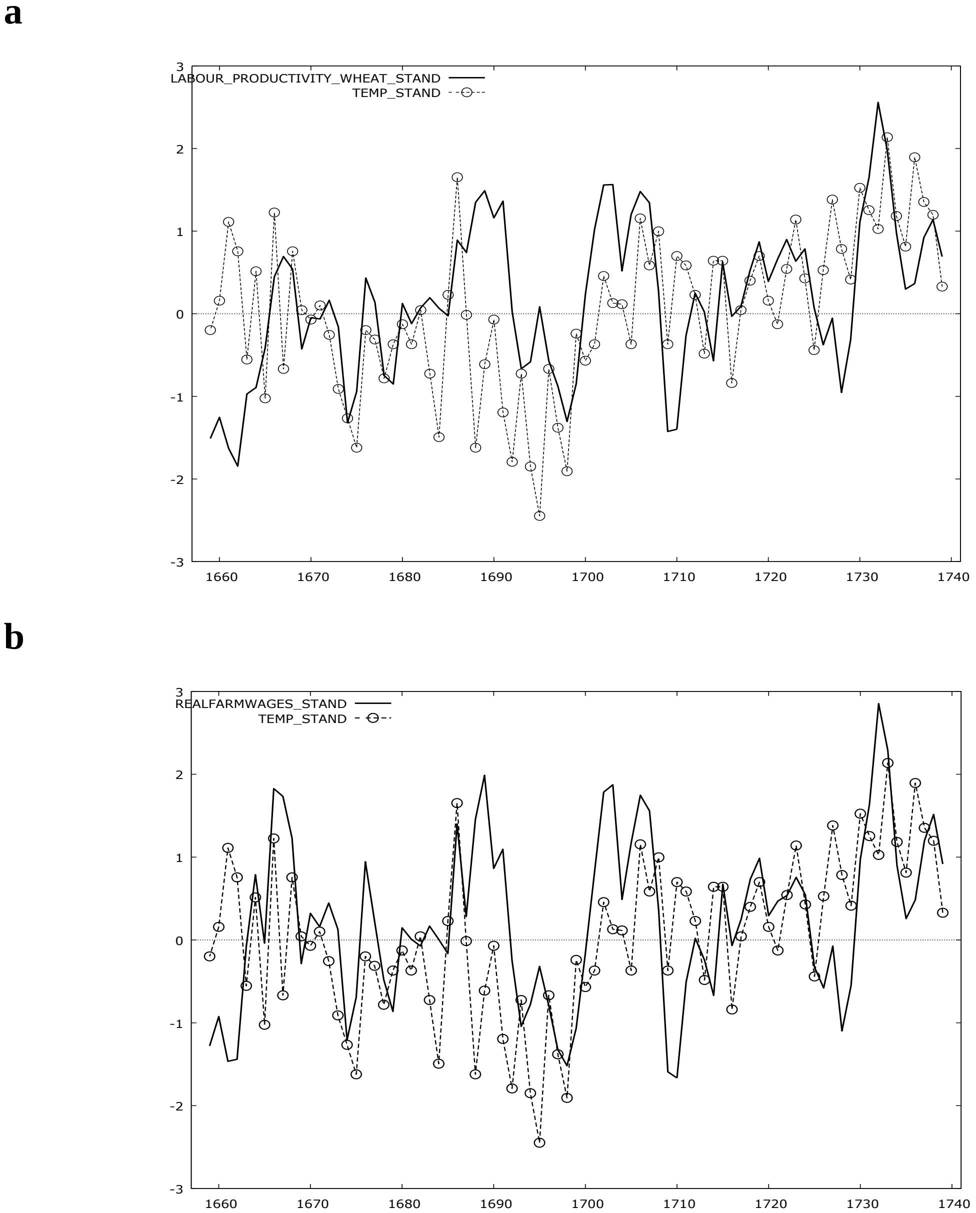

Fig. 2.2. Comparison of wheat-labour productivity: **a** and real agricultural daily wages **b** with temperatures, England, 1659-1740. Standardized data. Source: TEMP_STAND, LABOUR_PRODUCTIVITY_WHEAT_STAND, and REALFARMWAGES_STAND are standardized series based on their means and variances. Temperatures, productivity, and real wages move in a similar way. For more information, see section 3, "Sources and Methodology".

5. Conclusions.

The results obtained clearly indicate that climatic variation was a relevant factor in the transformations that occurred in England during the period 1645-1740. According to the best aggregated data available and using the standard econometric model for that purpose (Dell et al. 2014), a significant relationship between climate variables and wheat and barley production, population dynamics, energy consumption, productivity, wages, and income (GDP) is confirmed.

A noteworthy result is that the short-term negative impact of colder temperatures on wheat production did not led to long-term intensification of climate impacts on English agriculture during the first phase of the Maunder Minimum, according to the available production series. This can only be explained by agricultural improvements and adaptations carried out as a response to climatic conditions as well as to the growing rural and urban per head energy demand for food, and government incentives. The increase of agricultural produce of wheat and barley intensified during the second phase of the Maunder Minimum at the beginning of the eighteenth century, thanks to the ongoing dynamics of more favourable climate conditions, the keeping of the efforts to improve agricultural production, and growing urban and industrious demand (Tello et al. 2017).

The more adverse climate during the first phase of the Maunder Minimum also stimulated fuel energy consumption, and thus GDP. In the short term, we find climatic impacts (worsening) on the population (decreasing), mortality (increasing), and marriages (decreasing). From here, we observe two forces. First, the climate and demographic deterioration led to a greater need for energy consumption per person to maintain basal metabolism, health, and a level of energy enough to work and live. Second, rural and urban expansion required more energy per person to work. The convergence of the two forces may explain the result of our econometric models: a growth in energy demand and wages, and consequently, an increase in income and expenditure despite the climate worsening.

Given the need to be more productive and spend more in a colder, wetter, and more unstable context, the rigidity detected in daily agricultural wages suggests a reallocation of labour through different means, whether outside or within the agrarian sector. Depending on the capacities of each family, each social class and each region, that combination of driving forces ended up being associated with an improvement in aggregate income, and therefore in real GDP, in a way that avoided England to be caught in a Malthusian trap. When climate conditions improved in the second phase of the Maunder Minimum, the country had discovered a new economic path the continental Europe and the rest of the World would take it difficult to find.

6. Appendix. Electronic Supplementary Material.

Introduction. This supporting information provides detailed information from Tables 2.1., 2.2., 2.3., 2.4., 2.5.

Table 2.1. Response of gross wheat production, marriages and deaths, to temperatures, rainfall, craftsmen's daily wages and the Corn Bounties paid in exports, 1645-1740.

Dependent variable and methods	Gross Wheat Production in bushels, OLS (1)	Barley Price OLS (2)	Marriages OLS (3)	Deaths OLS (4)
Constant	25.2808*** (<0.001)	2.8073*** (<0.001)	−12328.9 (0.1849)	-89428** (0.0264)
TEMPERATURE	0.959425** (0.0129)	0.118138*** (0.0053)	2883.83*** (<0.001)	
TEMPERATURE (-1)		0.0699798* (0.0941	1763.88* (0.0655)	
TEMPERATURE (-2)	0.844384** (0.0377)			
SUMMER TEMPERATURE (-1)				7464.47*** (0.0021)
WINTER TEMPERATURE (-2)				-2554.86** (0.0483)
SUMMER RAINFALL	−0.0137884*** (<0.001)			
SUMMER RAINFALL (-1)	−0.0191260 *** (<0.001)	−0.00063621* (0.0767)		96.9867*** (0.0006)
SPRING RAINFALL			36.2327** (0.0169)	
SPRING RAINFALL (-1)			46.6197*** (<0.001)	
SPRING RAINFALL (-2)				193.083*** (<0.0001)
SUMMER RAINFALL (EAST)			−39.4568* (0.0609)	
DEATHS_YEAR (-1)				0.423814*** (<0.0001)
GROSS WHEAT PRODUCTION		−0.101047*** (<0.0001)		
BEER_PRICE (-1)		1.4579*** (0.0023)		
BARLEY PRICE (-1)		0.230162*** (0.0019)		
CRAFT WAGES (-2)				
CORN BOUNTIES				
N	80	80	81	79
R^2	0.46	0.72	0.50	0.55
F	16.24	35.26	14.52	17.56

*= level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%, p-values in brackets. All series are stationary except wages (correlogram and ADF test). The linear functional form is accepted except in DEATHS (Test Reset). All series are homocedastic (White and Breusch-Pagan Tests) and free of multicollinearity (VIF). There are no problems of non-normality in the residuals, except in equation (4). In general, the fact that all of the series are stationary and do not violate the basic hypothesis of the multiple regression model makes the results robust.

Table 2.2. Contrast in the response of London coal price and the consumption of coal to changes in temperatures, the correlation between craftsmen's wages/agricultural workers' wages, and population, England, 1659-1740.

Dependent variable	PR_COAL_LOND	COAL_EXPENSE	COAL_EXPENSE	COAL_EXPENSE	COAL_EXPENSE
Length	1661-1700	1661-1700	1661-1740	1659-1740	1661-1700
	(1)	(2)	(3)	(4)	(5)
Constant	47.4083***	7.54847e+08***	−2.67069e+08**	−1.30104e+09***	9.16422e+08**
	(<0.001)	(<0.001)	(0.0149)	(<0.001)	(0.0113)
TEMPERATURE		−2.64441e+07***			−2.06657e+07***
		(<0.001)			(<0.001)
TEMPERATURE (-1)		−1.66796e+07**	2.79423e+07**		−1.62709e+07**
		(0.0284)	(0.0252)		(0.0262)
TEMPERATURE (-2)		−2.57671e+07***	2.59915e+07**		−1.94363e+07**
		(<0.001)	(0.0370)		(0.0124)
WINTER_TEMPERAT	−0.400246*				
	(0.0517)				
WINTER_TEMPERAT (-1)	−0.454780**				
	(0.0281)				
AUTUMN_TEMPERAT	−1.28203***				
	(<0.001)				
COAL_SHIPPED	-2.4983***				
	(<0.001)				
COAL_SHIPPED (-1)	-1.4555***				
	(0.0016)				
CRAFT_VERSUS_FARM				1.79272e+08***	5.82808e+07
				(<0.0001)	(0.1232)
POPULATION				228.871***	−75.1825
				(<0.0001)	(0.2261)
N	40	40	80	82	40
R^2	0.72	0.60	0.21	0.66	0.66
F	21.26	17.82	10.28	77.55	13.12

*= level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%, p-values in brackets. All series are stationary except POPULATION (correlogram and ADF test). COAL_EXPENSE and CRAFT_VERSUS_FARM are weakly stationary (the ADF test with constant and trend shows stationarity but not only with constant or observing the correlogram). The linear form of the function is accepted less in Model 3 (Test Reset). All series are homocedastic (Breusch-Pagan Tests) and free of multicollinearity (VIF). There are no problems of normality in the error, except in Models 1, 3 and 4. In general, the results are robust because almost all series are stationary and the basic hypotheses of multiple regression are not unmet.

Table 2.3. Response of labour productivity, daily agricultural, craftsmen and construction wages, to changes in temperatures and rainfall, England, 1660-1740.

Dependent variable Length	LABOUR_WHEAT _PRODUCTIVITY 1662-1740 (T = 79) (1)	WAGE_FARM 1661-1740 (N = 80) (2)	WAGE_FARM 1661-1700 (N = 40) (3)	WAGE_CRAFT 1661-1740 (N = 80) (4)	WAGE_CRAFT 1660-1700 (N = 41) (5)	WAGE_BLDG 1661-1740 (N = 80) (6)	WAGE_BLDG 1661-1700 (N = 40) (7)
Constant	71.3199*** (<0.0001)	5.39511*** (<0.001)	−0.385809*** (0.8706)	13.5808*** (9.21e-011)	22.5172*** (<0.001)	14.6808*** (<0.001)	20.1029*** (<0.001)
TEMPERATURE		0.278425*** (0.0088)	0.480456** (0.0116)	0.396996*** (0.0052)			−0.203513*** (0.0095)
TEMPERATURE (-1)					−0.359314*** (0.0062)		−0.145596* (0.0624)
TEMPERATURE (-2)		0.239523** (0.0327)	0.51029*** (0.0082)	0.402089*** (0.0098)		−0.16471** (0.0114)	−0.3542*** (<0.001)
WINTER_TEMPERAT	0.834778*** (0.0021)						
WINTER_TEMPERAT (-2)	0.690311** (0.0167)						
SPRING_TEMPERAT (-2)	−1.252*** (0.0097)						
AUTUMN_TEMPERAT (-2)	1.13671*** (0.0081)						
SUMMER RAINFALL	−0.024*** (<0.0001)						
SUMMER RAINFALL (-1)	−0.0331451*** (<0.0001)		0.00354286** (0.0445)			−0.00123279** (0.0364)	−0.00251534*** (0.0009)
SUMMER RAINFALL (-2)	−0.0100019** (0.0439)		0.00432863** (0.0140)			−0.00112526* (0.0504)	−0.00160487** (0.0212)
SUMMER RAINFALL (EAST)				−0.0127439*** (0.0013)		−0.00674929*** (<0.001)	
SUMMER RAINFALL (EAST) (-1)					0.00563796* (0.0818)		
SUMMER RAINFALL (EAST) (-2)	−0.0284997** (0.0260)			−0.00994490** (0.0117)	−0.00471687* (0.0942)	−0.00450155*** (0.0066)	−0.00413973*** (0.0082)
SPRING RAINFALL				0.00506002* (0.0604)		0.003426*** (0.002)	
SPRING RAINFALL (-1)					−0.0069188*** (0.0042)	0.0016134* (0.0996)	
SPRING RAINFALL (-2)				0.009358*** (0.0002)		0.00371*** (0.0009)	
R^2	0.58	0.19	0.37	0.51	0.36	0.43	0.67
F	12.32	9.05	5.05	12.58	4.99	6.62	11.38

*= level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%, p-values in brackets. All series are stationary except WAGE_CRAFT (weakly stationary according to the ADF Test, in contrast and trend with a delay). The linear function form is accepted except in Model 2 (Reset Test). All series are homoclassic except for Model 2 (White and Breusch-Pagan Tests) and there are no multicollinearity problems (VIF).

Table 2.4. Evaluation of the impact of climate and demographics on the labour market and daily wages. England, 1659-1740. In brackets, whether the relationship was direct (+) or inverse (-).

Independent Variables

Dependent Variables	**CLIMATE (I)**	**POPULATION (II)**	**OTHER DEMOGR (III)**	**I+II**	**I+III**
REAL FARM WAGES	34% (+)	0%	34% (+)	46% (+)	61% (+)
FARM WAGES	17% (+)	0%	0%	17% (+)	17% (+)
CRAFT WAGES	61% (+)	60% (+)	68% (+)	68% (+)	68% (+)

Source: authors' own data using MCO method. *= level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%. The percentage indicates the coefficients of determination for each model. The Snedecor F contrast is correct in all cases and there is no multicollinearity or heterocedasticity. The CLIMATE series are Manley temperatures, volcanic activity from Mann et al, summer rainfall from Rinne et al., OTHER DEMOGR correspond to the mortality and birth series by Wrigley et al.

Table 2.5. Contrast in the response of real GDP to temperatures, volcanic dust and rainfall, England, 1661-1740.

Dependent variable Length	REAL GDP 1661-1740 (T = 80) (1)	REAL GDP 1661-1700 (T = 40) (2)	REAL GDP_PC 1661-1700 (T = 40) (3)
Constant	105.221*** (<0.0001)	197.283*** (<0.0001)	4.27043e-05*** (<0.0001)
TEMPERATURE		−7.11795*** (0.0005)	−1.50285e-06*** (0.0003)
TEMPERATURE (-2)	4.73488** (0.0206)	−5.69799*** (0.0039)	−1.00439e-06** (0.0142)
VOLCANIC AEROSOLS (-1)		−0.0226204* (0.0642)	−5.01962e-09** (0.0440)
VOLCANIC AEROSOLS (-2)	−0.0464903*** (0.0021)		
SUMMER RAINFALL (EAST)	−0.262298*** (<0.0001)		
SUMMER RAINFALL (EAST) (-2)	−0.207893*** (0.0002)		−1.42111e-08* (0.0781)
SPRING RAINFALL	0.133322*** (0.0004)		
SPRING RAINFALL (-2)	0.135600*** (<0.0001)		
N	80	40	40
adj. R^2	0.56	0.47	0.52
F	15.5	10.52	9.57

Source: authors’ own data using MCO method. *= level of significance at 10%, ** = level of significance at 5%, *** = level of significance at 1%. REAL GDP and REAL GDP_PC are stationary according to the ADF Test, in contrast and trend with six delays, but the correlogram indicates that they are not stationary. The rest of the variables are stationary. The linear functional form is accepted except in Model 2 (Test Reset), but if we reformulate the model with squares (non-linear form) the results are similar. No series present problems with heterocedasticity (White and Breusch-Pagan Tests), or multicollinearity (VIF), and the errors follow a normal distribution.

Chapter 3. The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients[13].

The period from 1645 to 1715 saw a series of extremely cold winters, with temperatures lower than average, even for the Little Ice Age (c.1300–c.1850), as well as a succession of weather extremes. According to some authors, the length of the growing season was shortened two to four weeks, and the ability of certain grains to withstand cold was severely tested, jeopardizing agricultural yields. Yet, this was exactly the time when the English Agricultural Revolution began, giving rise to one of the major improvements in traditional organic farm systems throughout preindustrial Europe. How can both facts be reconciled? Why did so many English farmers and writers about agriculture start to look for new crops, seeds, rotations, and tillage methods during that period? How can climate history be harmonized with English economic history at this critical juncture?[14]

This general question is related to another more specific one. Allen wondered what incentives English farmers might have had to strive for better fertilization when they introduced leguminous crops into their rotations. Given that the rewards through higher

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[13] Tello, E., Martínez-González, J.L., Jover, G., Olarieta, J.R., García-Ruiz, R., González de Molina, M., Badia-Miró, M., Winiwarter, V., Koepke, N. (2017). The Onset of the English Agricultural Revolution: Climate Factors and Soil Nutrients, *The Journal of Interdisciplinary History* 47(4), 445-474. https://www.muse.jhu.edu/article/648314 [JCR IF 2017: 0.563; Q2 in History]. The contributions of José Luis Martínez-González have been participating in the development of the main argument, the empirical data, the econometric evaluation, part of the bibliography and some passages of English history.

[14] For a summary of the climatological state of the art regarding the Little Ice Age, see Ulf Büntgen and Lena Hellmann, "The Little Ice Age in Scientific Perspective: Cold Spells and Caveats," *Journal of Interdisciplinary History*, XLIV (2014), 353–368—a reply to the skepticism of Michael Kelly and Cormac O'Gráda, "The Waning of the Little Ice Age: Climate Change in Early Modern Europe," *ibid.*, 301–325; *idem*, "Debating the Little Ice Age," *ibid.*, XLV (2014), 57–68. See also Sam White, "The Real Little Ice Age," *ibid.*, XLIV (2014), 327–352. For an overview of long-term climate changes, see Philip D. Jones, Timothy J. Osborn and Keith R. Briffa, "The Evolution of Climate over the Last Millennium," *Science*, CCXCII (2001), 662–667. According to the best climatic models and available evidence, the Late Maunder Minimum had relevant effects in all regions of the globe, as explained in Hubertus Fischer et al., *The Climate in Historical Times: Towards a Synthesis of Holocene Proxy Data and Climate Models* (Berlin, 2004), 397– 414; Yasuhiko T. Yamagucki et al., "Synchronized Northern Hemisphere Climate Change and Solar Magnetic Cycles during the Maunder Minimum," *Proceedings of the National Academy of Sciences*, CVII (2010), 20697–20702. For the shifts reducing cultivation in England's hills during this period, see E. L. Jones, *Seasons and Prices: The Role of the Weather in English Agricultural History* (London, 1964); Martin L. Parry, *Climatic Change, Agriculture and Settlement* (Hamden, Conn., 1978); P. R. Galloway, "Long-Term Fluctuations in Climate and Population in the Preindustrial Era," *Population and Development Review*, XII (1986), 1–24; Mark Overton, "Weather and Agricultural Change in England 1660–1739," *Agricultural History*, LXIII (1989), 77–88; Axel Michaelova, "The Impact of Short-Term Climate Change on British and French Agriculture and Population in the First Half of the 18th Century," in Philip Jones, et al. (eds.), *History and Climate: Memories of the Future?* (New York, 2001), 201–216; for these shifts as a worldwide phenomenon, J. Holopainen and S. Helama, "Little Ice Age Farming in Finland: Preindustrial Agriculture on the Edge of the Grim Reaper's Scythe," *Human Ecology*, XXXVII (2009), 213–225; Bruce M. Campbell, *The Great Transition: Climate, Disease and Society in the Late Medieval World* (New York, 2016).

yields would have been long delayed due to a slow mineralization of the nutrients caught into the soil organic matter, why did they adopt these new crops?[15]

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

1. Challenges and options during the Maunder minimum.

In overview, diversification and new rotations in England and Wales helped farmers to endure the harsh temperatures—in contrast with other parts of Europe where the entire food system still relied on the success or failure of a single annual crop. This interpretation does not question the explanations based on the role played by the institutions and economic incentives that existed in England but not yet in most other parts of Europe at that time. On the contrary, placing the onset of the English Agricultural Revolution in its climatic and agroecological context allows us to look at the role of socioeconomic agency in a more realistic way. It also provides a solution to Allen's conundrum about what induced farmers to search for new sources of organic N (nitrogen) to fertilize their soils despite the delay in obtaining higher yields.[16]

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

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

Might the initial aim of English farmers have been to maintain, rather than to increase, land fertility in the face of the harsh climatic conditions? This notion would be consistent with the economic history of the period only if we were to interpret the decrease in temperature as a specific context in which all of the socioeconomic variables played their own roles. From an economic standpoint, the century from 1640 to 1740 has been characterized as a long "agrarian depression," mainly because of the decreasing trend in population and prices for grain. The very fact that lower wheat prices became a problem does not fit with a period that might have had to endure food scarcities. No doubt, bad harvests and high grain prices in England became more intense during certain years but not more frequent during the Maunder Minimum than in earlier or later times. What stands out is the English farmers' ability to overcome these climatic shocks in a much better way than their continental counterparts.[17]

Indeed, English landowners found the persistent stagnation, or fall, in wheat prices so worrisome that an Act of 1663 promoted grain exports with public subsidies and imposed high duties on imports. Ceiling prices for cereal exports were abolished in 1670, and the bounties paid on overseas sales introduced in 1672 were suspended only in 1699, 1709, 1728, and 1740, when domestic grain prices temporarily rose. The drop in relative prices of wheat and rye, linked to population decreases among other things, was a general European trend. In the English case, the downturn in population went hand in hand with a significant increase in urbanization —the growth of London, in particular— following the rise of British colonial hegemony and trade. While grain prices stagnated or fell, those of other farm products like meat and dairy products, vegetables, fruits, beer, or industrial fibres (wool, hemp, and flax) remained steady or even increased, thanks to the growing urban demand. Thus, relative prices encouraged agricultural diversification and inaugurated a salient phase of alternative agriculture in England and Wales.[18]

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[17] Galloway, "Long-Term Fluctuations in Climate and Population," 20; Peter J. Bowden, "Agricultural Prices, Farm Profits and Rents," in Thirsk (ed.), *Agrarian History of England, and Wales* (New York, 1967), 650–663; William G. Hoskins, "Harvest Fluctuations and English Economic History, 1620–1759," *Agricultural History Review*, XVI (1968), 15–31; de Vries, "Measuring the Impact"; Allen, "The Great Divergence in European Wages and Prices from the Middle Ages to the First World War," *Explorations in Economic History*, XXXVIII (2001), 411–447. The European series of Koepke and Jorg Baten, in "Climate and Its Impact on the Biological Standard of Living in North-East, Centre-West and South Europe during the Last 2000 Years," *History of Meteorology*, II (2005), 147–159, show that the lowest levels of temperature and heights appear in the seventeenth century. For the capacity of England and Wales to endure and overcome the climate shock of the Maunder Minimum, see Richard W. Hoyle, "Why Was There No Crisis in England in the 1690s?" in *idem* (ed.), *The Farmer in England 1650–1980* (Farnham, 2013), 67–98; Stephen N. Broadberry et al., "British Economic Growth: 1270–1870," Working Paper of the Department of Economics (University of Warwick, 2011), available at http://www.grammatikhilfe.eu/economicHistory/pdf/ Broadberry/ BritishGDPappendix.pdf (accessed January 17, 2015).

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

[18] For English exports and policy, see Thirsk, *Alternative Agriculture*, 26; David Ormrod, *English Grain Exports and the Structure of Agrarian Capitalism, 1700–1760* (Hull, 1985); Stephen Hipkin, "The Coastal Metropolitan Corn Trade in Later Seventeenth-Century England," *Economic History Review*, LXV (2012), 220–255; for trends in relative prices, Abel, *Agricultural Fluctuations*; de Vries, *Economy of Europe*; Thirsk, *Alternative Agriculture*; Mauro Ambrosoli, *The Wild and the Sown: Botany and Agriculture in*

Unlike in France or Central Europe, spring-sown barley and oats became integral to a three-course crop rotation in England, helping to compensate for wheat harvest failures; beer production could be temporarily reduced in harsh times to absorb the shock, together with a reduction in grain exports. Thus, England could avoid severe grain shortages, even though consumption had to shift to cereals of lower quality during years of bad harvest. Fallow land underwent further innovations to ensure animal feeding. Given that grain intake by horses could impinge on human food supplies when crops failed, finding alternatives for animal feed became an issue. By cultivating leguminous forages in former fallows —sometimes even fodder swedes, mangel beets, or turnips— and by improving water meadows, farmers could sustain human food and animal feed alike in harsh weather conditions. These strategies paved the way to a tighter integration of livestock and cropland tillage during a time when the relative prices of cheese and meat were high. Although the scanty figures available do not show a countrywide increase in livestock densities throughout England and Wales, a tighter integration of animal husbandry with farming presumably provided more manure for the arable land. Shortening the crop-growing season and confining herds to barnyards for longer periods would have resulted in larger amounts of well-composted manure ready to be carted to cropland. This integration might not have been intentional at first. When the harsher temperatures from 1645 to 1700 became entrenched, farmers were far more interested in creating barnyards built of stone or brick to store grains, hay, and forage and to shelter livestock in winter.[19]

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

[19] For the general picture of English agricultural innovation, see E. L. Jones, "Agriculture and Economic Growth in England, 1660–1750: Agricultural Change," *Journal of Economic History*, XXV (1965), 1–18; Overton, *Agricultural Revolution in England: The Transformation of the Agrarian Economy 1500–1850* (New York, 1996), 76–80; *idem*, "English Agrarian History 1500–1850," available at http://www.neha.nl/publications/1998/1998_04overton.pdf (accessed January 17, 2015); Turner, Beckett, and Afton, *Farm Production in England, 1700–1914* (New York, 2001), 117–133; Broadberry et al., "British Economic Growth"; for the role of barley and other crops in preventing famines, Andrew B. Appleby, "Grain Prices and Subsistence Crises in England and France, 1590–1740," *Journal of Economic History*, XXXIX (1979), 865–887; *idem*, "History Epidemics and Famine in the Little Ice Age," *Journal of Interdisciplinary History*, XX (1980), 643–663; Michaelova, "Impact of Short-Term Climate Change"; Campbell and Overton, "New Perspective"; Hoyle, "Why Was There No Crisis in England"; for the predominance of barley and oats in English grain exports, Ormrod, *English Grain Exports*, 22, 26, 45–69; Craig Muldrew, *Food, Energy and the Creation of Industriousness* (New York, 2011); for the increase in livestock from 1500 to 1700, followed by stagnation until 1750, except for hogs and horses, Allen, "English and Welsh Agriculture, 1300–1850: Outputs, Inputs and Income," Oxford University Working Paper (2005), available at http://economics.ouls.ox.ac.uk/13622/1/Allen%20%20English%20and%20Welsh%20agriculture.pdf (accessed January 17, 2015); Jules N. Pretty, "Farmers' Extension Practice and Technology Adaptation: Agricultural Revolution in 17–19th Century Britain," *Agriculture and Human Values*, VIII (1991), 132–148. Broadberry et al., "British Economic Growth," 34, show little or no increase, except in sheep, and a

Hence, the combination of economic incentives and edaphoclimatic challenges during the second half of the seventeenth century fostered different regional specializations, depending on local natural resource endowments and socio-institutional landownership distributions and tenancy entitlements. In areas of light soils, farmers introduced legumes and sometimes swedes, fodder beets, or turnips in ever more complex rotations, fostering a higher land use intensity that provided them with a wider set of marketable products and alleviated the weather risks. In areas with clay-heavy soils, however, colder conditions and market trends drove farmers and large estates toward more extensive land uses, such as livestock rearing. The adaptations undertaken in areas of light soils facilitated more complex mixed farming, which allowed for grass leys and water meadows to replace diminishing fallow pastures in livestock feeding. Besides providing more animal feed and sources of N to the soil, these farming innovations also helped to protect from frost.[20]

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cattle decrease in stock densities per sown area. See also Broadberry et al., *British Economic Growth, 1270–1870* (New York, 2015), 99–113. In any case, bovine cattle declined (calves and cattle for milk and beef), whereas pigs and sheep (mainly for wool) increased. For the high land cost of animal feeding, see Gloria Guzmán and Manuel González de Molina, “Preindustrial Agriculture versus Organic Agriculture: The Land Cost of Sustainability,” *Land Use Policy*, XXVI (2009), 502–510; for the increase in stone barns during this period, Maurice W. Barley, “Rural Building in England,” in Thirsk (ed.), *Agrarian History of England and Wales*. *V. 1640–1750* (New York, 1985), 667–671.

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

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

Abundant evidence indicates that during the second half of the seventeenth century, farming, livestock husbandry, and gardening became highly fashionable among the English elites, intellectuals, and some politicians of the time, even while remaining the centerpieces of everyday life among tenants and laborers. Manure became a popular topic among agricultural writers and gardening activists searching for new crops and tighter integration between livestock feeding and cropland tillage. For example, John Worlidge (1640–1700), who wrote that the fertility problem had to be solved by "warming the soil," considered manure —above all, horse dung— to be the fertilizer with the most "heat." Old agricultural treatises describe how English and Scottish farmers managed different sources of manure—either human, animal, or vegetal—including the practice of burning sods in piles and scattering the ashes in the fields. As far away as in the Scottish Highlands, farmers increased their efforts to transfer nutrients from meadows to arable land via animal dung and collected seaweed from the shore to plough into the soil. They employed all sorts of organic fertilizing methods to replenish the nutrients extracted by crops, an issue that needs to be addressed from the standpoint of an overall nitrogen (N), phosphorus (P), and potassium (K) balance sheet.[21]

The discovery of crucial mixed-farming innovations based on the fertilizing role of legumes, grown to feed both humans and animals, relied on the traditional practical knowledge of peasants, yeomen, farmers, and the gentry. Horticulturists, first women and then men, tested the new methods before farmers took the risk of applying them on a larger scale. The English yeomanry led the first wave of agricultural change, which

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

mainly addressed land produce rather than labor productivity, as Allen and Overton stressed.[22]

However, knowing that grains thrive better when sown after legumes is not the same as implementing this information successfully; farmers had to identify the appropriate plants and varieties to introduce them into rotations amid the specific climatic and economic frame of the second half of the seventeenth century. This story involved the circulation of not only books and ideas but also germplasm, throughout Europe and as far south as the Mediterranean. French, Belgian, and Dutch refugees from the European religious wars connected England and the continent in this regard. The two fodder tubers first introduced in English rotations during the Maunder Minimum came from the colder territories of Sweden (hence the name swedes, called rutabaga in North America) and Germany (mangel-wurzel). British imports of a wide range of seeds of sainfoin and lucerne legumes from southern Europe soared when many English innovators attempted to acclimatize them before discovering that native clover was the best option for forage in the new rotations. These imported leguminous seeds could not be sown at a large scale at their point of origin, due to the lack of rainfall and soil moisture in the Mediterranean bioregion. A full understanding of the English Agricultural Revolution requires adopting a comparative perspective of the agroecological innovations of the time encompassing Europe as a whole.[23]

The search for historical explanations of farmers' responses to detrimental climate changes, and for answers to Allen's N question, has to be placed in this context. During the second half of the seventeenth century, English farmers adopted alternative crops, changed land uses, and implemented new tillage methods stimulated by trends in relative market prices, as well as by the challenges and options that presented themselves during the colder temperatures of the Maunder Minimum. Climate change might have played a role as important as market incentives in this endeavor. Although economic historians have paid much attention to market incentives as an explanation for the English

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[22] For gardening, see Jenny Uglow, *A Little History of British Gardening* (New York, 2004); Margaret Willes, *The Gardens of the British Working Class* (New Haven, 2014); for the widespread knowledge about legumes' fertilizing properties, John R. McNeill and Winiwarter (eds.), *Soils and Societies: Perspectives from Environmental History* (Winwick, U.K., 2006); *idem*, "Breaking the Sod: Humankind, History, and Soil," *Science*, CCCIV (2004), 1627–1629; for the roles of women and men, Carolyn Merchant, *Death of Nature: Women, Ecology and the Scientific Revolution* (San Francisco, 1983); Thirsk, *Alternative Agriculture*; Ambrosoli, *The Wild and the Sown*; for yeomen and gentry in raising land yields or labor productivity, Overton, *Agricultural Revolution*; Allen, "The Growth of Labor Productivity in Early Modern English Agriculture," *Explorations in Economic History*, XXV (1988), 117–146; *idem*, "Enclosure, Farming Methods and the Growth of Productivity in the South Midlands," *Research in Economic History*, V (1989), 69–88; *idem*, "The Two English Agricultural Revolutions, 1459–1850," in Campbell and Overton (eds.), *Land, Labour and Livestock*, 236–254.

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

Agricultural Revolution, scholars have paid relatively less attention to the former until recently.[24]

2. Strengths and weaknesses of Allen's Nitrogen model.

Allen's pivotal question, which we reiterated above, opens a research agenda about the capacity, as well as the motivations, of traditional organic farming in different agroclimatic contexts to make improvements. The answer requires an interdisciplinary approach, jointly developed by historians, economists, agronomists, biologists, soil scientists, and climatologists. It requires deep research into the N flows that attended the changes in farming procedure during the Maunder Minimum and a thorough analysis of Allen's pioneering attempt to link soil biophysical processes with economic incentives.[25]

Allen's model highlights the slow pace at which the mineral nitrogen (N) is released from the stock of organic N compounds through the decay of humus. Underlying this outcome is microbial growth and decay in the soil, which is an N-limited biological process also influenced by the stock of soil's organic carbon (C), acidity, moisture, soil composition, and temperature. Allen correctly points out that yields due to the investment of greater flows of organic matter into cropland may involve a delay. But how long this delay lasts depends on factors not taken into account in his model —for instance, the simultaneous supply of phosphorus (P) through manure or the N immobilization during the decomposition of organic matter with a high C-to-N ratio.[26]

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

Mineralization of soil organic N is a site-specific process that depends on highly variable spatiotemporal factors that support the activity of soil microorganisms—that is, the entire biomass of decomposers integrated by the microfauna, bacteria, and fungi that turn the molecules of organically bound N into simple chemical compounds like ammonia and nitrate made available to plants. Bacterial activity uses carbon to release simple N

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

[25] Allen, "Nitrogen Hypothesis."

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

compounds, provided that the C-to-N ratio of organic matter being decomposed is equal to or lower than 30. If the proportion of C relative to N is higher, microbial growth begins to incorporate available soil N into their bodies where it remains until their death, when available C is scarce. The result is some degree of N immobilization that sets a difference between gross and net N mineralization, which varies according to the composition of the organic matter involved. The process also depends on other environmental factors affecting the amount of bacterial biomass and its action, such as soil composition and texture, moisture, acidity, enzyme activity, and temperature. Farm management can modify some of these factors. Thus, soil N mineralization is a site-specific and variable process, for which it is difficult to establish reliable average values of decay rates. It also speaks to the extent of farmers' local knowledge, obtained by trial and error.

After having reviewed nearly 250 models of soil N mineralization published in the last eighty years, Manzoni and Porporato concluded that complexity and nonlinearity have increased in recent years, although they decrease as the spatial and temporal scale of observation grows larger. Keeping in mind their warning against transferring decay rates assessed in certain site-specific studies to other spatiotemporal scales, the figures reported a range from an increase in the annual net N mineralized of 9.5 kg/ ha for any increase of 1° centigrade in mean annual temperature (as found by Reich et al. in various types of forest soils in 1997), to an increase of 0.25–0.32 kg/ha (as obtained by Burke et al. in grassland soils in 1997), and to a 7 percent increase of mineralized N for each temperature increase of 1° centigrade—corresponding to a temperature quotient, Q10, for N mineralization of 1.7 —(according to figures proposed by Huang et al. and Koch et al. for organic alpine soils). To give a single example within these orders of magnitude, if total soil N in the top 50 cm of a hectare would have been 3,000 kg, about 2 percent of which was yearly mineralized, 60 kg N per hectare would become available each year. Under these circumstances, a decrease of 1° centigrade in the average annual temperature would lead to a reduction of 4.5 kg N/ha/year mineralized; during a span of fifty years, it would cause a reduction of 225 kg N mineralized per hectare. Most of this accumulated amount would become available when the temperature rose again.[27]

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

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

his fixed N mineralization rate; (2) his fixed lixiviation rate of N; (3) the linear relationship that he posits between the mineral N content of soil and the N uptake by all sorts of crops, grains, and legumes; and (4) the linear relationship that he posits between the mineral N taken by the biomass harvested above ground and the grain yield collected after threshing, which also depends on plant varieties and harvest indexes between grain and straw. All of these relationships vary depending on two types of conditioning factors, either natural ones or others technologically linked to farm management.

Among the natural factors, temperature is of particular interest in a period of climate change like the Maunder Minimum. Unlike weather oscillations that tend to even out in the short term, yearly average trends of temperature and precipitation were subject to profound change from 1645 to 1715; seasonal and annual variations were also more extreme than in the preceding or following decades. As noted, microbial populations, and their activity, heavily depend on soil temperature and water content. Leaching of nutrients from the soil also depends on the timing, as well as the amount and intensity, of precipitation. Other things being equal, the lower temperatures during the Maunder Minimum would have had an impact on microbiological activity by reducing soil N mineralization; the more intense spring and summer storms would have involved a stronger N leaching —perhaps countered by a greater flow of organic matter in the soil— and caused waterlogging and fungi diseases, thereby affecting wheat yields.[28]

Other things, however, did not remain equal, because crop yields depend on a variety of biocultural factors that create path dependencies. Allen's model assumes that soil N was the only limiting factor for crop yields. However, in the Broadbalk experiment in Rothamstead at the beginning of the twentieth century, yields were much higher for N mixed with P and K than for N alone. Similarly, in the Hoosfield experiment, current yields from soils with a low humus content are 75 percent of those from soils rich in organic matter, even with annual applications of up to 100 kg of mineral N/ha. Hence, organic-matter content—which can be taken as an indicator of the physical and biological properties of the soil— together with P and K, as well as pH, can also be a limiting factor in crop productivity. As a case in point, soil compaction reduces N uptake and wheat yields, whereas greater P availability increases crop N uptake and yields (although the effect depends on other soil characteristics as well). Furthermore, a number of authors suggest that traditional organic agriculture was P-limited rather than N-limited, thus stressing the role of compost, manure, and "humanure" in closing nutrient cycles in agroecosystems. A more realistic approach would consider N as one among a set of interlinked limiting factors.[29]

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

[29] Rothamsted Research, "Guide to the Classical and Other Long-Term Experiments, Datasets and Sample Archive 2006, Lawes Agriculture Trust Co. Ltd., Harpenden, UK," 8–18, available at

Given that bacterial growth and the activity of other decomposing microorganisms, like fungi, are also N-limited processes, the mineralization rate varies according to the mineral N content of soils. Instead of being constant, it is lower when the soil lacks mineral N — a situation that leads to a self-reinforcing virtuous circle when soil is enriched with N or to a vicious circle when it is depleted of N. However, these mineralization processes also depend on the type of organic matter being incorporated into the soil. When the C-to-N ratio in the organic matter incorporated is low, as in raw manures or in legume crop by-products, mineralization no longer depends on the N available in the soil. When the C-to-N ratio in the biomass that is incorporated is high, such as in mature compost, the mineralization rate depends on the quantity of N already available in the soil. Hence, even accepting Allen's assumption of an N-limited agriculture in seventeenth century England, farmers' efforts to increase the flow of organic matter that was incorporated in the soil would have found an increasing reward in yields sooner or later.

Yet, the quantity of mineral N available in the soil is one thing, and the N uptake by plants is another issue altogether. This point leads to another important missing variable, namely, the change of crop varieties. In an N-poor agriculture, like the one that Allen considered, farmers would have adapted traditional seed varieties to this environment. Current experiments show that simply adding N to existing varieties may result in decreased harvest indexes—that is, a lower proportion of grain relative to straw.[30]

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

[30] Thomas R. Sinclair, "Historical Changes in Harvest Index and Crop Nitrogen Accumulation," *Crop Science*, XXXVIII (1998), 638–643. The N intake by crops could also have varied with colder temperatures; we know that leaf N content declines toward the equator where temperatures and the length of the growing season increase: See Reich and Jacek Oleksyn, "Global Patterns of Plant Leaf N P in Relation to Temperature and Latitude," *Proceedings of the National Academy of Sciences*, CI (2004), 11001–11006.

Economic and agricultural historians tend to overlook that a great share of what usually passes statistically as yield increases is in fact the result of harvest indexes that became more favored from a market standpoint—that is, those showing more grain weight per plant rather than a higher amount of total biomass grown in the fields. Harvest indexes vary with plant breeding, but Allen's N-model assumes a constant harvest index of 0.45 without leaving room for changes in crop varieties. Historically, farmers tended to grow crop varieties with a relatively low harvest index (0.4) because straw was an important by-product for livestock feeding and bedding, roof thatching, and other uses. Modern varieties bred for higher harvest indexes do not always entail the translocation of more N into the grain. Even more, harvest index, crop biomass harvested, and N absorbed are not independent but interrelated variables.[31]

Another issue that prevents assuming a constant mineralization rate is the legume's adaptive responses to the soil N content. Legumes absorb more soil mineral N when the amount available in the soil is high. Otherwise, leguminous crops fix more N from the atmosphere by supplying more C to the root system that stimulates their Rhizobium colonies. Thus, under Allen's hypothesis of an N-poor farm system, pulses and legumes would have acted as net N fixers, not net N absorbers, as he assumed. Furthermore, equations A3 and A4 in Allen's model include a fixed productive response coefficient to mineral N in the soil for both grains and legumes (8.34 kg of yield per 1 kg of soil available N), which is not correct. Leguminous crops can have a depressive effect on subsequent wheat yields due to factors other than N availability (for instance, pulses require relatively high amounts of P).[32]

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

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The N/P foliar ratio also increases with average temperature toward the equator, because P is a major limiting nutrient in older tropical soils; N is the major limiting nutrient in younger temperate and high-latitude soils.

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

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

longer to mineralize stubble and other crop by products. These observations point to the importance of farmers' husbandry with respect to livestock densities in barns and folds, the use of straw as bedding to retain urine in manure, and the amount of N lost during composting a manure heap. All of these factors were variable rather than fixed.[33]

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

Allen's assumption of a constant lixiviation rate of N (50 percent of soil available N) for a process that is highly variable in space and time has an obvious effect on the stock of mineral N in soils given in his model. Nonetheless, farmers could have reduced lixiviation rates by enhancing the organic matter content of soils to improve water retention capacity. Grain root systems can reach down a full meter under favorable soil conditions, but Allen's model considers only the first 23 cm of soil. The organic matter content in 1 m may be four times that of the first 15 cm of soil; mineralization rates of 5 to 15 kg N/ha/year at depths of 30 to 60 cm have been reported in the literature. Furthermore, Allen does not take into account crop roots that may contain 50 percent of the total N in a plant.[34]

Allen's model wrongly adds the N in rain to the pool of organic N instead of accounting for it as a direct entry of mineral N into the soil. Last but not least, equation 1 in Allen's model is based on references that assume a linear relationship between yield and fertilizer N applied but not between yield and free N in soil as he assumes. The concentration of N in fertilizers (20 to 40 percent) is much higher than that of free N in soil (about 0.01percent). Allen mistakenly equates the mineral N input with the free N available in the soil, assuming a direct proportional relationship with yields. Although this direct

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

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

relationship has actually been observed with high applications of N fertilizer, it is not at all certain that it still holds when the N sources are less concentrated, as in N mineralization driven by traditional organic farm systems.[35]

Moreover, the absorption of N occurs with the flow of water into a plant. An N mineralization rate, as well as a crop's capacity of N intake, is amenable to improvement in accord with the physical properties of soil, such as porosity and moisture, which are related to soil organic matter content. Such improvement would require either soil conditioning (usually a highly labor-intensive task) or longer fallow and grassland periods within crop rotations. Swedes, turnips, and other tubers (such as mangel beets) can also alter soil structure and the water flowing through it for the better, thus making a greater N flow accessible to a plant—contrary to Allen's notion that turnips play no role in N availability. Older varieties of grains, usually adapted to environments with low water and N availability, show a greater ability to extract moisture deeply from the soil and are more efficient in N uptake.[36]

Although all of the factors discussed above are important, the whole is more than the sum of its parts. Various synergies can move a soil system beyond critical thresholds, leading to unexpected developments, as happened in the grassland soils of the North American Great Plains during the second half of the nineteenth century. In this true natural experiment, reductions in soil N content were not necessarily tied to a decrease in wheat yields until they reached a certain threshold. Even in this farming system that remained relatively unchanged for a long period, it took more than fifty years after the start of cultivation in the prairies for the land to reach equilibrium. The opposite would also be

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

[36] Allen, "Nitrogen Hypothesis," 197; Gražina Kadžiene, Lars J. Munkholm, and James K. Mutegi, "Root Growth Conditions in the Topsoil as Affected by Tillage Intensity," *Geoderma*, CLXVI (2011), 66–73; H. E. Mason and David Spaner, "Competitive Ability of Wheat in Conventional and Organic Management Systems: A Review of the Literature," *Canadian Journal of Plant Science*, LXXXVI (2006), 333–343; Anton Paul Wasson et al., "Traits and Selection Strategies to Improve Root Systems and Water Uptake in Water-Limited Wheat Crops," *Journal of Experimental Botany*, LXIII (2012), 3485–3498; Abdullah A. Jaradat, "Wheat Landraces: A Mini Review," *Emirates Journal of Food and Agriculture*, XXV (2013), 20–29; Michael J. Connell, R. John Raison, and Partap K. Khanna, "Nitrogen Mineralization in Relation to Site History and Soil Properties for a Range of Australian Forest Soils," *Biology and Fertility of Soils*, XX (1995), 213–220; Reich et al., "Nitrogen Mineralization and Productivity," 33–347; Ingrid C. Burke et al., "Nitrogen in the Central Grasslands Region of the United States," *BioScience*, LII (2002), 813–823. When pH increases, showing lower acidity, biological activities change from slow, fungi-dominated processes to faster bacterial-dominated ones with higher N-mineralization rates. Liming or combining marling with manure can increases pH. See Winiwarter and Winfried E. H. Blum, "From Marl to Rock Powder: On the History of Soil Fertility Management by Rock Materials," *Journal of Plant Nutrition and Soil Science*, CLXXI (2008), 316–324. Earthworms can dramatically change the structure and chemistry of soils; in temperate grasslands, they can consume as much as 90 tons of soil per hectare per year, thus improving its porosity, aeration, water-retention, and drainage capacity. See Winiwarter, "The View from Below: On Energy in Soils (and Food)," in Richard W. Unger (ed.), *Energy Transitions in History: Global Cases of Continuity and Change* (Munich, 2013), 43–48.

true. We cannot assume that a stabilization in yield is always related to a stabilization in the mineral N content of soil, as the linearity of Allen's N model does.[37]

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

This chapter views the start of the English Agricultural Revolution as based more on the use of synergies than on the optimization of single factors. After all, the agriculturalists of the time had a specific understanding of their farm systems as a whole, and a perception of how it might be improved, but they did not discriminate between nutrients, let alone between their mineral and organic forms. They worked in an economy in which labor and capital were seriously constrained, and yields were inelastic and highly volatile in the short term. Farmers relied on experience. When yields tended to decline during the harsher climate of the Maunder Minimum, they reacted by altering a preexisting combination of strategies (by increasing tillage and manure) and therefore intervening into the synergetic possibilities of their agroecosystems.[38]

Allen's problem with farmers' incentives emerges again when considering the time frame of their expectations with regard to the customary short-term volatility of their yields. The discoveries of Gregory King and Charles Davenant in 1696 about the quantitative inverse relationship between prices and quantities are telling on this score. Although seventeenth-century common farmers were probably as unaware of the King–Davenant formula of price elasticity as they were of the English translations of ancient agricultural treatises of Columela or Palladius or Samuel Hartlib's correspondence about gardening, they were certainly familiar with large yearly variations in yield and the ensuing price changes. Any attempt at modifying crop rotations and fertilizing methods had to discount these market ups and downs.[39]

As Loomis and Conor pointed out, there is no way to predict accurately the exact amount of nutrients necessary for a crop to avoid both a surplus and a deficit during the growing

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

[38] Pretty, "Farmers' Extension Practice and Technology"; Turner et al., "Agricultural Sustainability and Open-Field." For the agro-ecosystem's synergies, and the holistic approach to agro-ecology, see Stephen R. Gliessman (ed.), *Agroecology: Ecological Processes in Sustainable Agriculture* (Boca Raton, 1998); Miguel A. Altieri and Clara I. Nicholls, *Agroecology and the Search for a Truly Sustainable Agriculture* (Mexico City, 2005).

[39] Wrigley, *People, Cities and Wealth*; John Creedy, "On the King–Davenant 'Law' of Demand," *Scottish Journal of Political Economy*, XXXIII (1986), 193–212; Campbell, "Nature as Historical Protagonist," 288, 292.

season. Farmers, unaware of the mechanisms but well aware of the effects, had to rely on field histories and past experience, hoping to apply just the right dose, or maybe a little extra that would remain in the soil and profit future crops. The cost was one year's interest on the investment. Most likely, farmers would have put any available manure, latrine sludge, and vegetable fertilizers on the fields to counteract the risk of serious nutrient deficiencies. Such is the assumption from which we launch a reconstruction of the incentives that lay behind the first steps that farmers took in the management of soils during a time of climate change that eventually led to the English high farming.[40]

3. Testing English farming adaptation to climate change.

During the first phase of the Maunder Minimum, from 1645 to 1695, annual average temperatures in central and southern England decreased; they were 5 percent lower than they were during the subsequent rise, which lasted up to the 1730s. Average rainfall from May to August decreased 10 percent; storms became more intense; and agricultural production was 3 percent lower (Figure 3.1a and 3.1b).

From our perspective, the colder temperatures would have reduced wheat yields by shortening the growing season and by diminishing soil microbial activity and N mineralization. Farmers might have compensated to some extent by improving manuring and tillage and growing more legumes. While temperature kept falling, investments would have led to a small and delayed reward that was good enough to withstand the Maunder Minimum and to justify the attempt to boost fertilization. The rising temperatures that followed stimulated bacterial activity and fostered soil N mineralization during a time when the wheat-growing season extended again, producing a striking mid-term effect. The greater reward from wheat yields due to the improvements of the earlier period induced farmers to continue their approach.[41]

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

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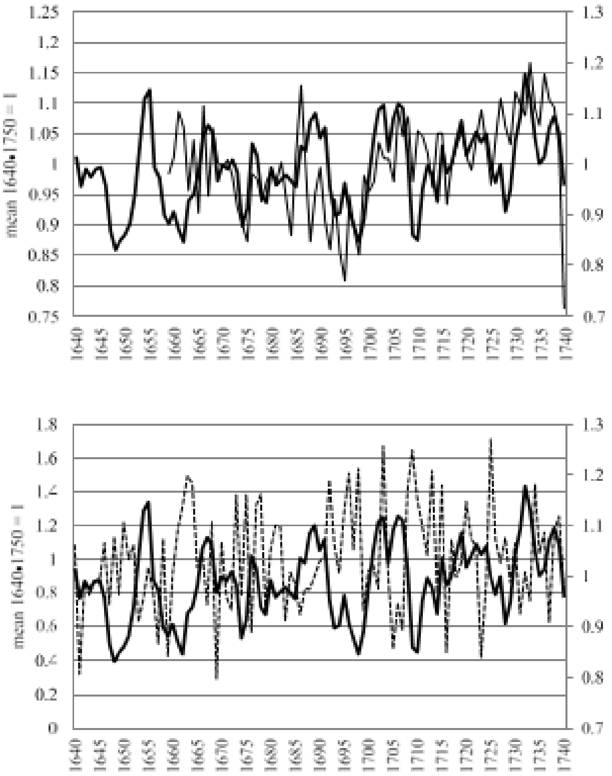
[40] Loomis and Conor, *Crop Ecology*, 332.

[41] Michaelova, "Impact of Short-Term Climate Change." Besides being congruent with the national aggregate data provided in Broadberry et al., "British Economic Growth," 36–44, which contributes to our statistical model, our hypothesis also fits with the evidence about the long-term trends of grain yields in Norfolk collected by Campbell and Overton, "New Perspective," 70–71, 79, particularly with the slight fall that occurred in Norfolk from 1640 to 1709 in spite of the increased livestock densities of the time.

effect not only by their ongoing methods but also by the delayed cumulative benefits of their earlier innovations.[42]

Figure 3.1. (a) Annual Mean Temperature and Wheat Output in England, 1640–1740. (b) Spring and Summer Rainfall and Wheat Output, England, 1640–1740



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

To test for this hypothesis, we used as dependent variable the series of wheat produced in England and Wales, as estimated by Martínez from previously published data about

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

physical wheat product in 1700. We also turned the variation in price series into annual quantity variations in line with a price elasticity of −0.4, as observed by King and Davenant in 1696. We adopted this elasticity as an independent empirical observation made in England precisely during our period of study—that is, as a reliable historical source that prevents us from falling into the circularity of employing the same price data again to construct the series of the agricultural product. Our independent explanatory variables include the instrumental temperature record compiled for central England from 1659 onward (the longest one in the world) and the late spring and summer rainfall measurements derived from oxygen isotopes in tree rings. A dummy D1 differentiates the years before and after 1700. Finally, another dummy, "corn bounties," tests the effect of export subsidies paid by the British government. The results are shown in Table 3.1.[43]

The coefficient of temperature in regression 1 (Table 3.1) implies that a variation of 1° centigrade increased wheat production by nearly 1 million bushels (which represents 3 to 4 percent of the country's wheat crop at the time). However, when applying a temporal dummy that interacts with temperature (D1 * Temperatures), the effect of warmer temperatures on wheat production is 18 percent greater after 1700 than in the previous cooling period, a result that clearly fits with our hypothesis. To check the robustness of this test, we included both variables in regressions 3 and 4. The first effect is that rainfall renders temperature nonsignificant for the whole period under consideration. However, when the interaction of the temperature with the time dummy was introduced as a

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[43] We took multiple steps to construct the series used as a dependent variable in the regression: First, we obtained the variations of the product from the wheat-price series through the price elasticity inferred by King and Davenant and specified later in the King-Davenant-Jevons-Bouniatian equation y=0.757/(x−0.13)2. The implicit price elasticity of this formula is −0.403, which is situated between the higher (−0.57) and lower (−0.23) ranges proposed for the long-term price decreases in England from the years 1268–1480 to 1750–1850 by Campbell and Ó Gráda, "Harvest Shortfalls, Grain Prices, and Famines in Preindustrial England," *Journal of Economic History* LXXI, (2011), 859– 886. Second, to give rise to a first approximation of the physical series in millions of bushels of wheat, we applied these variations to the wheat product estimated for 1700—a year of normal, average harvest—by Broadberry et al., "British Economic Growth," as well as to the one estimated by Phyllis Deane and William A. Cole, *Economic Growth, 1688–1959: Trends and Structure* (New York, 1967). The resulting series met the price-elasticity equation given above but lacked trend. Third, to rectify the situation, we used the English-population series to infer an initial trend of wheat demand. Fourth, we refined this demand by adding a rent elasticity that starts from a low level and grows at a slow pace along the series, in accord with the English per capita GDP given in Broadberry et al., "British Economic Growth." Fifth, we applied the same steps either to the gross or net estimates of wheat product given for 1700 in "British Economic Growth" or in *Economic Growth*, and adjusted the evolution of net trade balance to approximate the data obtained from the production or the demand side. Sixth, we compared the range of variation in the series obtained in this way with all of the previous long- term estimates in the literature—with shorter local series directly compiled in physical terms from probate inventories and bookkeeping, and with the yields resulting from the division of our series with the available estimates of wheat sown acreage—to choose the more plausible figures. Finally, in order to check its coherence, we tested that the series that we chose has a good splice with the official statistics of wheat product that start in 1884, and an average rent elasticity of 0.6 from 1645 to 1884 that fits well with the existing literature on the subject. For other details about the criteria for selecting the most coherent data, see Martínez, "Construyendo una serie física annual de trigo en Inglaterra (1645–1761)." We also used two different regression models before and after 1695 with similar results. However, the number of observations is so small that we prefer a single model with temporal dummies. We also ran other regressions using interactions with other temporal dummies and including different climatic variables (volcanic eruptions and yearly rainfall) that led to similar results. See Martínez, "Did Climate Change Influence the English Agricultural Revolution?"

variable, we found in regressions 3 and 4 that the warmer temperatures from 1700 onward became significant and carried higher coefficients. This outcome further accentuates how temperature affected wheat production during the cooling and warming periods, thus bolstering the results obtained from temperature and spring/summer rainfall separately.[44]

Table 3.1. Testing the Response of Net Wheat Production to Temperature, Rainfall, and Corn Bounties Paid for Exports, England and Wales, 1659–1740

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

NOTES: The ordinary least square (OLS) regressions (1), (3), and (4) consider temperature, and a specific dummy for the period 1700–1740, as explanatory variables of the net production of wheat. OLS regression (2) considers summer rainfall and the same dummy for the period 1700–1740; values presented are estimated coefficients; *p*-values in parenthesis; *F*-statistic values confirm that a relationship between exogenous and endogenous variables exists. The dependent variable is the wheat physical output recalculated from Stephen N. Broadberry et al., "British Economic Growth: 1270–1870," Working Paper of the Department of Economics (University of Warwick, 2011), available at http://www.grammatikhilfe.eu/economicHistory/pdf/Broadberry/ BritishGDPappendix.pdf (accessed January 17, 2015), as explained in Figure 3.1. Explanatory variables: Temperatures=mean annual temperature in centigrade; summer rainfall (−1)=May to August rainfall, the previous year in mm. The dummy variable D1 takes value 1 after 1700 and value 0 before; 1700 is considered a breakpoint for the wheat physical output series following Bai–Perron's methodology to obtain endogenous structural changes (Jushan Bai and Pierre Perron, "Estimating and Testing Linear Models with Multiple Structural Changes," *Econometrica*, LXVI, 1 [1998], 47–78). Corn bounties=a dummy variable that takes value 1 when export subsidies were paid and 0 when they were not. VIF values are close to 1 in all regressions.

SOURCE: Authors' own work, based on the sources listed in Figure 3.1.

In all of the regressions, the effect of spring/summer rainfall is significant —more than that of temperature— with a negative sign (Table 3.1). In an Atlantic bioregion where water was hardly a limiting factor late in the season, this result captures the damage that the waterlogging of soils from heavy rainfall did to ripening cereals, stimulating fungi diseases and perhaps increasing N leaching. Unlike the yearly average temperatures, spring and summer storms are site-specific phenomena—against which the open-field

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[44] We obtained similar results from the smoothed series of output (with a Hodrick–Prescott filter), regressed with temperature and summer rainfall. That is, temperature is significant only after 1700; the coefficients remain in the same order of magnitude; and the values of R-squared adjusted are higher. When the actual values of the series are subtracted from the trend to capture the series' volatility, only the summer rainfall remains significant. Instead of a simple annual average of temperature, we also tried as a variable the seasonal accumulated temperature of growing degree-days along the wheat vegetative period, but the results were nearly the same, probably because the thermal integral was calculated from mean monthly data, since daily averages are available only starting in 1772 (see footnote 33).

system would have afforded some degree of protection. The amount of spring and summer precipitation in the previous year has a similar impact on agricultural production.[45]

The introduction of temporal dummies that interact with spring and summer rainfall also shows that heavy seasonal storms caused less damage to wheat crops after 1700, even though their frequency and intensity did not decrease (Figure 3.1). The English farm systems became more resilient to them. By increasing the flow of organic matter in the soil, by altering tillage to prevent waterlogging and nutrient leaching, and by adopting more resistant grain varieties, did English farmers become better prepared to endure heavy storms during the late ripening periods of their wheat crops? Answering this question requires research far beyond the scope of this chapter.[46]

Overall, the temporarily broken down statistical tests shown in Table 3.1 fit with our hypothesis that the changes in English farming might have partially counteracted the effect of the colder temperatures on wheat yields because of a shortening of the growing season and a reduction in the N mineralization rate during the first period of the Maunder Minimum. Conversely, these new methods would have reinforced the effect of the temperature rise that occurred during the subsequent period of the Maunder Minimum. Nonetheless, these innovations in farming could only counter, not completely cancel, the

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

[46] The white-eared red wheat introduced in the 1650s and the stalked wheat in 1670s were more resistant to cold and humidity, and thus to the smut fungi. See Thirsk, "Farming Techniques," 168. For how climate change factored into Scottish farmers importing these improved wheat varieties from England, see Mary Young, "Scottish Crop Yields in the Second Half of the Seventeenth Century: Evidence from the Mains of Castle Lyon in the Carse of Gowrie," *Agricultural History Review*, LV (2007), 51–74, esp. 24. Without better soil drainage, turnips would have been difficult to add into the rotations, since they are vulnerable to fungi; we know that drainage became relevant later in the English Agricultural Revolution. A large-scale construction of hollow draining systems, which was incompatible with the open fields, required a previous land consolidation. Hence, it had to await the second wave of improvements linked to the parliamentary enclosures of the eighteenth and nineteenth centuries. See Allen, "Enclosure, Farming Methods and the Growth of Productivity"; *idem, Enclosure and the Yeoman: The Agricultural Development of the South Midlands, 1450–1850* (New York, 1992), 165–167; Andrew Gritt, "Making Good Land from Bad: The Drainage of West Lancashire, c.1650–1850," *Rural History*, XIX (2008), 1–27. Other soft improvements in drainage, such as plowing the fields gradually to create a convex profile that led runoff toward the margins, predated the deep hollow drains and other heavy hydraulic works. See, for example, Turner et al., "Agricultural Sustainability and Open-Field Farming." Furthermore, farmers could have had recourse to other harder tubers like swedes (*Brassica napobrassica*) and other fodder beets like the German mangel-wurzel (*Beta vulgaris*) before the diffusion of turnips (*Brassica rapa*).

effect of climate change on wheat production, thus explaining why we checked for correlations in both periods, with temperature taken alone but at different intensities. The clear effect of the temporal dummies indicates that we cannot interpret the trends in wheat production and yield as the result of a linear impact of temperature variation on harvests. The interplay between climate change and farmers' responses to it is what matters, not climate change alone.

As stated at the outset, other climatic and socioeconomic variables affected net wheat production in England and Wales. Unfortunately, the same price series used to estimate our dependent variable cannot be included again in the regressions. Instead, we used a dummy in column 5 of Table 3.1 that tests the effect of corn bounties paid for English exports, or their absence. The results are statistically significant; the other climate variables remain significant; and the coefficient indicates that the matter of public subsidies is associated with a 5 percent variation in the amount of English wheat produced.

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

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

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

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

A deeper understanding of the British case also requires a comparative, European-wide perspective. The collective task is to understand when, where, how, and why Europe's diverse pre-industrial organic agricultures were able to achieve a higher cropping intensity without opening a rift in nutrient replenishment that would cause decreasing yields in the long run; or, conversely, when, where, how, and why they were not able to do so. This approach entails opening the agricultural black box, adopting an agroecological viewpoint that demands a close collaboration of historians with social and natural scientists.[47]

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

Chapter 4. Revisiting Allen’s nitrogen hypothesis from a climate perspective (1645-1740)[48].

1. Introduction[49]

The profound transformation of the English agricultural landscape has proved to be a controversial field of study. Although the traditional historiography focused on enclosures, farm size and the leadership of “learned pioneers” during the 18th and 19th centuries, other studies have stressed the importance of developments in earlier periods. E. L Jones (1965) argued that not only improvements were carried out between 1660-1750 but also that these improvements were applied both in open fields and enclosures. According to this author, tenants were the first to increase their investments, whose efforts were later replaced by those of the landowners[50]. This debate was revived in the works of Robert Allen (1992) and Mark Overton (1996), amongst others (Campbell and Overton, 1992). Whilst the former agreed with Jones’s thesis emphasizing the leading role of the yeomen in the spread of agrarian innovations, especially during the period 1650-1750, the latter followed the tradition that linked agrarian innovation and enclosure processes (Chambers and Mingay, 1966), placing the period of increase in yields in the second half of 18th century and giving more importance to the landowners’ investments[51]. Recent research reconstructing the occupational structure of the population confirms the precocity of the agricultural revolution by sustaining a growing number of people working outside the agricultural sector. By 1700, only around 48 per cent of the population was working in agriculture, thus making England a historical exception at that time (Wallis et al. 2018; Shaw-Taylor et al. 2018).

In this regard, Robert C. Allen has related the exceptional growth of agricultural productivity to the yeomen’s revolution and the open fields[52]. This author argues that there were two main factors explaining the improvement in grain yields. On the one hand,

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[48] José L. Martínez-González & Francisco J. Beltrán Tapia, 2019. "Revisiting Allen's nitrogen hypothesis from a climate perspective (1645-1740)," *Documentos de Trabajo de la Sociedad Española de Historia Agraria 1902*, Sociedad Española de Historia Agraria. José Luis Martínez is the lead author. Beltrán Tapia has participated in the improvement of the English text, and in a small visual improvement of the econometric part and has helped to ensure the global quality of the paper.

[49] We would like to express the deepest appreciation to the professors E. Tello, G. Jover, M. Badia, J. R.. Olarrieta, P. Malanima, I. Iriarte, N. Koepke, J. A. Mateos, T. Rinne, J. M. Lana, Morgan Kelly, and our anonymous referees. We also thank the constructive comments given by Sam White. In addition, our gratitude to the *British Agricultural History Society* and the interest shown by the professors Mark Overton and Liz Scott. We would also like to thank Richard Hoyle and Bruce Campbell (Girona Rural History Conference 2015), to the seminar participants at Prato (Datini Ester, Shocks), Zaragoza (Agrocliometrics II), London (ICHG 2015), Barcelona (PhD seminars), Alicante (AEHE seminar).This work was supported by the Spanish research projects HAR2009-13748-C03, HAR2012-38920-C02-02, ECO2015-65582 and HAR2015-64076-P and the Partnership Grant SSHRC 895-2011-1020 on Sustainable Farm Systems: long-term socio-ecological metabolism in Western agriculture funded by the Social Sciences and Humanities Research Council of Canada (2012-2017).

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

[51] See also Thirsk, 1967, 1984, 1985, 1997.

[52] Allen 1992.

farmers gradually adopted better cultivation techniques, seeds and improved drainage and, on the other hand, they also introduced legumes and convertible husbandry that led to an increase in the nitrogen stock. The latter mechanism would explain about half of the rise in yields. Likewise, Allen stressed that the word "revolution" needs qualifying: the process of change to higher yields was gradual, due to the slow growth of the stock of nitrogen in the land, so nitrogen fixation was very slow and has a small impact in the short term[53],

The impact of climate on English agriculture history, however, has received little attention. During the 17th century the climate in England generally worsened. This phenomenon has been related to a long fall in the solar activity, the Maunder Minimum[54], but this solar minimum is likely to have coincided with other adverse climatic forces[55]. Average temperature fell but rainfall variability and humidity increased[56]. The production of dry materials from crops decreased further, in proportion to reduced solar radiation absorbed by plants[57]. The energy balance between the heat latent in the soil and the evotranspiration levels of the plants, as well as photosynthesis processes and respiration, became more unstable.

Although some research explores how climate affects agricultural yields both in the short and long term[58], there is little research exploring how the coldest phase (1645-1715) interacted with the Agrarian Revolution and the possible adaptive response from farmers. By expanding on the Nitrogen model proposed by Allen and framing the agricultural revolution into the wider climate changes that occurred during the 17th and early 18th century, this paper re-asesses the role of improved farming techniques on the evolution of agricultural productivity. In this regard, our contribution stresses that the cold phase would have reduced nitrogen levels and yields unless farmers compensated with their efforts. Their role therefore was even higher than what it is implied by the observed yields. Increasing temperatures in the next phase (starting c.1715), however, had a positive effect on agricultural productivity, so the role of the farmers in this stage has been previously over-rated.

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[53] Allen 2008.

[54] The astronomer Jack Eddy published in the magazine *Science* (1976, pp. 1189-1202) a famous article in which he provided scientific evidence of the existence of this solar minimum, named after the English astronomer who discovered it, E. W. Maunder (1851-1928). See also Parker, 2013.

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

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

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

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

2. The standard nitrogen model: a theoretical review.

The introduction of legumes and convertible husbandry increased the nitrogen stock and greatly contributed to the agricultural revolution that took place during the 17th century. The "nitrogen hypothesis" suggested by Allen is based on the following model[59]:

$$Y = m \cdot F \quad (1)$$

$$N_t = N_{t-1} + A_t - rN_{t-1} \quad (2)$$

$$rN_t^e = A_t \quad (3)$$

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

This model allows Allen to divide the rise in yields into two mechanisms: those that increased nitrogen (mostly from natural deposition and nitrogen-fixing plants) and those that increased the efficiency with which nitrogen was used. In order to obtain the concept of "efficiency", Allen states that m equals the harvest index (*HI*) multiplied by the ratio of dry matter to nitrogen assimilated by the plant and at the same time multiplied by the take-up ratio K (the fraction of the F in the soil absorbed by the plant). Allen assumes that the two first elements do not vary very much because "the morphology and chemistry of grain is fairly stable", so the take-up ratio is equivalent to efficiency[60]. In this respect, "new tools, new seeds and better working of the earth increased the take-up of nitrogen". This is where factors such as human work and horses are included, or new techniques, for example. Therefore, an equivalent form of Equation 1 is Equation 4, where K is the take-up ratio and F is the free nitrogen, which depends on the agricultural activity variables X_t.

$$Y = f\ (K, F) = f\ [K(X_t), F(X_t)] = g\ (X_t) \quad (4)$$

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[59] Allen 2008, p. 188.

[60] Allen 2008, p. 187.

However, Allen did not consider the temporal variability of the stock of nitrogen (N) or its mineralization rate (r). According to the soil science literature, this variability can be explained, directly or indirectly, by changes in temperature, rainfall, solar radiation and volcanic aerosols. It is difficult, for example, to accept a constant r=0.015 over long periods because it decreases during climatic cooling[61]. Ceteris paribus, lower temperatures and shorter growing seasons lead to a lower mineralization rate and a slower loss of the stock of organic matter (OM) in the soil and humus (Jenny 1930; Loomis et al. 2002).

Likewise, the quantity of mineralised nitrogen (F in Allen's model) does not only depend on r and OM variability. First, there is a direct input flow (rainfalls and free, non-symbiotic fixation) and output (denitrification, volatilization and leaching), which also depend on the climate, as well as other factors[62]. Allen assumes that these inputs and outputs were balanced but this is surely not the case in colder and wetter periods. We must bear in mind that the microbiological processes of the soil depend on temperature, humidity and acidity level (pH), as well as the photosynthesis or the action of insects, diseases and plagues[63]. Microbial activity slows down at low temperatures, affecting the speed of decomposition of OM. One of the processes of mineralization, ammonification, generated by microbial matter, is also very sensitive to temperature. The increase of humidity promotes denitrification and, consequently, nitrogen returns to the atmosphere as gas in greater quantities. In addition, there are some factors which affect the performance of legumes and the stock of nitrogen fixed yearly. The assimilation and fixing of nitrogen are proportional to biomass production, so if biomass declines in colder weather, nitrogen-fixing also declines.

The model also fails to take into account that nitrogen (N) is only one of the main nutrients of the land, together with phosphorus (P) and potassium (K). According to Liebig's Law, yields are determined by the most limiting of these factors[64]. In this regard, apart from influencing nitrogen content, climate also shaped fertility in other ways, including the content of phosphorus, potassium, and acidity in the soil. In the case of phosphorus, although its function has been historically minimized[65], Edward I. Newman and Paul Dean A. Harvey pointed out that it could have been the main soil fertility factor until the 19th century[66]. Phosphorus generation (from OM mineralization) is usually deficient

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

[62] The increase in humidity and soil reflectiveness generates greater denitrification; the increase of urine in the soil generates greater ammonium volatilization and a greater humidity index together with higher nitrate levels from manure or urine cause higher lixiviation (Loomis 2002, pp. 225 - 229).

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

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

[65] Allen 2008.

[66] Newman and Harvey (1997, p. 136). On the other hand, pH seems to be affected by temperatures in the very long term. However, historiography indicates that farmers, in their struggle, increased their OM contributions, but they did it in a rather much wetter soil, which meant more acidification.

during cold periods. Therefore, its replacement management had to be improved in order to maintain its levels during the Little Ice Age.

Climate change also affected the development phases of plants (the germination and growth of plants). The flowering period of the winter variety of wheat was critical and frost or a deep temperature fall could ruin the crops. The wet and cold springs, typical of the second half of the 17th century, would therefore affect agrarian production, forcing farmers to introduce new seeds such as Red-Stalked Wheat in 1670 (Oxfordshire), or White-Eared Red Wheat in 1650. Varieties of great resilience to climate such as *Lammas*, good performers and of excellent bread making quality, became very important to fight against the smut[67]. As for barley, early varieties such as narrow-eared barley became predominant in the 17th century. These varieties were planted in May "better than in March" and stored in the barn for two months or less, becoming very valuable in the wet and cold springs typical of the climatic downturn, and were very well-known in Cornwall and widely planted in Oxfordshire[68]. Another variety which was widely spread was a spring barley, planted in Lincolnshire, and typical northern species were successfully adopted in the south. All this suggests that climate was an influential factor in seed selection, an issue that still further research[69].

Balancing all these factors was extremely challenging and, when crops grew in less than ideal conditions, slight variations in the environment could have caused great variation in yields and the harvest index (*HI*)[70]. For example, in the pre-industrial era, the nitrogen available to crops from rainfall and free nitrogen was as little as 6kg per ha per year. With a harvest index *HI* of 0.4 (at that time it must have been lower than today) and 0.02 kilograms of N/ha per kilogram of grain, it equalled about 120 kilograms of wheat on an average crop of 900 kilograms, that is 13.3 per cent of the total. With an elasticity of price for the demand of -0.4, this implied price variations of about 33 per cent. Consequently, slight variation of N caused by weather changes affected prices considerably[71].

3. Integrating climate into the standard nitrogen model.

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

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

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

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

[69] Overton 1989b, p. 90.

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

[71] We have supposed elasticity of 0.4 but some authors place to the figure as low as 0.1 (Fogel). This means that prices would be even more sensitive (133 per cent). A 900-1000 kg production of wheat was somewhat common in those times. R. S. Loomis estimated the N cycle on an English farm of the 14th century where 16.1 kg/ha of N were yearly produced. Rainfalls, free $N2$ and fixing with peas was 8 kg/ha of N, higher than that of the seed (2.5 kg/ha), straw waste (2.5 kg/ha) or manure (3.1 kg/ha). If the direct contribution of N was already relevant by then, it is reinforced by the indirect effect of climate, catalyzing changes in almost all the processes that affected the yield of the crops as the ones mentioned above (fixing, waste, manure).

Where $\mathrm{A_t}$ and *r* now also depend on climatic variables (C_t). Consequently, N_t is a function of C_t. Given that F originates from organic nitrogen $N_t\ (C_t)$, equation (1) becomes:

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

An important point here is the descriptive character of the standard model: it does not explain why innovation occurred. If in (1), m were (nearly) constant in the short term, the marginal product of nitrogen would be m, as well as its average product. Undoubtedly, this is too rigid an assumption for innovation to happen[72]. However, if the level of free nitrogen F were conditioned by climate, the marginal product Y' would be $m^* \cdot F'(C_t)$. The marginal product could then be above or below the average product, according to weather variations, and in the short term $m \neq m^*$. Therefore, the exclusion of the weather factor overestimates or underestimates output, thus making it difficult to understand farmers' behaviour.

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

Consequently, we can reformulate *m* as follows:

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

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

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

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

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

The climate of the 17th century is certainly exogenous. Let us take a model, where K is the take-up ratio and $\frac{\partial K(t)}{K(t)} = a > 0$. C stands for the climatic parameter. Let us add the take-up ratio and the climatic impact on the production function $Y = (KL)^{1-\propto}(CF)^{\propto}$. K stands for the number of units of labor efficiency, since only the take-up (that increases labor efficiency) allows the existence of equilibrium with constant growth rates through time. C would indicate a greater efficiency of nitrogen thanks to the improvement of climate. The contribution of the stock of nitrogen in the output is $\propto$, and the condition $0 < \propto < 1$ is met. The function of the per capita production is $y = K^{1-\propto}(Cn)^{\propto}$, where y stands for per capita production and n is the stock of nitrogen per capita. The golden rule applied to a model where the capital is nitrogen is $s \cdot f(n) = (p + \delta) \cdot n,$ where s stands for the savings rate, p stands for the population and δ is the depreciation of nitrogen. Substituting $f(n)$ by the former expression, finding the stock of nitrogen per capita n, applying the Napierian logarithms and deriving respect time we obtain that the growth rate of the nitrogen per capita equals the take-up ratio plus the variation rate of the climatic parameter:

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

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

A simple arithmetical exercise confirms these theoretical conclusions, thus strengthening the need to make the model less rigid. As mentioned before, although the standard model that the harvest index (*HI*) is fixed, temperature variations actually lead to changes in the *HI*. If the *HI* is higher, so is m and vice versa[73]. Let us consider now two hypotheses regarding *N* contributions in wheat output: a constant *HI* with of a value 0.3 and a flexible *HI varying* between 0.2 and 0.4 according to temperature[74]. As shown in Figure 4.1, which reports the evolution of nitrogen in wheat production, variations in F are higher when the harvest indexes depend on temperatures. The mechanism behind this figure is

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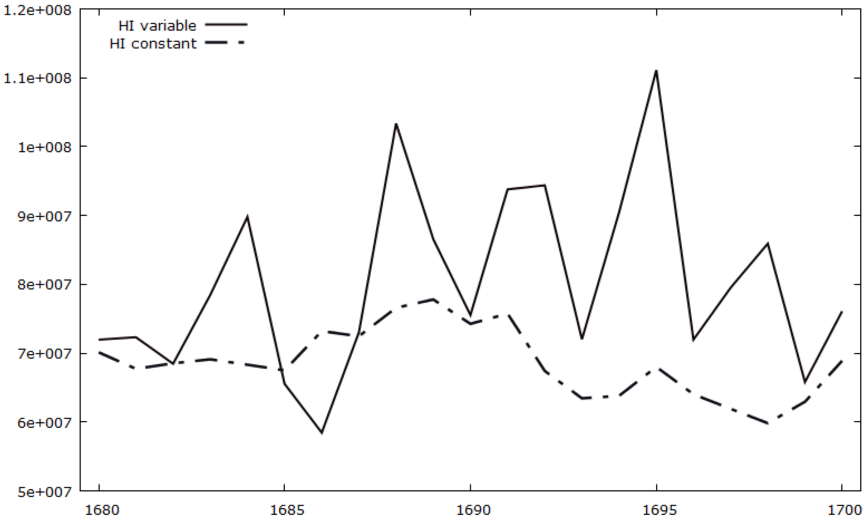
[73] Given a stock of mineral nitrogen, if the *HI* is higher, so are yields. Therefore, *m* is also higher.

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

reflected in Table 4.1, which shows how m fluctuates according to changes in temperatures. These examples stress how climate intensified the agrarian improvements through the additions of organic nitrogen A_t, thus further evidencing the need to expand the standard model.

Figure 4.1. Total nitrogen in wheat production (million kgs.). England and Wales, 1680-1700.



Note: The broken line shows total variations of *N* maintaining *HI* constant (0.3) and *N* content in the grain (0.02 kg of *N*/ha per kg of grain). The continuous line shows variations in N with a flexible *HI* (between 0.2 and 0.4) depending on temperature. An increase in *N* (*F*) is observed during the cooling phase (Maunder Minimum). The calculation of *N* variations (*F*) is explained in table 4.1.

Table 4.1. Average annual temperature versus non-constant m ratio ($m = \frac{Y}{F}$). England and Wales, 1660-1739.

Year	Temp average	m
1660-1664	9.2	15.84
1665-1669	9.0	15.07
1670-1674	8.6	13.79
1675-1679	8.5	13.38
1680-1684	8.6	13.66
1685-1689	8.9	14.74
1690-1694	8.2	12.28
1695-1699	8.0	11.80
1700-1704	8.9	14.80
1705-1709	9.3	15.85
1710-1714	9.2	15.70
1715-1719	9.1	15.36
1720-1724	9.3	15.92
1725-1729	9.3	16.16
1730-1734	10.0	18.25
1735-1739	9.8	17.53

Note: In Allen's equation, Y is grain yield and F is the level of mineralized nitrogen. Taking Loomis's modified formula (total production variation * *N* content in the grain (0.02 kg of *N*/Kg of grain)/(Harvest Index *HI*)= total variation of *N*, we calculate a proxy of *F*. The grain production series is estimated as explained in the data section. The novelty is that here the *HI* depends on temperatures. This variability is calculated giving *HI*=0.03 for 9ºC and modifying the *HI* proportionally according to temperature deviations from 9ºC (Loomis 2002, p. 67).

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

4. Methodology and data.

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

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

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

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

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

The objectives of this approach are twofold. On the one hand, this model includes climate as a relevant dimension in the short term, a fact that allows qualifying the standard nitrogen model and correcting potential biases in the traditional estimates of land yields. On the other hand, it opens up the possibility of exploring long-term effects, as well as farmers' adaptive processes. This second step analyses the relationship between climate and adaptations relying on the dummy variables approach.

4.1. Production Data.

Since there are no monthly/annual physical measures of output (in volume or weight), we use a robust estimation of production in bushels and kilograms (Martínez-González 2019)[75]. According to Davenant (1699), the grain warehouses had limited mitigating power, just five months and only in case of good harvests. Their influence on the interannual prices was therefore minimal (Hutchison 1988, pp. 51-52). On the other hand, the total surface cultivated with wheat between 1650 and 1750 remained stable in about 2 million acres (Broadberry *et al.* 2015). This allows us to use the wheat output as a measure of yield.

4.2. Climatic Data.

Although information on pre-industrial climate is scarce, it is possible to gather estimates of temperature, solar radiation, volcanic dust and rainfall[76]. The CET temperatures assembles together a series of monthly records of temperature from several towns in the Midlands starting in 1659 (Manley, 1974). Although there are other temperature series[77], this chapter primarily relies on Manley's series for various reasons: firstly, it offers monthly information; secondly, it is the only one resulting from direct measurements on the ground (instead of climate reconstructions), even when it is likely to contain biased calibration (Kelly & Ó'Gráda 2014); thirdly, these temperatures are from England which is the focus of this study. We should however bear in mind that Manley's series presents some limitations. In this regard, the series starts in 1659, that is, a bit after the phase of accelerated cooling began (approximately in 1645), so many years of analysis are missing. It also does not represent the whole country but only a few specific locations. In this regard, it's important to note that CET exaggerates interannual variability, because there is more short-term temperature variability in any one region of the country than in the country as a whole, and understates low-frequency variability, due to the way that early instrumental temperature series are homogenized to remove artificial breaks and trends (D. E. Parker 2010). Lastly, it also seems that, before 1700, the temperature drop was more intense (Macadam 2012). Therefore, to further test the results of this study, we will also use the series by van Engelen, Buisman and Ijnsen (2001), suggested by its reliability by Kelly and O'Grada (2014).

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

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

[77] One of them corresponds to those of J. Luterbacher's *et al.* (2006), which presents the average European temperatures organized by seasons. A second reconstruction is the one developed by Guiot *et al.* (2010), with annual temperatures April-September organized by latitude and longitude of the earth every 50º. The most suitable are the case of England TAS_2_5W_52_5N (west of England, near Birmingham) and TAS_2_5E_52_5N (east of England, but near the sea), reconstructed from 117 different intermediate indicators (including tree rings, historical documents, pollen and ice records).

As for solar radiation and volcanic activity, we have the series presented in Mann et *al.* (2000). Capturing solar irradiation is especially useful because irradiation explains 74 per cent of temperature variations in the pre-industrial phase (Lean *et al.* 1995)[78]. Moreover, solar radiation falls on England in a nearly uniform way[79] and the different distribution of rainfalls determines the potential evaporation (Monteith 1977). Monteith (1977) indeed established a positive relationship between dry material from the crops and the radiation intercepted. According to this author, most of the cultivated lands are in +/- 10% of 9MJ/m2 daily average per year. This means that the regional differences would have been caused by other factors, such as rainfall[80]. Unfortunately, there are no direct humidity, rainfall or weather instability records for the 17th century apart from the references written at the time by Adam Smith (1778), W. T. Comber (1808) or Thomas Tooke (1838). However, recent research has reconstructed spring-summer rainfall in the southern, eastern and south-central England (Rinne *et al.* 2013; Cooper *et al.* 2013; Wilson *et al.* 2012). These series will be used bearing in mind that: a) they are reconstructions; b) measurements come from trees located in specific territories, when the whole country should be analysed; and c) rainfall has a more local and diverse incidence than temperatures, thus depending upon many geographical factors[81].

Reassuringly, the climate variables employed here are shown to have a direct impact on yields (see Table 4.2). The variables show the expected signs: higher temperatures are associated with higher wheat production and more rainfall in summer not only negatively affects harvests that year but also the following year due to their effect on the nitrogen cycle (also because some of the organic matter generated in the previous year is used in the following years)[82]. Relying on the series of provided by Van Engelen *et al.* (model 2) yields similar results. Temperature and rainfall alone explain between 38 and 44 per cent of the variation in grain yields, thus supporting the adequacy of these series. We can advance here a quantitative assessment of what an adverse climate could bring. First, an excess of summer rains can damage crops (storms, floods, diseases), dropping temperatures also have a direct effect on plant growth. Second, there is another order of indirect impacts through changes in the amount of nitrogen and other nutrients, by varying the mineralization rate of nitrogen (r) and other mechanisms, thus affecting crop yields. But there are also delayed effects in that temperatures and rains from previous years can also influence the levels of nitrogen and those of the other nutrients and affect future crops. This is summarized in model 1. While year t captures direct and indirect effects, year t-i reflects the indirect effects of previous years. A 1°C-decrease in temperature and a 50mm-increase in summer rainfall resulted in a fall of about 2.6 million bushels in gross

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[78] Global data, geographically speaking.

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

[80] Monteith 1977, p. 280.

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

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

wheat production[83]. In model 2, with van Engelen *et al.* temperatures, wheat output falls even further, about 3.2 million bushels.

Table 4.2. Testing the Response of Gross Wheat Production to temperature and rainfall. England and Wales, 1645-1740.

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

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

4.3. Agricultural Inputs Data.

Given that there are no statistical series of "Allen variables" able to directly capture how nitrogen is added from manure, feeding beans or spring grains, we employ a set of proxies that attempt to proxy for the importance of different agricultural practices such as the use of spring grain, hay, legumes and gross wheat. We therefore use variations in the price of bean, barley and hay to proxy for biomass variations associated to those agricultural practices, as well as wheat production in the previous year. Table 4.5 in the Appendix reflects the equivalence between "Allen variables" and the variables used here. Although the available information does not allow to measure the take-up ratio with precision, it should be stressed that this working paper is not intended to build a model that fully explains grain yield, but rather to make the Allen model more flexible by stressing the interactions between climate, agricultural productivity and farmers' responses.

5. Results and discussion.

5.1. Production approach and climate.

Table 4.3 present the results of estimating equation (9) relying on the variables explained above[84]. The regressions presented are a simplified and flexible version of Allen's model. Column (1) introduces the proxy variables "legumes_use", "spring grains_use", "gross wheat_use" and "hay_use" and confirms Allen's standard model. *Ceteris paribus,* the increase of the price of the spring grains between the years t and $t-1$ involves a fall of the crops and consequently a decrease of the quantity of N from the manure from feeding spring grain, the free nitrogen on the spring grain field, the nitrogen mineralized or the

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

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

stock of nitrogen[85]. The partial impact is a decrease of 4.1 million bushels of the wheat production. If a similar fall of spring grains also occurs between the periods t-1 and t-2, the total impact multiplier is a reduction of 7.46 million bushels, as it is necessary to add the effect of the fall of spring grain production to the wheat production of the year $t-1$, which at the same time has impact on the wheat output of the year t through a fall of the addition of N from wheat chaff, wheat seed sown, free nitrogen on the wheat field, the nitrogen mineralized and the stock of nitrogen in year t.

Allen indicates that the short-term effect of the nitrogen supplied by the legumes is irrelevant. This assumption seems to be confirmed in model 2. A variation of the nitrogen coming from the production of legumes of the year $t-1$ or $t-2$ has no noticeable effect in the production of wheat. However, decrease in the bean crops between $t-2$ and $t-3$ involves a slight decrease of the wheat output of -0.47 million bushels, from the nitrogen supplied by manure from feeding beans, the nitrogen stock from legume residues, the nitrogen mineralized and the stock of nitrogen[86].

On the other hand, low *HI* is associated with low *r* and low wheat yields. The contribution of *N* through the seeds, as well as the straw waste and the handling of the seeds, depend on the grain harvested in previous years. That is, past production captures the nitrogen associated with the harvest index and influences the practice of sowing. For example, the use of older seeds in the new crops -especially if these seeds are from a low-quality and unproductive previous crop- can make yields worse from a comparative point of view. In addition, previous agronomic practices, proxied by wheat production from a previous year, had a positive sign (i.e., a good crop led to another good crop and a bad crop led to a bad one as well), thus confirming Hoskins's wheat-price series theory (1968, pp. 17-19).

Including the climate variables described above greatly improves the explanatory power of the model. Taking into account this dimension also reduces the role played by Allen’s variables (around 12-15 per cent for the use of Spring grains and around 4 per cent for the use of legumes), thus stressing the importance of considering climate when assessing the role agricultural practices on yields[87]. An ANOVA analysis and the residual plot (figure 4.2) shows an over or under estimation of the residuals in relation to model 2 and a biased estimate of the coefficients which affect the exogenous variables [88].

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

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

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

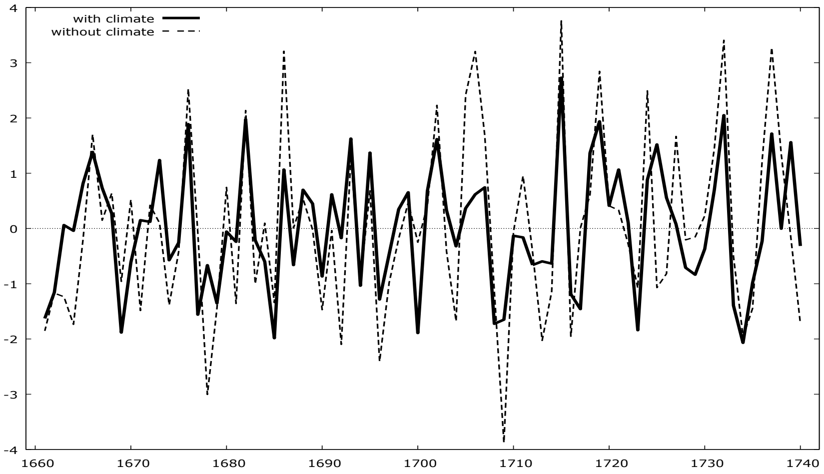
[88] Results available upon request.

Table 4.3. Testing the Response of Gross Wheat Production (models 1, 2, 3) to climate and soil management. England and Wales, 1645-1740.

	(1) 1661-1740	(2) 1661-1740	(3) 1647-1740
SPRING_GRAIN_USE	−4.094*** (<0.0001)	−3.607*** (<0.0001)	−3.398*** (<0.0001)
SPRING_GRAIN_USE (-1)	−1.374** (0.0281)	−1.158*** (0.0129)	−0.948** (0.0420)
SPRING_GRAIN_USE (-2)	--	--	−0.857* (0.0867)
LEGUMES_USE (-2)	−1.335** (0.0103)	−1.284*** (0.0011)	--
GROSS_WHEAT_USE (-1)	0.719*** (<0.0001)	0.641*** (<0.0001)	0.710*** (<0.0001)
CET TEMPERATURE	--	0.606*** (0.0032)	
ENGELEN TEMPERATURE	--	--	0.550*** (0.0021)
SUMMER RAINFALL	--	−0.009*** (<0.0001)	−0.008*** (<0.001)
SUMMER RAINFALL (-1)	--	−0.009*** (<0.0001)	−0.007*** (<0.001)
SUMMER RAINFALL (-2)	--	0.006*** (0.0092)	0.006*** (0.0054)
SPRING RAINFALL (-1)	--	−0.015*** (0.0036)	−0.015*** (0.0035)
N	80	80	94
R-squared	0.69	0.83	0.82
F	44.70	44.76	48.28

Source: See text. p-value between brackets. *= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. For simplicity, the intercept is not reported. All the series are stationary (correlograms and ADF Test). The lineal functional form is accepted (Reset Test). All the series are homocedastitic (White and Breusch-Pagan Tests) and free of multicollinearity (VIF). The error series follows a normal distribution (Normal Test) and there are no outlier problems. The regression is free of autocorrelation problems (h-Durbin Test, LM and Ljung-Box Tests, no ARCH effects). No changes in parameters are detected (CUSUM and Harvey-Collier Tests) The fact that all series are stationery and they do not violate any of the basic hypotheses of a multiple regression make the results robust.

Figure 4.2. Residual plot of the model with and without climate variables.



Combining all the effects together[89], climate (a 1ºC-decrese in temperatures plus a 50mm-increase in rainfall) and agricultural practices (a 0.5 shilling-decrease in nitrogen inputs: the seeds of previous wheat harvests and spring grains harvests, as well as nitrogen from legumes), results in a fall of the harvest of approximately 13.7 million bushels. Obviously, this disastrous combination never occurred but allows us to illustrate the importance of each factor: 51.6 per cent of this impact comes from the direct and indirect effects of the

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

weather on *N* and the rest of nutrients (with lags included), and 48.3 per cent comes from the lagged indirect effects from agricultural practices, which, in turn, affect *r*. The hay biomass from previous years show no effects; for this reason, we do not include this variable in the equation. This calculation serves to illustrate the importance of each factor because a combination of adverse weather was always accompanied by an increase in effort of farmers in nitrogen additions. Therefore, total climate impacts accounted for about half of the variations in yields, the rest came from nitrogen-fixing plants and better cultivation, seeds, and other factors.

5.2. Long-term impacts and adaptation.

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

Table 4.4 reports the result of estimating the effect of temperature and rainfall on wheat production but allowing this effect to change between periods. In this regard, the dummy variables *D1* takes value 1 from 1700 and value 0 before 1700 (we have also tested the robustness of this approach by constructing the dummy variable *D2* with a value 1 from 1715 onwards). The dummy variable *D*3 took value 1 between 1664 and 1691 and 0 in the rest. These results suggest structural changes in 1664, 1700 and 1715. These findings confirm that in the first period the climatic variables had less effect on wheat production. That means that there were great efforts to lessen the climatic shock from 1640 to 1660, at the beginning of the Maunder Minimum[90].

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[90] There are three aspects to be taken into account: first, that the climate impact is asymmetric. When it harms the farmer, it reacts more dramatically; when it benefits him, it relaxes. This means that during the cold period farmers worked hard to overcome the difficulties, increasing the content of nitrogen, cushioning the environmental impact of the climatic variables. On the other hand, when the weather improved they did not need to struggle so much, so *the explanatory capacity of the climatic variables was higher*. Secondly, the relationship climate-agrarian production is a reflection of human activity and must not be considered an input, at the same level as those supplied by the farmer. Therefore, the agrarian improvements boosted the positive effect of climate in the short term. Third, since 1700 the critical episodes were more isolated (although hard) as in 1709, 1714, 1727 and 1739, catching farmers off their guard. This leads to a major explanatory capacity of the climatic variables, since the previous phase, more changeable, cold and wet, allowed the farmer to be more prudent.

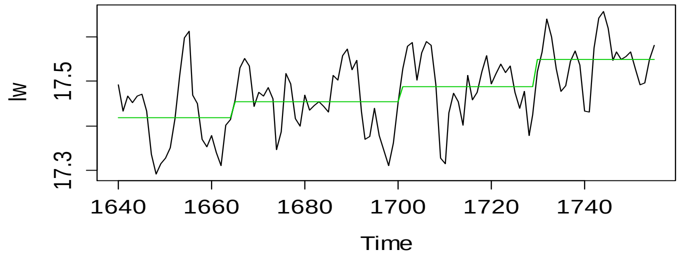
Table 4.4. Testing Adaptive Response of Wheat Net Output, England and Wales, 1640-1740.

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

Source: compiled by the authors. p-value between brackets. *TEMPERATURE*, temperatures; *SUMMER_RAIN*, summer rainfalls. The dummy variable *D1* took value 1 from 1700 and value 0 before 1700. The dummy variable *D2* took value 1 since 1715 and value 0 before 1715. The dummy variable *D*3 took value 1 between 1664 and 1691 and 0 in the rest. These results suggest structural changes in 1664, 1700 and 1715. There could be more break points, since this analysis has not been carried out with all the "candidate" years. For simplicity, the intercept is not reported.

The adaptive efforts carried out by the farmers can also be ascertained using an endogenous Bai-Perron test, thus avoiding the division of the series and the resulting reduction in the number of observations[91]. The detected breakpoints are 1664, 1689-90, 1700, 1715 and 1730 (see figure 4.3).

Figure 4.3. Bai-Perron Test to value the existence of agrarian adaptation. England, 1640-1740.



Source: compiled by the invaluable assistance of Professor Marc Badia Miró. Lw is the wheat production logarithm in bushels. The detected breakpoints are 1664, 1700 and 1730.

In this regard, the farmers were able to increase nitrogen additions and the take-up ratio during the cooling phase. Probably, they engaged in the following practices in order to maintain or increase the OM. First, including more pulse rotations in order to fix nitrogen

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

in the soil. Second, slowing down the conversion of fallow land to crops[92]. Third, slowing down the increase of the cultivated area[93]. Fourth, maintaining permanent separation between crop and pastures within a convertible system[94]. Fifth, replacing crops with pastures, in both uplands and lowlands[95]. Sixth, opening new pastures. Seventh, with improvements of the techniques applied to pastures, such as the progressive reduction of common lands, enclosures and stone removal and finally use of water meadows. According to Allen, one of the most impressive aspects of agrarian change was the increase of pasture and the reduction of communal tenure[96]. Besides the strong increase in surface (from 4 to 9 million acres between 1600 and 1700, and from 9 to 12 million between 1700 and 1750), two other relevant changes occurred; one related to communal pasture enclosures and the other related to the technological improvement. In the highlands of England and Wales enclosing pastures increased their productivity, since enclosures were made with the stones from the pastures and their removal from the surface improved yield. In short, Allen draws our attention to some key developments in English agriculture, such as changes in pastures management and the improvement of their yield. This could have begun an increase of the OM stock.

Another great qualitative advance was the better use of water meadows. During the period 1645-50 the “difficult” technique of floating started to become relevant, even giving rise to professional floaters. Although not new, this system was considered to be one of the great innovations in the management of English pastures by J. Thirsk and E.L. Jones[97]. There were “water” pastures placed next to rivers or streams of water, driven to produce rich hay crops and stimulate grazing, with canalizations that allowed a continuous water flow at certain times. Through floating, mud rich in nutrients settled and a beneficial oxidation of the soil occurred. This technique also allowed a reduction of the effect of frost in winter, promoting early grass growth and higher hay production in summer. Water meadows yielded up to four times the usual quantity and density of hay, which enabled

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[92] This process became stagnant during the 1650-1700 period: 3.24 million acres in 1500, 2.16 in 1600, 1.88 in 1650, 1.91 in 1700, 1.59 in 1750, 1.28 in 1800 (Broadberry *et al.* 2015, p.89).

[93] The data show a decrease in the total cultivated land from 7.74 to 7.64 million acres between 1650 and 1700, in contrast to its long-term rise since 1450 (Broadberry *et al.* 2015, p.89).

[94] See Overton (1989, p. 291) or A. Smith (1778, p. 286). Despite the generation of manure in barns (winter), the division system between pastures and crops was relatively inefficient (Shiel 1989, pp. 666-67). On the contrary, it was an OM reserve: with the increase in the new rotation systems, the “night manure”, the new ploughs and the changes in agrarian constructions, this reserve allowed higher productivity. Although Kerridge focused the agrarian revolution on the up and down or convertible agriculture (rotation of pastures into crops and vice versa), E.L. Jones (1965a, p. 156) and Shiel considered it of little importance during the 17th century (Overton 1989, pp. 293-294). Despite the important release of nitrogen through the ploughing of these pastures, the situation became the same or even worse after a few years (soil acidification). Overton even pointed out that there was scarce written proof of its feasibility in the probate inventories. Neither did Kerridge provide enough proof, so more research in needed on this issue.

[95] Broadberry *et al.*, quoting Grove 2004, and admitting the Little Ice Age or LIA (2015, p. 55). On the long trend to turn crops from the heavy claylands in the center of England into pastures, see Bowden (1985, pp. 47-48, pp. 55-56, pp. 61-62). According to Broadberry *et al.*, the importance of pastures in England was increasing, including permanent pastures. There was a process of elimination of forests in favour of crops and pastures with the change of the energy model from wood to coal. The increasing urban demand also stood in need of more permanent pastures to the detriment of permanent crops.

[96] Allen 2005, pp. 6.

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

all the year-round feeding and the early breeding of livestock. Water meadows also allowed preventing against climatic adversity by the management of canalization with chalk and covering to protect water against frost. This water was later drained and many essential nutrients for plants were collected. As a result, the quantity of sheep and cattle could be kept and even increased in winter and summer as well, producing much more manure, OM, and nitrogen. If it were not for this system, the impact of the climate change on livestock would have been more intense.

6. Conclusions.

The evidence presented here confirms the validity of Allen's nitrogen standard model. The nitrogen additions arising from cultivating springs grains, wheat and legumes had a significant impact on yields. Also, as Allen predicts, the effect from legumes is slow. However, this chapter stresses that climate factors should also be considered in the model. Climatic variations affect yields both directly and through its effect on nitrogen levels. The colder and more humid climate that characterised the period 1645-1715 negatively affected yields, thus forcing farmers to compensate via increased investments in Nitrogen-fixing plants, better cultivation and improved seed. By contrast, the milder climate that started circa 1715 improved yields regardless of farmers' efforts. Our results therefore highlight that observed yields under- and over-estimate agricultural practices during those two periods respectively, thus providing further support to the precocity of the English Agricultural Revolution and, given the harsher climatic conditions, the heroic accomplishments of the yeomen.

7. Appendix.

Table 4.5. Equivalence between our proxy variables and Allen's variables.

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

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

Chapter V. High Wages or Wages for Energy? An Alternative View of The British Case (1645-1700)[98]

1. Introduction.

In this chapter we explore English economic history from energy. This approach allows us to open a new perspective and helps us to uncover some debates. Energy equals everything a human or animal needs to meet their energy needs, be it food, heating or related goods such as clothing or housing. Here, key elements were the increase per head in consumption and production of energy. If this need is not met, it affects health or the possibility of being active (one of these activities is working). If it is attended, it implies an improvement in productivity, income and health.

At the beginning of this story, the unusual cold and wet period during the 17th and early 18th centuries was one of the worst climatic depressions in the history of England in the last four hundred years. This climate problem was recognized in many agronomic works of the time (John Mortimer 1712, Robert Plot 1676), or in diaries and registers[99]. The climate crisis negatively affected land yields in the short term, leading to an increase in soil organic matter, but also helped to accelerate change in the agricultural sector and yields. Climate impacts accounted for about half of the variations in wheat yields, the rest came from nitrogen-fixing plants, better crops and seeds, and better work (Allen 2008, Martínez-González & Beltrán, 2019). Farmers' efforts were good enough to withstand the cold phase and continue to make progress in soil fertilization. On a trial and error basis, they discovered that the new methods adopted were more productive and profitable than their old methods. Thus, the slow English agrarian revolution was probably more of a discovery than an invention, induced by a combination of climate challenges and market incentives (Tello et al. 2017).

However, the issue of climate remains a controversial one (Hoyle 2018). Furthermore, there is a small historiographic tradition that has studied its effects on the most obvious aspects such as agriculture and population, but not in human behaviour on energy and labour. Recent research seems to show that a decrease in temperatures and wetter environments generate a significant increase in the metabolic rate of people and their daily activity (a substitutive of thermoregulation; see the following section). But on the other hand, with new agricultural methods and improvements, with the need to ensure self-sufficiency, political instability, growing urban demand, or with also a declining or stagnant peasant population, farmers and draught animals had to work harder. All this would lead to a sharp increase in the demand for energy per head, productivity and wages.

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[98] José L. Martínez González, 2019. "High Wages or Wages for Energy? An Alternative View of The British Case (1645-1700)", *Working Papers 0158, European Historical Economics Society* (EHES).

[99] Ralph Josselin’s, 1640-1683; Locke 1666, 1667, 1681, 1682 in Oxford, 1669-1675 in London; Robert Hooke, 1672-1673 in London; Phillip Skippon, 1673-1674, Sufflok; Samuel Clarke, 1658-1686, in Norfolk; William Turner Comber, 1808 or Thomas Tooke, 1838, see Joyce Macadam, 2012.

Nevertheless, in a historical context of climatic depression, these effects have been little studied. The absence of research has led to an omission that overestimates the role of urban and trade demand (although we agree that it was the main factor). Let us analyse for a moment the argument of a growing urban demand, pointed out as the main engine of yields and agricultural production. If in the second half of the 17th century, the population declined, and the foreign sector was still small, the urban demand for food per head had to be very high to compensate for the demographic fall, and even more with the rural demographic fall. However, this is difficult to sustain. Following Wrigley (1981), between 1657 and 1686 the population decreased by 419,205 people. Assuming a per capita consumption of 7.12 bushels per year of bread wheat[100], this implied a decrease in demand by 3 million bushels of wheat (11 per cent of the average annual English production between 1645 and 1700, see estimates by Martínez-González, Jover et al. 2019)[101]. In fact, it was the opposite. According to our calculations, in 1657 there were 32.8 million gross production of wheat bushels, and in 1686, 35.3 million, this is, 2.5 million more. On the other hand, between 1670 and 1700 the English urban population grew by about 170,000 people, 5,667 people per year, a sustained growth thanks to immigration. For national demand to have been maintained (only maintained), the urban population should have increased its consumption of bread wheat by 17.6 bus. per head and year, that is, 2.5 times more than its previous average consumption (going from consuming 7.12 to 24.72 bus.). The differential between the daily wage of a London labourer and one outside London (Southern England) was only 1.5 times greater (J. Chartres 1986, p. 171). With income elasticity less than one unit, any increase in real income especially stimulates demand for secondary and tertiary sector goods more than agricultural ones (Wrigley 1985, p. 684). Thus, this radical increase in wheat consumption, mainly in London, was unfeasible. Furthermore, according to Wrigley, between 1670 and 1700, the English population fell by 5,096 people. If the population of London was about 530,000 souls (King gave that figure for 1695), the population in the countryside fell by 175,096 people. That is, in London it grew by 170,000 people and in the rest of the country, it fell by 175,096 people. Logically, all these calculations are certainly very imperfect, but we can see that it is impossible to explain an increase in total demand only from the cities. Consumption per head should have grown everywhere, and in the countryside as well.

As we just said, these calculations are simple, but they illustrate that we cannot entrust everything to the issue of urban demand. This idea is nothing new, although it has been relegated by the mainstream. For example, Everit (1966) criticized the idea that economic change in the southern counties was due exclusively to London: "Even the demands of a town of half a million people were not inexhaustible. Though incomparably larger than other towns, London was, after all, no more populous than modern Sheffield (…) For every person within it, there were ten or a dozen in the provinces to be clothed and fed".

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[100] Chartres (1985), citing C. Smith, said that wheat consumption for bread was 0.89 quarters per capita per year in London and South-east. One quarter is equal to eight bushels.

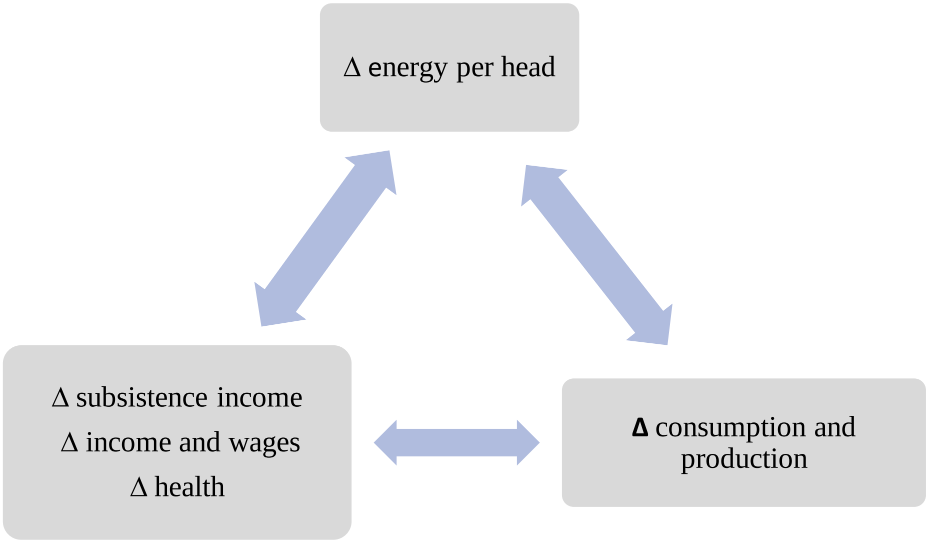
[101] Let us assume for now that there is an equivalence between bread and wheat. Later we will develop this difference a little more.

Thus, the increase in productivity and agricultural production cannot be explained by urban development alone between 1650 and 1700. There had to be something else. It also had to come from rural areas or villages. They were less, but they ate more, had more energy or distributed it better, as was the case in urban areas. Exports, although useful, were not a permanent general stimulus factor in the period. The discontinuity of harvests and the government's stimulus policies did not allow a very relevant weight of external demand. Between 1700 and 1709, exports were only 2 per cent of the total produced (John 1968). It was not until the middle of the 18th century that the golden age of cereal exports was reached (Ormrod 1985). If we only have the countryside left, how can we fit an increase in total rural demand for wheat into an environment of declining rural population, greater in proportion to the fall of the nation's population?

The purpose of this study is to learn more about the relationship between climate, energy and work. To be honest, it is a speculative exercise because we do not have much theory or research. In the future we propose new and deeper local explorations to economic historians. For now, to achieve this goal, we use a cross-sectional methodology that combines econometrics, primary sources, historiography, and economic thinking, that is, everything we have within our reach.

Low temperatures and higher humidity cause an increase in the metabolic rate and activity of humans and animals. Therefore, the demand of energy per head increases. In rural and urban areas, humans expand their activity as a direct response to lower temperatures (an intrinsic and physical, off-market effect, as we will see later). A greater demand for energy and materials to maintain or protect the body implies more work and changes. Part of the physical work is a part of the sphere of the economy, say labour, because they need money, goods, services, or other mechanisms to increase or maintain their energy. Therefore, subsistence wages rise. The population needs more “goods – energy” and energy flows per head, and the agricultural and non-agricultural sectors require more labour to satisfy the needs (the demand for labour increases), so we conclude an increase in spending and production per head in energy-goods. Moreover, farmers in rural areas can increase the supply of calories, but an increase in nitrogen fertilization in the soil also improves the nutritional quality of the grain (richer in zinc, iron and selenium) and in urban areas gardeners also enrich the diet with new fruits and vegetables. Since the end of the seventeenth century, this has also improved the health of the population, reduced mortality, and increased the consumption of surplus energy for living and working. Until the improvement of health and calorie intake had been stabilized, the population did not re-grow, when the expenditure of energy on women during their pregnancy and lactation had been guaranteed, on average. Of course, all this in turn influenced wages and incomes. If the farmer is a little more productive but the prices of the grain, he produces fall slightly, farm wages remain stable or rise a little (this also considering rural institutional constraints). If horses are more productive than oxen and people, horse prices increase more. If the rural sector needs more energy, and the value of the marginal product of the horse is greater than the value of a man's or ox's marginal product, the relative prices between horses (their price or cost) and men (their farm wage or annual income) or oxen (their cost) increase. Moreover, if the prices and productivity of non-food energy goods (cloth, fuel, heat, housing) increase, wages also increase in these sectors. In other words, in this paper, the worsening of the climate is associated with an expansion of per capita demand for “goods-energy”, “work-energy”, productivity, wages and income (along with other factors that we don't study here). In addition, in this paper we suggest that such an energy shock drives a divergence in wage growth between the agricultural and non-agricultural sectors. Also, it helps us to understand very well why open fields a special productive role had but also why they were in crisis.

However, here climate change is not the cause. It only accelerates changes and trends, as well as other reasons, if institutions and other factors allow it. We ignore whether it was an important or secondary factor, but in our opinion, it was at least significant. In any case, the remarkable increase in per capita income and GDP in this period is partly explained by this increase in per capita energy needs (Martínez-González, Suriñach et al. 2020). However, this does not mean that England became a paradise. During the latter part of the 17th century, deviating food consumption to a more caloric basket reduced the consumption of animal protein per head. In the short term, in the countryside, owners knew that it was advisable to increase subsistence wages if they did not want to jeopardize their rents and incomes. For this, they preferred to do so with annual contracts, a sort of "efficiency wage", which guaranteed their profits, and a way not to increase the cost per hour and increase productivity. But on the contrary, "marginalized" daily wages and generated underemployment and inequality, expelling those who were not "better" to seek employment in the city or non-agricultural activities.



The argument seems simple, but it has very strong implications. Some contributions are the following. First, it broadens our understanding of how exogenous factors of the economy such as climate (or politics) accelerate the effects on societies in transition. Not only does it influence crops or demographic variables but also a key factor such as energy. In this sense, we used an interdisciplinary approach to advance in the understanding of the problem. Second, it links energy transition to economic development, a path advocated by Wrigley, Kander, Warde, Malamina (2013) and others. An important novelty is the effort to connect a physical phenomenon around energy with the economic sphere. Third, the agricultural and urban revolution was also a manifestation of something deeper. People needed more energy, either to meet their metabolic needs or to work harder. Yeomen and landowners accelerated improvements to protect their families or their rents. In urban and non-agricultural activities, rising prices and productivity increased incomes, which explains in part the remarkable increase in per capita GDP between 1650 and 1700. It changes the idea of the origin of the economic change (whether it was agrarian or urban-commercial), when in fact it occurred everywhere. Fourth, it explains why and when non-agricultural wages began to diverge from agricultural wages and clarifies the debate between daily wages and annual income. Fifth, it explains very well why during this period a whole debate was opened among mercantilist philosophers on inequality, unemployment or underemployment. Sixth, clarifies that the Malthusian adjustment is only 50 per cent of the story. We agree with Kelly and O'Grada (2012, 2013) in their criticism of Broadberry et al. (2015) on their low-calorie consumption valuation. Seventh, it helps us understand the behaviour of each of the actors, based on their energy requirements. There was a phenomenon of "energy seekers" in many aspects, for example, there was a trend to more caloric goods (grains), more energy was sought in the city, the horse became more and more important with respect to the ox. We found signs of energy attraction in London. Ninth, there is an important gap in the debate on enclosures and open fields in the area of wages and incomes. Here we try to understand the logic of this relationship through our approach. The productive success of the open and common fields was at the same time one of the causes of their decline. Tenth, only a general factor such as the increase in energy production and consumption per head could lead to structural change in England. This idea of change from the middle of the 17th century and of a general change, everywhere, from agriculture to other activities, not always urban, is well supported by the findings of Wallis, Colson & Chilosi (2018): in the middle of the 17th century there was a general structural change in England that did not occur in Wales. People left agriculture in most parts of England, both in the North and South, but not everyone went to the cities. The proportion of labour employed in industry and services increased substantially in both rural and urban areas. Most of the transition from agriculture was completed by the end of the 17th century. Above all, however, this research must be understood as an attempt to capture and bring together the most important pieces of British success, because they must form part of a whole.

This chapter is organized as follows. First, we review the literature and carry out a theoretical analysis of the question. Second, we study the implications of what this literature and theoretical analysis predict. To do so, we use a methodology that combines the use of primary and secondary sources, as well as graphic and econometric support. In this part the results are presented and discussed. Finally, we conclude.

2. Background and theory.

2.1. Definitions.

Total Energy Expenditure (TEE), or total number of calories used per day, is composed of basal metabolic rate, physical activity, thermoregulation, growth, maintenance, immune function, reproduction and digestive costs. The importance of each of these components depends on body mass and height, age, sex, health status, reproductive status, level of physical activity and environmental factors such as temperature (Ocobock 2014, p.10, 30-31; Pontzer 2015, p. 169). Basal metabolic rate (BMR) is the minimum amount of energy required to sustain the life of a non-moving, non-growing, non-reproducing and non-digesting organism (Ocobock 2014, p. 9). In conditions outside the thermoneutral zone (22-26◦C for clothed human subjects) the metabolic rate is increased to heat or cool the body and defend a core temperature of 37◦C. This is thermoregulation. In addition, reproduction requires a lot of energy than usual. A negative energy balance, or failure to meet maintenance needs, can hinder growth and fertility (Froehle, Yokley, and Churchill 2013, in Smith & Ahern, p. 287). In fact, reproduction is very expensive for humans, with an estimated total metabolic cost of pregnancy of 78.000 kcal, and peak lactation costs of 630 kcal/day. The cost of lactation is offset by the mobilization of fat reserves, so that daily energy needs during peak at ∼450 kcal/day, like the daily energy cost of pregnancy during the third trimester. Ellison (1990, 2001, 2003) and others have shown that human ovarian function is remarkably sensitive to energy availability and stress, reducing the likelihood of conception during unfavourable conditions. Mothers in traditional farming populations, with physically demanding lifestyles, may reduce BMR during pregnancy and lactation to keep total daily energy requirements in check.

2.2. Metabolic cold effects and short-term effects with mild cold exposure.

Acclimatization responses to whole-body cold in humans are classified as hypothermic, insulating, or metabolic. If a cooling of the entire body occurs repeatedly, the main responses of adaptation to cold are to allow a falling core temperature before heat production mechanisms are initiated (hypothermic response), to increase the amount of insulation (insulating response due to a greater amount of subcutaneous fat and/or greater vasoconstriction), or the level of heat production (metabolic response due to shivering or non-shivering thermogenesis) (Mäkinen 2007, p. 158).

A large part of research focuses on exposure to mild cold because exposure to strong cold is very unanimous. Studies find that heat production was significantly higher at the lowest temperature: 7.0 +/- 1.1 per cent (mean+/- SE) between 28 and 22 degrees (Dauncey 1981) and 5.2+/-2 per cent between 22ºC to 16ºC (Westerterp-Plantenga et al. 2002). Claessens-van Ooijen et al. (2006) found a large variation that was around +30 per cent in winter. In Mäkinen (2006, p. 20), a decrease in temperature from 27°C to 22°C increased energy expenditure by an average of 156 kJ-°C-1, i.e. 798 kJ or 186 kcal. This might seem little, but a human spends 2,500 kcal a day, allocating 1,800 kcal to BMR, maintenance and digestive expenses, and 700 kcal to work. So, his working capacity is reduced by 27 per cent.

Van Ooijen et al. (2004, pp. 545-549) investigated the metabolic and temperature response to mild cold in summer and winter in a moderate oceanic climate. The average metabolic response during cold exposure, measured as the increase in kJ/min over time, was significantly higher in winter (11.5%+/-9.1%) compared to summer. The metabolic response ranged to an increase of 30 per cent in winter. Total heat production during cold exposure was inversely related to the temperature response in both seasons.

2.3. Long-term effects of cold exposure on total energy expenditure and activity.

In cold conditions, peripheral vasoconstriction, non-shivering thermogenesis, behavioural responses and increased basal metabolic rate have been identified as physiological responses that help to maintain core body temperature despite low environmental temperatures. Ocobock (2014) measured total energy expenditure (TEE) and compared it in temperate, hot and cold climates. In his research, he found that in cold climate, BMR was 26 per cent higher than temperate climate. Cold activity levels were 67 and 80 per cent higher than temperate and hot climates respectively. Cold thermoregulatory costs were 53 and 71 per cent higher, respectively. Comparisons within each subject for the different climates revealed the same pattern: cold climate thermoregulatory costs were significantly higher than that of temperate climates. The most remarkable difference in allocation breakdown between the climates is the proportion of TEE that is made up by activity cost. Activity comprises 36+3.6 per cent of TEE for cold climates compared to 21+4.7 per cent and 14+4.3 per cent in temperate and hot climates respectively. BMRs from the cold climates were significantly higher than those of the temperate climates. Activity took up a far greater proportion of TEE in cold climates than in either temperate or hot climates. Besides, environmental constraints lead to necessary energy trade-offs. Limited resources could simultaneously demand increased activity levels to gather resources while also reducing reproductive output. Cold climates produced both resource limitation and increased energy demand for both metabolically and behaviourally mitigating the harsh environment. Ocobock found that high levels of activity can mitigate the expected increased metabolic cost due to thermoregulation in cold climates. Estimated thermoregulatory costs without activity costs included were significantly higher than thermoregulatory costs with activity in the cold climates (29 per cent). This suggests that activity helps to lower thermoregulatory costs in the face of cold conditions. When zero activity is assumed, thermoregulatory costs were exceptionally large in cold climates, greater than 2000 kcal day-1. Like the laboratory studies, this suggests that heat produced through activity can be an effective means of maintaining core body temperature and reducing the potential metabolic cost of thermoregulation, particularly in cold conditions. Ocobock's research demonstrated that it is metabolically expensive to live in cold climates. Both basal metabolic rate and thermoregulatory costs were significantly higher in cold climates than in either temperate or hot climates. An unexpected result from this research was the amount of energy spent on activity in cold climates compared to the other conditions. Activity costs comprised 36 per cent of the total energy budget in cold climates compared to 21 and 14 per cent in temperate and hot climates respectively (Ocobock 2014, p. 153). Moreover, Daanen & Lichtenbelt (2016, p. 106), argues that in the cold, physical activity may increase to generate more heat, and according to Mäkinen (2007, pp. 156-157), extra effort may be needed to complete the same task compared to a warm environment.

2.4. Effects of caloric intake on health and labour.

On the other hand, mounting an immune response to infection requires energy **(**immune function). Muehlenbein et al. (2010), reported an 8 per cent increase in RMR (resting metabolic rate) among nonfebrile men with relatively minor respiratory tract infections. Torine et al. (2007) compared premature infants with sepsis to age-matched healthy controls and found 43 per cent greater TEE among those fighting infection (Pontzer 2015, pp. 176-177). Likewise, cold exposure is a significant health risk, because it is associated with several complaints and symptoms related often to chronic and cardiovascular diseases. Seasonal increases in morbidity from cardiovascular and respiratory diseases have been demonstrated in many studies (Mäkinen 2007, pp. 156-157). If this is what happens today, to the past we must add the multiplier effect of the lack of hygiene and malnutrition. Freudenberger & Cummins (1976, pp. 2-5) explain the abundance of nonworking time in the pre-industrial era because when well-fed workers were deprived of food their output fell relatively much more than their intake of calories. A reduction of 20 per cent in total intake implied a reduction of more than 40 per cent in calories available for other activities, including work. They also added that “conditions of health and nutrition before the Industrial Revolution were such as to restrict seriously people’s choices of activities; that subsequent improvements were such as to widen significantly the range of choice; and that the special conditions of the time made it likely that better health would have increased the supply of effort. Moreover, we have reason to believe that the supply of effort could not have increased as it did without improvements in health”. On the other hand, it has been found, just since the middle of the XVII century, a decrease in the height of people. This decrease has been associated with the increase in working days, the incidence of child labour, and inequality (Gallofré-Vilà et al. 2018). As we will see below, these phenomena are associated with an increase in energy needs per head.

2.5. Calorie intake, health, productivity, and wages. Theorical and empirical perspectives.

So far, a somewhat harsher climate ultimately implies an increase in energy expenditure and activity per head and worsens the health of the population in the short term. This is not a thing of the past. This is also the case today. In the United States, poor and wealthier families increase their fuel costs in response to cold weather. Poor families reduce food expenditures by about the same amount as their increase in fuel expenditures, while wealthier families increase food expenditures. Poor parents and their children spend less on food and eat less during cold weather budget crises (Bhattacharya et al. 2003). Longer-term health is another issue. It will depend on whether this increased demand for energy leads to more real income or not, and here we find the big difference with the rest of Europe.

At this point, we wonder how this situation can affect productivity and wages (income). Recent economic literature argues that there is an inverted U relationship between temperatures and work. A colder and more humid climate causes direct physical effects or psychological discomfort in the short term. It reduces productivity, altering the marginal product of an additional hour of work, or provoking a variation of the effort per hour. However, in a utility model of work, it has been found a greater volume of hours worked and in effort with lower temperatures. In a colder environment, a worker can get warmer, resort to heating (if it is within reach) or consume more calories. They can also decide to work more intensively, rest shorter, adjust the hours worked and the effort according to the compensations they receive, whether in money, in kind, in maintenance or with a more comfortable home (Zivin & Neidell 2014; Seppanen et al. 2006; Heal & Park 2016).

In the previous section, we have seen how a cooling of the climate implies a growth in energy expenditure and generates an increase in activity, the latter phenomenon understood as something strictly physical. But how can we understand this phenomenon in the field of economics, how can we establish a connection between different scientific disciplines? At this point, a more formal analysis may be appropriate. In the short term, the producer only decides, in theory, on the use of the human and/or animal labour factor (figure 5.1, annex 1). An adverse climate, ceteris paribus, reduces the number of workers from L'' to L', so the product is reduced to Q' (extensive effect). However, there is a second effect that could go unnoticed: it also shifts the marginal product curve downwards, from Pmg to Pmg', because the available energy input per unit of work has decreased, leaving the final output at Z. This means that a climate impact has two effects (first from Q'' to Q', after Q' to Z), the second of them being undetectable if we use L in man-units and not in kilocalories. Only with the aggregation of the two effects would the impact of the climate be fully captured. The logic of the above reasoning suggests that measuring (or analysing) labour force in man-units is insufficient: it must be done in energy-units. Can we isolate the effect of the impact on L (reducing Q from Q'' to Q', and from L'' to L') from the effect derived from the reduction of marginal labour productivity (reducing Q from Q' to Z, and the marginal output from Pmg to Pmg')? That is, can we differentiate the demographic effect (man-units) from the purely energetic (available energy-labour) effect? In this way, the incentive of the producer to improve his situation is even greater, expanding the cultivated surface or making it more productive with new methods, as well as the work force will try to recover its energy by increasing the intake of calories, improving its conservation with more heating and shelter or extending its offer by increasing working hours, compensating for the decrease in productivity. In this context, an excellent solution for the producer is to "imitate" the open fields, "creating community" through annual contracts, guaranteeing stability, higher productivity, and a subsistence income for the peasants. But then the problem here is that it generates more unemployment or underemployment.

Let us analyse what happens in the “labour market” in more detail, understood as a partially non-monetary market. First, it is difficult to find a theoretical analysis of the problem. There are no more research studies here. We refer to an economic context in which agriculture is still the main sector and a significant part of the population lives at levels close to subsistence levels.

The basic idea is as follows. Imagine that peasants have a band of comfort in the level of temperatures, say, between 27 and 23 C. As we have been able to read in previous scientific literature, when this comfort band breaks, the human body reacts. If the temperatures are very low, it increases its calorie consumption to maintain the basal metabolism and increases its activity, because this activity compensates for the cost of thermoregulation. On the other hand, if temperatures are very high, the body tries to maintain the temperature through sweating, inactivity, drinking more and consuming less caloric food. Until now, we have understood this reasoning, thanks also to the fact that there are many research studies. But what happens in the labour market when climate change reduces temperatures in an underdeveloped region, whose main source of economic activity is agriculture?

This is where the problem becomes complicated because it is very difficult to find something seriously reasoned. Searching though, we have found an interesting book by Harvey Leibenstein, an American economist and professor at the University of California, published in 1957. Leibenstein is one of the pioneers of the theory of efficient wages. The central theme of his book was the search for some of the reasons that led some countries to be trapped in underdevelopment. However, what interests me now especially about Leibenstein is that he establishes a clear relationship between income (or wages) and nutrition, on the one hand, and calorie consumption and productivity, on the other. The more income, the better nutrition; the better nutrition, the higher the worker's productivity. Bliss & Stern (1978) also find a clear relationship between calorie intake and work, through various empirical studies. In other words, the intensity of work per hour (effort or work units, as he describes it), depends on his level of energy, health, vitality, etc., which in turn depends on the level of consumption of the worker. Leibenstein then explains in various figures the relationship between wages and productivity, considering productivity per man-hour or per man, on the one hand, and productivity per unit of effort and unit of time (or physical work), on the other. With this he wants to distinguish between the fact that, normally, in the short term, the labourer dedicates a series of daily working hours, but within these hours he can devote himself more intensely to work if the hourly or daily wage is higher and vice versa. In any case, he comes to the conclusion that at very low wages there may be a labour deficit because the units of work (work intensity in our argot) produced by a labourer are very low (i.e. very low work intensity, or little effort), but at higher wages the units of work (intensity or effort) per man increase so rapidly that a surplus of work is created. For underdeveloped areas, this may mean that supposedly observed labour surpluses in agriculture do not exist when wages are very low (it is not worth working), but become a fact when wages increase sufficiently, so that not very high wages coexist with unemployment or underemployment, something that was difficult to understand according to traditional economic theory.

This idea was the origin of the current theory of the efficiency wage. Some of Leibenstein's proposals were later worked on by Stiglitz (1976), when he studied the "paradox" in developing economies about the coexistence of unemployment with a positive (albeit low) wage for workers. While accepting the idea of rural institutional constraints in the form of "communal pressure", he concludes that there are important conflicts between equity and efficiency. For farms that are poor enough, full equality may not be feasible; maximizing family welfare may entail some degree of inequality. Low-wage individuals are less efficient than high-wage individuals. The presence of a positive wage (and a corresponding positive marginal product) for workers in a competitive labour market cannot be taken as evidence that labour is not surplus (as some authors seem to have done).

Although that is another story. Let us continue with a graphical analysis in figure 5.2, annex 1. In the vertical axis, we have the wages and the marginal productivity of labour. On the horizontal axis, the number of workers. MP1 is the curve of marginal productivity of the labour, it has this form because at the beginning, when workers are incorporated, the marginal productivity increases, but there is a moment when more incorporations no longer contribute more productivity, but it declines (although the total output continues growing). w1 is, on the other hand, the subsistence wage (or the level of real subsistence income, in the case of a poorly monetized economy). Point C where MP1 coincides with w1 represents the demand for labour (we assume that the owner will pay a maximum wage equivalent to the value of productivity, but no more).

Let us suppose now that the supply of labour SS (vertical in the short term) is also in C. We therefore have a first equilibrium point in the labour market where OS labourers receive the subsistence wage w1. Imagine that temperatures are falling. The labour supply is reduced to OS’ because it worsens the health of some workers. On the other hand, now each worker must devote more calories to maintain his basal metabolism and has fewer calories to work with. Therefore, their productivity per unit of effort is reduced and produces less than before per unit of time and therefore the marginal productivity curve shifts down to MP2. Let us suppose now, for the sake of simplicity, that the decrease in productivity is offset by the reduction of peasants to work at OS’, so that subsistence wages are maintained at w1.

But here is a problem. w1 stays below the subsistence level, and here we have the main difference with the Malthusian adjustment, which argues that we will always return to the natural wage rate. w1 is no longer the subsistence wage. Now every labourer needs a higher wage to get the extra energy he needs, say w2. However, the consequence of all this is that with w2, employers do not need so many workers, reducing their number to OS”, so that unemployment is generated even at subsistence levels (the difference between OS’ and OS”). The difference in C”, is that they are fewer workers than before, there is unemployment, they earn the same in real terms to subsist. But here the employer has two problems (which we will see later). First, open and communal fields are increasing their marginal productivity and therefore workers' incomes. Second, off-farm wages are increasing. So, the supply of labour shifts a little more to the left, so in the end we stay at C”, with OS”’ workers and a higher wage rate w3, which goes very well with the employer to prevent worker losses. The conclusions are, if we compare the starting point with the end, first, that a cooling of the climate tends to generate more inequality, combining a lot of involuntary unemployment and a little voluntary unemployment. Second, wages would be a little above subsistence wages, but with a more productive workforce than before. And third, the Malthusian circle is broken (which defends a tendency to return to the subsistence wage), simply because the subsistence wage is now higher. If later energy needs per head are reduced because the climate improves or because the economy is moving closer to works that require fewer calories, it is very difficult for them to fall back. As David Ricardo rightly said, the subsistence wage had a lot of habits and customs. Some readers might add here that a worsening climate surely reduces agricultural production. Well, this would imply that labour supply would shift more to the left because of the demographic crisis, and that marginal productivity would shift even more downwards (there is less agricultural production per worker than before). This would lead to results like the previous ones even worse, depending on the movements of both curves.

All this analysis would be applied to a farm that maximizes profits. But is this really the case in an underdeveloped country? Surely, the answer is no. For example, we may find common fields (what matters is equality in the community, that everyone has work). In this case, all labourers have the right to obtain the new w2 subsistence wage (or real income), without any of them losing their jobs. For this reason, the community is forced to increase its marginal productivity up to E, keeping the labour supply in OS’. At this point, it is very interesting to see how both the capitalist and the common farms remain. In the first, MP is lower, productivity is achieved by reducing the workforce and paying a slightly higher wage than the new subsistence wage. On the common farm, they are forced to innovate or increase marginal productivity, so that the same number of workers are more productive (the only way to be able to keep everyone on a higher w2 wage).

The problem here is that in the common farm the innovation effort is more intense and possibly the peasants will have a wage a little lower and closer to subsistence, which could cause them to migrate to the capitalist farm or to the city. Broadening the horizon, if the common farms are not able to innovate, they will disappear. If they can innovate, they will resist, although everything will depend on their innovative capacity and the existing alternatives, the greater the degree of innovation and the lesser the alternatives, the greater the resilience. But it is to be expected, on the one hand, that their innovations will also be transmitted to capitalist farms, or that new alternatives will appear (migration to places with better living conditions), or even that, in many common areas, the properties will be bought, and therefore they will also end up languishing.

We must also include in this point the variations in the food demand and prices. Productivity growth adjusts very well to the increased demand and tends to maintain prices over the long term. On the other hand, there is competition with wages outside the countryside, which are higher, and this pushes them up. Finally, rural institutions control wages. The difference between the desired wage and the actually paid wage is even greater. All this causes the annual income of workers to rise more than the daily agricultural wages, but in any case, less than in sectors outside the countryside.

Let us extend the argument to non-agricultural labour markets, for example building. There are no “bad building harvests” here that in the short term will put downward pressure on marginal productivity or slow down the upward trend in wages. So, the effects of the climate are concentrated on the labour factor (most of them work outdoors). Here there are no reports of innovations and productivity gains in building during the 17th century. Thus, adjustments almost always occur through changes in the number of workers, wages, and housing prices. We always move on the MP2 curve. In addition, there are no "housing cooperatives" or similar common institutions in this sector (we are not sure if the guilds had this function, because they did not play a leading role in urban expansion), and we assume that the demand for housing is growing steadily. In comparison, all these differential elements make building wages rise more than agricultural wages (towards w4 and beyond).

As we mentioned earlier, too low a wage was a good reason for some to think that it was not worth working "honestly" and thus reinforcing some of the existing "reprehensible" social habits, such as the presence of frequent holidays. According to Petty, a "moderate worker" was equivalent to 10 to 12 hours of work per day, except on Sundays, and needed about 20 meals per week (1687 p. 57, 1691, p. 110). Depending on the characteristics of the European and English family structure (De Vries 2008, pp.29-31), we can segment people's reactions in two ways. Firstly, in cases of greater "family weakness", the net energy balance could be negative (the difference between wasted energy at work and insufficient energy intake through food, clothing and heating). As G. Becker rightly says, poor health "reduces hourly earnings because a lower level of energy reduces the energy spent on every hour of work or household chores. It was not always a problem of a lack of demand for labour, but of control over the weakest by not allowing wages to rise or to move and start a new life: you could only free up work in big cities like London or in new sectors, embark on an uncertain future overseas or join the army. This is seen in the evolution of the building/agricultural wage ratio, favourable to the former (figure 5.14, annex 1). Secondly, the most resistant family nuclei would react differently. According to Becker, income in some jobs is very sensitive to changes in energy consumption, while others are more sensitive to changes in the amount of time. People who devote a lot of time to strenuous household activities (childcare) would try to save their energy consumption by looking for strenuous and intensive work and the opposite would happen to people who devote most of their time at home to leisure (Becker 1985). These more consistent household units would be the origin of the launch of the family. Thirdly, another alternative they had was to secure their annual income. If they were not part of common fields, many found a solution with annual contracts. In this way, they guaranteed the growing consumption of energy they needed, and on the other hand it was a good business for the owners, as they continued to pay the equivalent of a better subsistence wage that allowed them to increase labour productivity, a strategy of "efficient wages" that left many peasants with daily wages and relocations to the city. According to several authors (Woordward, Kussmaul, Foster, Whittle, see Humphries & Weisdorf 2017), the traditional service contract made it easier for employers to harmonize incentives, ensured the availability of labour at the demand peaks of agricultural cycles, reduced supervision and meeting costs, travelling expenses to and from work, and protected workers against rising rents and food prices.

In conclusion, the main theoretical points are here: 1) if the energy need per head increases, the demand for food, heating and other goods related to the maintenance and conservation of energy (clothing or housing) rises; 2) this produces an upward adjustment of subsistence wage (or income), in all sectors, from w1 to w2; 3) henceforth, the productivity and wages (or income) of the two sectors (agricultural and non-agricultural) begin to grow differently, and there is a divergence in favour of the related non-agricultural sector (w4 relative to the w3-w2 range in agriculture); 4) common farms (at one end) make the increased productivity adjustment in order to maintain everyone; capitalist farms (at the other end) increase efficiency wages (incomes) and reduce the number of labourers; 5) wages (or incomes) in the non-agricultural sector are easier to diverge from those in agriculture because a) there are no "bad harvests" that limit wage improvements, b) long-term demand for these energy-goods increases, and c) adjustments are concentrated on prices rather than technical innovations; 6) there is a growing phenomenon of unemployment, underemployment and inequality; 7) daily or hourly wages are a good indicator of what happens to prices and productivity in each sector, as well as labour movements between them, and annual incomes respond instead to the final outcome for the workers of this whole struggle (Humphries & Weisdorff , 2017).

3. Implications.

3.1. Implication one: demand increase of energy-goods.

3.1.1 Food-energy for humans and animals.

Here, the key is the increase in the demand for energy per head. One of the main conclusions of all previous research is that a mild drop in temperatures drives energy demand and activity level. These results are obtained in investigations of the present, not the past, in developed countries, with people who are well fed, heavier, taller and healthier. However, with a colder climate, Broadberry et al’s estimations (2015) capture only an increase of 13 per cent of daily intake of calories per head during the second half of the seventeenth century. This estimate confirms the previous studies summarized here, but given their conclusions, this figure could be low. The same conclusion is reached by Kelly & Ó'Gráda (2012, 2013). They found that calorie intake should be higher, because the GDP and the agricultural output per head increased notably and there was an improvement in health and a disappearance of mortality crises, *inter alia*. Now, the problem with these arguments, no doubt right, is that they are “circular” in the sense that we can say: "Okay, but then tell me why the agricultural output increases, or why health, heating, insulation improve, and so on".

Although it seems low to us, let us now accept the estimate provided by Broadberry et al. (2015). According to them, between 1650 and 1700 the daily consumption of kcal in grain increased from 1,576 to 1,777 kcal, or about 201 kcal more. Suppose that 200 kcal comes from 100 grams of bread (old bread, wholemeal and with many impurities) and that these 100 grams are equivalent to 75 grams of flour (you needed at least three parts of flour for 4 parts of bread, Petersen 1995). These 75 grams are in turn obtained from 100 grams of grain per day (the degree of flour extraction with respect to the grain was 75 per 100). We obtain a consumption of 36.5 kg per year, i.e. 1.34 bu/year (1 bu=60 pounds, 1 pound=0.454 kgs, so 1 bu=27.24 kgs). Therefore, we could say approximately that there was an additional consumption of grain at 1.34 bu/year. Taking an average population in the 1700s of 5,145,531 inhabitants (or Gregory King's 1695 figure of 5,500,000), this increase in per head consumption implied 6.9 million additional bushels of grain (7.37 million, taking King's population). If of this total grain consumption, only 40 per cent was wheat, the increase in wheat consumption caused by higher per capita energy demand was about 2.76 million bushels (3 million with King's data).

It is quite surprising to see how this calculation fits with what we calculated in the introduction of this paper. The demand for wheat would have fallen by 2.9 million bushels because of the decline of the entire population in England, if it had not changed its diet. We have also just seen how a higher per capita energy demand for wheat, according to the conservative estimate by Broadberry et al., causes an increase in wheat consumption of between 2.76 and 3 million bushels. This surprising coincidence of values could indicate a simple Malthusian adjustment, a higher real income in terms of wheat, that is, the increase in calorie consumption occurred simply because there were fewer people and they had higher real wages. This is what has been believed so far. The problem here is that wheat production did not remain stagnant but output increased. That implies something intrinsically new: an increase in energy demand per capita, very different from eating more for being less. According to our estimates, between 1657 and 1686, wheat output grew by about 2.5 million bushels. The average for the 1650's was 32.89 million and the average for the 1700's was 35.76 million (+2.87 million bushels). Therefore, we should expand the range of possible options in increasing calorie intake from 13 per cent on Broadberry to about 25-30 per cent, if per head consumption also increased in the rest of the cereals. As we can see, this 30 per cent fits very well with the results of much of the current research on the effects of a coldest climate, summarized in the first part of this paper. Half is due to Malthusian adjustment and the other half to an exclusively energetic phenomenon, and here is the novelty. It is not necessary to assess now that demographic oscillations could also be associated with changes in the weather.

The worsening of the climate remains today a phenomenon not well understood, but the general nature of its effects fits well with two of the conclusions obtained. First, that general per head consumption, not just urban consumption, offset the decline in demand caused by a smaller population. The increase in consumption occurred everywhere, in the countryside and in the city. It is unlikely that urban demand was the only stimulus for agricultural innovation. We suggest that a fundamental part of the origin of British success is located in the countryside and that it had much to do with the different behaviours of its actors, open fields, yeomen and landowners. Secondly, without the increase in per head energy demand, England would not have been able to open the "little convergence" gap any further. That was the key factor, and it could not have been otherwise than a general phenomenon. Another thing is that the increase in demand was more noticeable in the city because the population was tilting towards the urban perimeters, so there was also a displacement of the most productive areas oriented towards London, but it must be clear that in the countryside per head consumption also grew, and that in absolute numbers it was the highest. On the other hand, Wrigley (1985) proves that urbanization is for the first time a general phenomenon since 1670, not only in London, so the causes must have had a common denominator.

English farmers needed their families and communities to eat more, landowners needed to protect their rents, and from urban areas more food was demanded because there were more of them and because each person needed more energy. In figure 5.3, annex 1, we can see how between the 1650s and the 1700s consumption per head of wheat increased. This conclusion is not incompatible with the idea that urban demand was a stimulus to increase productivity, especially in nearby and better communicated regions, but it does not explain 100 per cent why wheat production increased throughout the country. Not only did they ask for more wheat because they were more and more in the city (while in the countryside they were less) but also because they needed more energy-wheat per head. In addition, the productive improvement of peri-urban areas was not unrelated to supply factors related to the environment. During the 17th century, London was already a highly polluted city (R. Fouquet 2008, p.57). Increased emissions of carbon dioxide and other wastes should have increased the yields of the land in the surrounding regions. And the high productivity of black soils, which fed on soot to fertilize the soil, is well known (Mingay 1984, p. 97; B. M. Short 1984, p. 290; R. C. Richardson 1984, pp. 242-248).

Table 5.1 (annex 1), shows how consumption/output per head of wheat is associated with temperatures and rainfall. In the short term, a drop in temperatures worsens the outcome (3-4 lags). Conversely, in the long run, colder temperatures are associated with better harvests because farmers can manage the situation (6-10 lags). With summer rains the same thing happens. In the short term, excessive rainfall worsens the consumption of calories-wheat per head. In the long run, farmers react, and people “eat” more calories.

And so, it is with spring rains. We observe the same rule with rye and oats. The conclusion is that, while in the short term, a cooling climate reduces the consumption/output of wheat calories, in the long-term consumption/production increased. At this point we must say that we are not interested in developing a complete model, our goal is to find a meaningful relationship in the variables of interest. The slowness in reacting is explained by the low predictive capacity of farmers. And even if their capacity had been higher, they would have tended to underestimate the risks and would have believed that they were incapable of solving the problem in the short term. These two aspects have been well studied in modern and developing economies (Grothmann & Patt, 2005). For this reason, the reaction is slower when two factors (land and work) come into play instead of only one (work).

Another evidence that relates the increase in wheat consumption with a higher energy demand per head is the higher energy capacity of wheat compared to other cereals. Campbell et al (1993) reported that the kcal per bushel content of barley and oats, relative to wheat, was 82 per cent and 74 per cent of the caloric content, respectively (among ground grains). For this reason, just in the cold period, it is well visible how the preference for wheat in relation to rye increases its price (figure 5.4, annex 1). The old sources obviously do not speak of calories, but we did find references to preferences for bread and wheat: "*he that tilleth his land, shall be satisfied with bread, and shall have plenty*" (W. Blith, 1649). For Blith, the greatest incentive for agricultural improvements was that farmers and the poor could eat more bread. Surveys conducted by the Royal Society in 1667 collected testimonies of the farmers' preference for wheat and how they tested new varieties "*...They sow noe winter corne (nott butt that theire ground would produce Good-Dod-red wheat as hath beene tried of late yeares att Kilham, with great success*" (Lennard 1968, p.168)[102].

Seed improvement is a little-known subject. It was a resource for farmers with little capital. It is known that English farmers rotated their seeds between different fields and lands. An example is *Pendule Wheat*, a variety grown in Oxfordshire, which was very useful the first year (twenty to one). After two years, the seed was no longer productive, and farmers were forced to source their produce from outside Berkshire at the Abington market. Another variety, *Double Ear Wheat*, although widespread, was also not to the satisfaction of the farmer because its yield on the same soil fell rapidly (Plot 1676, p. 155).

There may be many reasons for the improvements in seed profits, but without a doubt, the ability of farmers to improve them was crucial. Allen has failed to solve the "mystery" of the 1650-1750 production increase, especially in open fields, even with a nitrogen-centred approach (2008). His "something else" is still alive (1999, p. 227). One of its

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[102] Direct testimonies like this are scarce, but very valuable and reliable. For example, the Martínez-González, Jover et al. series (2019) for that year provides an estimate of 18.45 bushels per acre, and in this survey the average production was 18.1 acres.

"escape routes" has always been to point out, in a very generic way, the improvement of seeds. This was one of the main causes of the increase in land yields during the Modern Age, thanks to interregional trade and grain selection. These actions "perhaps improved" the genetic characteristics of the English seed, regardless of the level of nitrogen in the soil (1999, 2008). Overton, before Allen, already said: "random mutations must have productive varieties of cereal crops and it is likely that farmers would have selected these in preference to others" (1989, p. 90).

The writings of the period reveal an important movement of seeds. The *Red Stalk Wheat* was a wheat variety introduced in 1626 until it "proved marketable" (Plot 1676, pp. 153-156). If in 1676 it was still not known in many places, in 1712 it was already a common cereal (Mortimer 1712, pp. 94-96). The *White Eared Red Wheat*, also called *Mixt Lammas*, was also introduced into Oxfordshire successfully because it was more productive than most (twenty to one), and much coveted under the Chilterns. However, it remained a very localized seed: even in some parts of the same territory, such as Banbury or Burford, little was known about it. The *Lammas* (Red and White) varieties had a great capacity to combat smut, thanks to their early ripening, which hardened the grain and prevented the entry of the fungus. Added to this was its great longevity. This made them become the most appreciated, especially in open fields (Plot 1676, p. 153). One fact was confirmed by John R. Walton: before the 19th century, the most successful native autumn varieties were the *Red Lammas* (1999, p. 47). At the other extreme was the Cone Wheat. High yielding in clayey soils, birds could not easily attack it, so it did not require much manpower. This made it more of a good seed for large landowners than for yeomen and bakers, who found it too thick and sensitive to mould (Plot, 1676).

Two hundred years later, on Oxfordshire farms there were only seven or eight local varieties, including the *Red Lammas*. This was no longer the most productive (37.8 bu/acre according to experiments carried out in Rothamsted between 1871 and 1881) but maintained one of the highest percentages of gluten among British seeds (25.2 per 100 out of an average of 18.6, while foreign wheat gave an average gluten of 22.3). Another English variety, the *Rivet*, yielded much more (45.8 bu/acre), but barely had traces of gluten. *Lammas* were still, at the end of the 19th century, the champions of resilience, and *Rivets* were just the opposite. Faced with an adverse climate, *Lammas* yields were among the best. And while the flours of the Rivets were not used to make bread, the *Lammas* provided good quality. But times had changed. Climate problems had been reduced and agricultural techniques had improved, and there was not much interest in producing bread wheat, in an agricultural sector more concerned with maximizing yields than the destination of production, well guaranteed by the demand for livestock and the British cookie industry. Thus, many of the autochthonous seeds were residual in 1852, surviving in marginal crops where adaptation to the environment was the problem to be solved. As there was no cereal capable of having high yields in stems and seeds at the same time, there was a tendency for the harvest rate to fall in favour of the Straw (the stem), with animal consumption taking precedence over human consumption (Walton 1999, pp. 39-50).

Another question is how the farmers managed to improve them and why between 1650 and 1750. The primary sources consulted point to possible avenues. First, increasing the rotation of seeds between plots and territories, reserving the best to sow and the rest to eat or sell. Before 1750 improved seed selection was such a regional phenomenon that many varieties became alien to English travellers from other regions (Walton 1999, p. 32). Mortimer clearly describes how they moved from South Staffordshire to the North, and from "North to South", except in Moorlands, where farmers "always took the best seeds to avoid being left in nothing". For Mortimer, this racking was the "greatest advantage". But this argument was certainly descriptive. Why did local and regional rotation increase right then? The answers can be many. The 17th century was a period of great internal migrations, motivated by the political crisis of the monarchy. Before 1640, most of the male population could not legally leave without a certificate, but between the fall of the political reconciliation and the establishment of new and greater restrictions deriving from the Residence Act of 1682, there was a period of greater labour mobility, thanks to the increased movements of armies and soldiers, which surely increased the trafficking of ideas and things (C. Hill 1961). Second, regarding why between 1645 and 1700, one of the answers is that the climate became colder, wetter and more variable. The environmental pressure on farmers multiplied. In Mortimer's book, the disadvantages of weather, storms, rain or frost, the dangers of humidity and how to avoid *smut*, were a constant threat. It was no coincidence that at that time the *Lammas* varieties flourished, some of the most resilient, productive and best accepted by bakers. It was the Yeomen and small farmers who were looking for more daring solutions, since seeds are a much cheaper resource than drainage or water meadows. Thirdly, in addition to land rotation or regional rotation, part of the solution also focused on post-harvest treatments and the storage and conservation of wheat. By treating with brine, powdered chalk, and drying the seed well, farmers reduced the risk of *smut.* They also did this by dissolving sheep dung in water by adding salt, soaking the grain in the formulation eighteen hours for wheat and thirty-six hours for barley, then drying with powdered chalk, and adding wormwood to avoid birds. According to Mortimer, the best barns were made of stone and brick. In this way, rodents and humidity were better avoided, in a century characterised by the substitution of wood by stone, a process intensified by the fire in London in 1666 and the diversion of wood towards the Navy. Likewise, it seems that the greater diversity of agricultural practices and the pressure of the climate modified some guidelines in agricultural constructions. Adaptations were made by heavy rains in the western highlands or by the cold winds of the eastern counties, all to minimize the exposure of humans and animals to the worst of the weather. Combinations were sought between grain and feed storage with housing and feeding of horses and livestock. In the *Penine Counties*, cold and wet winters determined the management of stabled cattle, giving rise to a practice that became very popular since 1650: a barn, separated from the house, with accommodation for livestock. Barns with stables were also extended to grazing areas, or they were used to store grain as well as for fodder and hay (M.W. Barley 1985, pp. 667-671).

We can also see in figure 5.16, annex1, that seed yields have fallen since 1760. This fact confirms Walton, when he detects a *turning point* in the seed during the second half of the 17th century, as Allen did in 1750 (1999, p. 225). The triumph of parliamentary closures and the increasing inflow of foreign wheat may have implied a relative slowdown of improvements with local seeds. While in Thirsk, Thick or Ambrosoli there is hardly any mention of foreign seeds between 1650 and 1750, in the second half of the 18th century scientific curiosity towards European seeds began to be recorded in writing. It is therefore not unreasonable to suggest that business and livestock principles, based on profit, were gradually being imposed in the field, while English food sovereignty and living standards suffered (Walton 1999, pp. 32-37).

On the other hand, milk production fell from 72.52 million gallons in the 1650's to 59.10 in the 1700's. Milk prices, except for a few short periods, remained fairly stable. Beef production fell from £24.83 million to £21.16 million. The price of beef also remained stable. The overall conclusion is that per head consumption of meat probably remained stable. The increase in consumption was redirected to more energetic food and more energy in this period, rather than protein, so the population's height probably had to remain stagnant or fall (Galofré-Vilà et al. 2018).

If in wheat there was a relative productive success, in the case of rye this success was even more spectacular, as we can see in figure 5.4, annex 1. The preference for wheat could only be converted into consumption in those social groups that could afford it, regardless of their level of income or their proximity to production. For this reason, in the 1650-1700 period, rye consumption increased much more in proportion, doubling from 3.7 to 6.7 million bushels (Broadberry et al. 2015). If we look at the immediately preceding periods (1600-1650, decrease from 7.8 to 3.7 million) and subsequent periods (1700-1750, decrease from 6.7 to 1.5 million), we observe that 1650-1700 was clearly anomalous, the only one where the demand for rye increased again. The fact that cereal consumption grew, especially rye, proves a greater demand for calories, but also a period of food crises, where rye bread and other inferior breads played an important role in preventing famines (Appleby 1979, 1980; Hoyle 2013).

Not only were adaptations made via energy. Thirsk (1990) claims about the importance of poor harvests and food shortages to increase the production of grains and others crops. This fact had also the effect of stimulating interest in food crops other than grain, and vegetable growing meant food and work for the poor. Vegetables were consumed in London in such quantities that in some seasons the gardens feed more people than the fields. It was even suggested in the 1670's that so much were the poor substituting grain by vegetables in their diet that it was a cause of the deadness of the markets for corn. On the other hand, recent studies have shown that increasing nitrogen fertilization is related to a much higher dose of zinc, iron, copper and protein in wheat, in the order of 50-80 per cent more, which significantly improves health. Zinc and iron are essential nutrients that contribute to human health, the immune system, and the formation of haemoglobin, which spreads oxygen throughout the human body. These nutrients are also key players today, as it has been found that zinc, iron and protein levels are likely to be reduced by up to 10 per cent in wheat and rice to the expected levels of CO2 in the atmosphere by 2050 (Myers et al. 2014). Other research has shown that ancient cereals (landrace seeds) are richer in nutrients than modern varieties because modern plant breeding has been historically oriented toward high agronomic yield rather than the nutritional quality (Zhao et al. 2009, Shi et al. 2010, Gómez-Becerra et al. 2010, Kutman et al. 2011). Farmers, especially yeomen, got better seeds, more resilient, with better gluten for bread, and more nutrients. Thomas & Frankenberg (2002) find that a nutritional deficit, especially a deficit of iron and a lower intake of energy reduce work capacity and the opposite.

In conclusion, the needs of peasant communities and urban horticulturists drove the slow agricultural revolution, resulting in more calories measured in cereals, but also in more and better nutrients, which had a second effect through improved health, further favouring the ability to work and choice among people.

3.1.2. Firewood, charcoal, and coal.

Wood, firewood, and charcoal were used for heating, cooking, producing bricks, boats, horse-drawn carriages, housing, iron, salt, pottery and many other everyday items. An important part of the firewood (in its different forms, faggots, bavins, billets or turf), was consumed in the countryside. The costs of transport prevented its distribution more than 20 miles away from where it was produced (Clark 2004 (Rackham (1980)). Coal was consumed in a much more concentrated form, especially in London, and was largely used for household consumption (heating). For any of these variables, we do not have annual or monthly data on physical amounts spent. This forces us to work with price estimates (figures 5.5, 5.6. 5.7 and 5.8, annex 1). Analysing those provided by Clark, we see that the price of firewood increased until the last quarter of the seventeenth century, where it remained at peak levels. If in this period the peasant population decreased (due to demographic stagnation and urban migration), the price of firewood should have decreased. However, prices rose, indicating a higher per head demand for firewood and a greater need for energy. It has been pointed out that there was an energy crisis in Britain during the 17th century, caused by increased demand for shipbuilding (the demand for iron, could only be met with imports, Thomas 1986). With firewood, however, we cannot go much further. Clark's series does not explain in detail how the sources used have been combined or what their characteristics were. Furthermore, if the market was markedly regional, we would find many local prices, not just one (Hammersley 1957, 1973; Hatcher 1993; Allen 2003). It is possible that many families did not pay for firewood with money, and it is hard to believe that the demand for wood and iron derived from the construction of boats and other materials ceased. Therefore, it is risky to draw conclusions from a single series because it might not be representative.

Looking at figures 5.5, 5.6, 5.7, 5.8, annex 1, it seems that the supply of coal successfully meets the growing urban demand until the 1690s, when its price seems to overflow, just like wood, wood or charcoal. This general increase in the price of energy, in a depressed demographic environment and absence of external demand, can only indicate a strong increase in per head demand for energy-heat. Unlike firewood, coal consumption was concentrated in London and industries. In fact, London's growth was determinant (Allen 2003). Therefore, we can be reasonably sure that the price series is more reliable (figure 5.6, annex 1). Going into detail, we observe that coal supply successfully meets urban needs until the 1690's, where prices seem to overflow, probably due to intense energy demand. We can also venture some more conclusions from figures 5.9,5.10 and 5.11, annex 1. The per head expenditure on coal increases steadily and has several important peaks in situations of extreme cold or supply failure[103]. On the other hand, the real expenditure per head on coal (in terms of wheat) has a similar evolution. Coal consumption, in real terms, became more expensive. That is, the population devoted more and more resources to coal. This idea is well taken up in Martínez-González, Suriñach et al. (2020). Lower temperatures would accelerate the consumption of coal, in contrast to the warmest period, when temperatures would lose importance in favour of other demand factors (urbanisation and population).

In the previous pages we have commented how the greatest need for energy per head had different responses depending on the context of each person or family. One of these answers could have been in the migration to London, what we can call a temporary or permanent migration of "energy seekers". In our opinion, a greater ease in heating was a powerful attraction. At this point it would be ideal to do a simple quantitative exercise on this "attraction", for example, linking the variation of the London population with the price of coal. We are in “collision” again with the absence of data or estimates. However, we can make a first attempt. Based on the calculations provided by Petty in 1686, we have a short series of baptisms between 1665 and 1682. This series could be a proxy for the population, since much of the emigration consisted of women of childbearing age. In figure 5.12 and table 5.2, annex 1, we see how population growth in London was associated with coal prices. If these went up, the baptisms descended, that is, population grew less. Another surprising finding, using two primary sources from more than three hundred years ago and without any relationship between them (Petty's series of baptisms and the Newcastle coal shipments, which we explain below), we observe a strong correlation. Coal availability was a very significant factor in births and child survival (figure 5.13 and table 5.3, annex 1).

However, we have carried out an additional exercise (Table 5.4, annex 1). First, we took as a variable to explain, Clark's London coal prices, a proxy indicator of coal demand. Second, we took two primary sources as explanatory variables. The first source is coal shipments from Newcastle from mining accounts. According to Hatcher, 75 per cent of these shipments were to London (Hatcher 1993). According to Broadberry et al 2015, these shipments are an excellent indicator of the increase in coal consumption in England. The second source are seasonal temperatures. The main message of the model is that London coal prices increased when coal shipments fell and when autumn and winter

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[103] The calculation of coal expenditure can be found in Martínez-González, Suriñach et al 2020.

temperatures were lower. In Table 5.4, 72 per cent of the London coal price is explained by autumn and winter temperatures, and Newcastle coal shipments. The colder the temperature, the more expensive the coal and vice versa. A 1ºC reduction in temperature resulted in a price increase of 2.13 shillings, 15 per cent in the average price of coal for the period studied. Knowing that the 1645-1700 period was especially cold, we understand that it was an important added stimulus to the demand of fuel per head. The lower the coal shipments, the more expensive it was. On the other hand, Hatcher (1993) has shown that shipments were radically reduced when the weather worsened, especially in autumn and winter. Therefore, the increase in prices reflects two things, an increase in the demand for heat, and an increase in the relative scarcity of coal. At that time, it was not easy to increase total winter energy consumption in proportion to low temperatures. According to this, total consumption could be more related to average temperatures based on forecasts and expectations. Thus, we have seen before that the 1645-1700 period was very cold and humid. Therefore, cold was an important stimulus in demand, which is in line with the conclusions of our work.

Our conclusion is, firstly, that we find signs of "energy attraction" on the part of London and, secondly, that the price of coal is directly linked to the worsening climate.

3.2 Implication two: higher energy, therefore higher and divergent wages.

In the previous sections we found a relationship between temperature, energy need and demand for food or goods related to energy maintenance. On the other hand, we have predicted, based on theoretical analysis and empirical studies, that this causal line will lead to increased productivity and wages (incomes) and divergent growth between wages (incomes) in the non-agricultural and agricultural sectors. Figure 5.14 seems to show how our prediction is met. Right at the beginning of the climate crisis (1646) the daily wages of both sectors begin to diverge for the reasons explained in section 2.5. Furthermore, if we put the real daily wages estimated by Clark and the real annual income estimated by Humphries & Weisdorff in the same chart (figure 5.15), we observe how they begin to grow just after 1645, as the theory predicts.

Regarding productivity, table 5.1 (annex 1) suggests how the output of wheat per labourer is affected in the short term by a more adverse climate, but in the long term it rises. This fits quite well our forecast of "jump" from C to C' and then to E, C" in Figure 5.2. Second, Malthus and David Ricardo's wages theory argues that the "natural wage" is marked by the subsistence level. Therefore, if the basic need for energy per head increases, the "natural wage" also increases. Otherwise, there would be a demographic and migratory crisis. A current, more settled argument defends the idea that the wage adjusts quite well to the value of the labourer's marginal productivity (the value of marginal productivity is equal to the result of times the marginal productivity by the price of the goods produced). Greater availability of energy per hour for work implies an increase in productivity. If the price of the produced goods remains stable or rises, the value of the marginal productivity rises and therefore wages rise as well. Labour employers are inclined to pay more. If the price of what is produced decreases in the same proportion as the marginal product increases, the value of the marginal productivity remains stable and the wage also increases. Returning to theoretical section 2.5, it predicts an increase in agricultural wages from w1 to w2-w3, depending on whether it is a farm that maximizes profits or rents (adjusting the number of workers and wages), or if they are common fields (adjusting productivity), if there are no additional institutional constraints. A higher increase in non-agricultural wages (w4) is also expected. In other words, in the cold period a direct relationship between wages and temperatures must be found in the short term, and the opposite relationship in the long term. The relationship is expected to be weaker in the agricultural sector, because 1) the effects of climate on harvests play a corrective role, 2) agricultural labourers are both producers and consumers, and 3) a whole series of institutions and operating rules moderate these effects.

Let us now make a comparative exercise between agricultural and building day wages (skilled or unskilled workers). The logical line begins, let us remember, in a worsening of the climate and the political situation, and an increase in energy consumption per head. More energy per hour means more productivity. From this point, there is a divergence between the countryside and the city. Agriculture would be able to improve or maintain its productivity (especially in open and common fields) and agricultural prices would tend to fall in the long term. Therefore, the value of productivity should be stable or slightly higher (the rise in productivity is offset by the fall in prices). Thus, daily wages would remain stable in the long run (or rise smoothly), ranging from the highest levels on "capitalist" farms (paying more with fewer labourers) to the somewhat lower levels on common and open fields (because more workers and families are being maintained).

On the other hand, in the building sector (craftsmen or unskilled), the increase in energy consumption per head is achieved by adjusting the number of labourers, wages and prices. As the price of energy-housing rises, so do the wages of building labourers (we do not know whether there is a substantial improvement in marginal productivity). The consequence of all this is that (1) there should be a stronger relationship between climate variables and wages in non-agricultural sectors than in agricultural sectors, and (2) adjustment is faster in the non-agricultural sector because poor harvests slowed the growth process, rural institutions limited wages through wage and mobility controls between counties. In urban areas, on the other hand, guilds lost power.

The results of table 5.5 (annex 1) are close to our intuitions. The parameters of the explanatory variables are significant. As predicted, the relationship between temperatures and real agricultural wages is weaker (R2 lower) and adjustment is slower. At first, declines in temperatures mean lower real wages. In the long run, these end up rising because the subsistence minimum and productivity increase (a process that can take nine years to complete). In any case, the relationship is significant but weak. However, in building wages, the ratio is stronger (R2 higher) and this adaptation is faster (between two and three years). Obviously, these results are still quite speculative. The only way to prove this is with local comparative studies.

A similar exercise can be done with animal force. It also had to increase the need for energy in bullocks and horses. This meant higher costs and higher requirements for production. Horses were much more versatile as draught animals in the transport of people, goods or coal. In an environment where more energy-work was required to obtain more energy, the value of the marginal productivity of horses was higher than of oxen. Therefore, the price of the former rose in relation to the latter. Table 5.6 (annex 1) offers an empirical approximation to this idea. We observe a significative relationship between the increase in the price of the horse and the fall in temperature, and vice versa with bullocks. In fact, the number of draught bullocks was halved, from 80,000 to 40,000, and beef and milk productions were also reduced. On the other hand, in food-animals such as pigs or cows, their price increased as their energy requirements and maintenance costs increased.

3.3. Implication three: If the open fields were successful, why were they disappearing?

In order to cope with a higher need for energy and minimum subsistence, section 2.5. concludes that common farms are obliged to effect productivity improvements in order to maintain the number of working families and individuals. This theoretical prediction has long been demonstrated in Allen and others. An increase of energy requirements of the rural families was a stimulus for the agrarian communities, because they will protect calories intake for their women and children or to increases energy to attend the market demand. We know by Allen (1992) that yeomen and open fields were the key protagonists in the increase of agricultural yields and output, between 1650 and 1750. How can we harmonize this success in a more adverse environment? Dyer (2018) explains that the basic characteristic of peasant communities was the need to achieve a certain degree of self-sufficiency, so that open fields were specially designed to minimize the risks of bad harvests, with a landholding structure and social balance between arable and pasture managed by by-laws. McCloskey (1972) explains “that strips were scattered by villagers to reduce risk and they were driven to hold land in scattered strips to hedge against disasters befalling only one type of soil and to diversify their crops, holding land in each of the open fields of the village, to hedge against disasters raising the price of only one part of their food”. Allen (2001) talks about this again, admitting the efficient management of climate risks and high productivity. “Land was not uniform, so the productivity of different parts of a village's land responded differentially to variation in the weather. In years of high rain fall, low lying land might have been waterlogged and given low yields, while higher land might have been productive. Conversely, when rainfall was light, the upland might have been too dry to produce well, while yields might have been high in the low land”.

In our opinion, the cost-benefit ratio was well managed in that they did not need a high capital investment individually, because this capital was shared as investment in horses, diversification into furlongs and strips, and the contribution of new seeds. According to John (1968), small farmers did not benefit from poor harvests. The profit depended on two years of tenure, the fallow year and the year in which the crop grew, while the third was devoted to what we call the Quaresma grain, such as oats, or with legumes, intended for the subsistence of horses and cattle. This precariousness explains, in large part, the rapid turnover of small tenants in many arable areas of central England. On the other hand, where animal husbandry was the predominant activity of the small farmer, the effects of harvest conditions were somewhat different. Here grains were grown mainly for on-farm consumption and affected the economic survival of the farmer less directly. However, as in the case of the small farmer, a farmer suffered severely when the crops were bad. When he had money, he appeared in the markets as a food buyer; more often, however, he and his family went hungry.

Therefore, here urban demand was not an important pull factor for them. A drop in temperatures and more humidity, together with an increase in the variability of weather, implied a greater demand for energy to protect the needs of peasant families, who were forced to sharpen their ingenuity. This fact is confirmed by Allen (2001) and McCloskey (1972) when they mention that common and open fields were organized in dispersed plots, very suitable for managing climate risks. In a period with greater probability of risks, the response capacity could be significant in the farmers, hence also their productive success. Allen (2001) has also pointed out that in open fields, small farmers had an adequate system to increase yields, something necessary to maintain their families, and they also introduced turnips, clovers, new rotation systems and new seeds. All this also explains why there was an incentive to the enclosures. The increased value of the land generated renewed interest from landlords and landowners, so many did not renew tenure contracts. On the other hand, as we have already discussed in section 2.5, the pressure to be more productive was greater, and wages were probably lower. These factors made their long-term viability more difficult. More productivity for a lower wage could lead to a process of depopulation in some of the open or communal fields. This phenomenon (and others) are what Walter Blith (1649) notes, defending enclosures to avoid the loss of rural population.

3.4. Implication four: inequality, involuntary and voluntary unemployment.

However, depopulation on capitalist farms was more general, due, as we have seen before, to a decline in the number of workers per acre in the face of rising energy requirements. Fortrey (1663), another supporter of enclosures, acknowledged the prevailing view of the moment. Enclosures were a problem because they generated depopulation, unemployment for families and grain shortages. That is why the old parliaments opposed them. The land would become pasture. One hundred acres would barely maintain a shepherd and his dog, while "now many families and employees are maintained on the farm, and from experience one finds that many families, now in enclosures, do not have as many inhabitants on them". Therefore, it matches the theoretical prediction that the "capitalist" farms generate less employment and that part of it is forced to change occupation as the manufacture of wool, as Fortrey defended.

Another important conclusion of our research was the prediction that higher per head energy requirements led to more unemployment and underemployment. In this sense, during the second half of the 17th century a whole body of evidence emerges, around a growing concern of British philosophers and intellectuals for these issues. If with the emergence of classical economics (18th century) leisure was harshly criticized, during the 17th century mercantile economic philosophers believed that involuntary underemployment predominated over voluntary underemployment. William Petty concluded in his *Treatise of Taxes and Contributions* (1662) that the government should not allow mendicity. It was far costlier to tolerate than to provide money to the less fortunate. Petty believed that it was unfair to starve people with wage controls when they wanted to work and prosper. This has been corroborated by Christopher Hill: in most counties the official wage rates set by the judges remained almost unchanged from around 1580 to 1640, while prices kept rising. Even workers who earned more than the officially marked wage or those who attempted to leave their parish without permission could be punished with a terrible fine and imprisonment (Hill 1969).

A common idea developed by almost all English thinkers was that the prosperity of the nation would be achieved by combining low prices and wages. Although there was no unanimity on the desirability of keeping wages low, almost all views pointed in this direction. Petty believed that wages should be competitive, but he also criticized the fact that wage ceilings were so low as not to allow workers more prosperity. Against such a backdrop, it becomes very difficult to think that the workforce had an "irrational" propensity for leisure. Petty had a positive view of work: people wanted to work and prosper, it was unfair to limit wages. On the one hand, he believed that the market always tended towards a natural subsistence wage, but he also agreed with the unstoppable phenomenon of migration for the sake of a better life. According to Petty, wages were limited by the Law (1662, p. 52), hence the good reasons to go to the city: more equitable taxes, better justice, accessibility to consumption and commerce, a greater division of labour with more opportunities and more educational possibilities (1683, pp. 470-75).

Josiah Child (1630-99) published an 18-page pamphlet called *Brief Observations*, in which he analysed Dutch prosperity. He insisted on the importance of increasing the population and facilitating work for the poor, but above all he thought like Petty (there was a lot of involuntary unemployment), although he also emphasized the strong tendency of the workers to leisure as their real wages increased as the poor,

> "will no provide for a hard time, but just work so much and no more, as may maintain them in that mean condition to which they have accustomed"[104]

George Berkeley, an Irish bishop and author of *The Querist* (1735), was concerned about several issues, especially chronic and widespread unemployment or underemployment. For him, there was no doubt that unemployment in England, Scotland and elsewhere was largely involuntary, but there was also a component of idleness (in modern terms, the

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[104] Hutchison, 1988.

supply curve pulled back once a wage level was reached). To solve both types of unemployment it was necessary to apply a carrot and stick policy: forced labour houses (those who do not work do not eat) and "wants",

> "Whether the creating of wants be likeliest way to produce industry in a people? And whether if our peasants were accustomed to eat beef and wear shoes they would not be more industrious? Whether comfortable living doth no produce wants, and wants industry, and industry wealth?"

Berkeley was very clear that there was an involuntary part of employment and leisure, so there was a tension between the two extremes, because he could even see poverty face to face. For the bishop, fiscal policy was a good solution to reduce luxury spending and bring the poor into employment. Income inequality was undoubtedly a real brake on development:

> "Whether as seed equally scattered produces a goodly harvest, even so an equal distribution of wealth doth not cause a nation to flourish?"[105]

Underlying here is a rational explanation of "voluntary unemployment". Any exogenous impact that reduced the demand for labour in the short term caused downward pressure on wages. If the maximum wages were already at the subsistence threshold and the workforce was not free, it was a perfectly rational choice not to work and live on charity, to escape the forests, to go on an overseas adventure, to break the rules or to migrate to the city. "There was a large movement of surplus labour from villages to forest settlements in many parts of England" (Hill 1969). Faced with the weakness of European family networks (nuclear family units), the only alternatives available to them were, in addition to "an escape" in the case of the less consistent ones, the extension of the work force with women and children either by extending the number of working hours, or even diverting their time and energy in seeking sustenance through other alternative systems (De Vries 2009).

Inequality, the distribution of time and energy within family units, wage and non-wage levels, the existence of social benefits and coverage, or restrictions on labour mobility may have been influencing factors. For Edmund Halley (1656-1742), a pioneer in the development of population statistics, Fellow of the Royal Society and widely known for his work *Degrees of Mortality of Mankind* (1693), inequality was the main cause of demographic and economic stagnation. The population size was maintained not by disease and hunger but because people considered marriage an adventure. Taking on the burden of supporting a family could be an insurmountable problem. The population did not grow so much because of hunger and disease but because of decisions not to marry, a kind of "moral" restraint. Halley's argument connects with Clark's "Law of Social Mobility" (2014). If wealthy social groups maintained their marriage and fertility rates, but the lower strata did not (and so globally the number of marriages fell), the "winning genes" of the future Industrial Revolution spread to the lower layers for several

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[105] Hutchison, 1988.

generations, which could help to understand the progressive shift in British economic thinking between the 17th and 18th centuries, as well as other factors such as Dutch immigration or the economic boom of the early 18th century.

In a context where the per head need for energy grew, the fact that this need was much greater during pregnancy and lactation (see above) had to slow down the rate of nuptiality and births, especially among the poor.

Be that as it may, from everything we have seen up to now we can see a clear concern of "modern" thought in promoting employment (industries and businesses were judged for their capacity to absorb labour or stimulate employment), where the discourse of the "idle" is also making its way, according to the declarations of writers and pamphleteers, the preambles of a long series of laws, writings of statesmen or reports of public bodies. There was a preoccupation with seeking work rather for reasons of wealth than for the existence of a certain sensitivity in improving the welfare of the population. Did all these elements reflect a destruction of the collective or communal spirit of the Middle Ages, the beginning of the triumph of the individual over the collective in a century of transition? This is obvious to Hill, as feudal relations were already in clear retreat from the sixteenth century: "villainy ends, tenure leases and wage labour extend," "scruples did not prevent owners from expelling settlers who were no longer obligated to serve them. The law was strongly inclined against the poor", or quoting Professor Richard H. Tawney, "the villainy ends, the law of the poor begins", when feudal protection of agricultural work gave way to welfare protection (C. Hill 1969). Be that as it may, a large part of the references in social matters come from the studies of the Law of the Poor, and on the other hand at the level of labour force, peasants and workers, there is very little. The writings of the mercantilists distil analysis of political economy but little of the labour market and genuine social history. And in no case did they speak of the role played by women, children or servants.

In this general context, the strategies followed were different. The increase in calorie intake was a slow and gradual process, as well as the improvement in health. Neither sooner nor later did this benefit everyone. Gregory King's population distribution in 1688 shows that a very large proportion lived at levels close to poverty. In a time of such controversial change, many could not benefit. Gregory King (1648-1742), genealogist, accountant, social and economic statistician, wrote two works that have had much influence in this field, the *Natural and Political Observations and Conclusions upon the State and Condition of England*, not published until 1802, and *Scheme of the Income and Expense of the Several Families of England calculated for the Year 1688*, where he presented a table that was well recognized and accepted by later economic and social historians. King's research showed a grim history. He classified 23 per cent of the national population as "working people, servants apart" and another 24 per cent as "cottagers and poor," estimating that both groups had an annual family expenditure greater than income. The sum of both groups was no less than 47 per cent of the total population. These accounts may have been clearly falsified to avoid paying taxes, but Coleman (1956) was inclined to accept King's figures: a quarter and half of the population was below the poverty line, including the skilled and semi-skilled working class, farm workers, the poor, day labourers, and the most modest weavers.

It is certain that a greater need for calories weakened many people. All those who did not find ways to increase their need for energy reduced their work capability. Freudenberger & Cummins (1976) insist that before "losing" calories to survive, many of these people preferred to keep sacrificing work for leisure, this leisure being largely voluntary. The question of the poor and their "aversion to work" became fashionable in the field of political economy. Therefore, there seemed to be an association between a greater need for calories and the growing situation of vulnerability in a part of the British population.

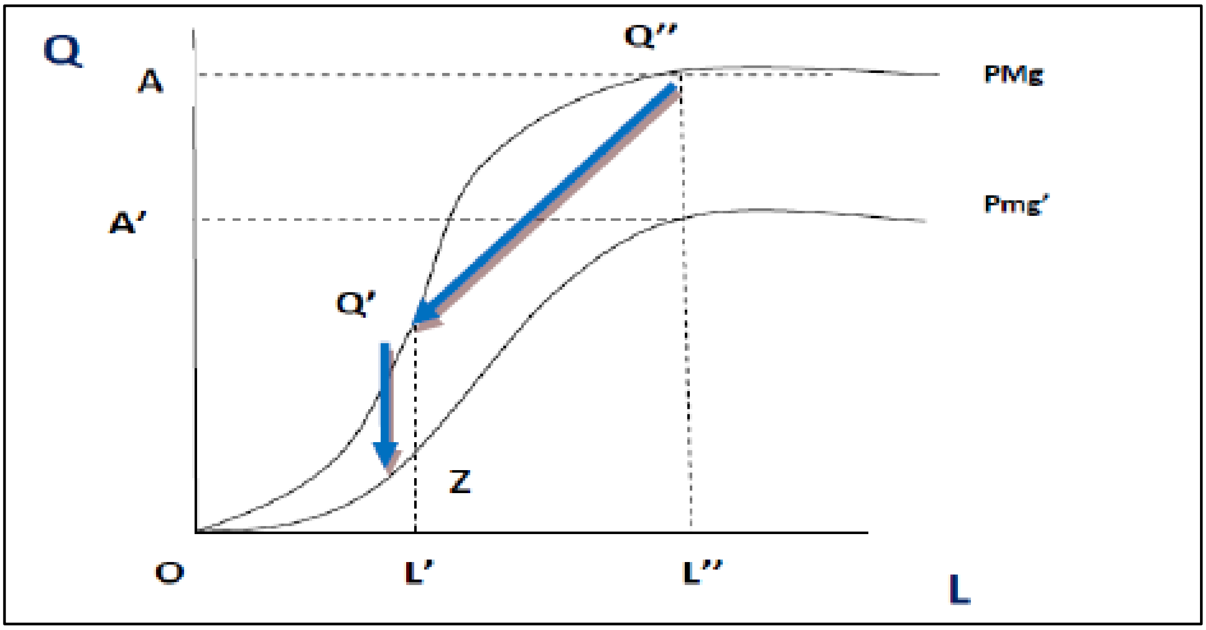
4. Conclusions.

There are several factors associated with an increase in energy needs. In this chapter we focus on one of these factors, climate. A worsening climate means more energy expenditure in a variety of ways. The English population was mostly poor and with subsistence wages (or income) concentrated on food, clothing, housing, and energy to burn. Thus, to spend more energy they needed higher subsistence incomes. The increase in the wage fund may then be one of the causes of the remarkable growth of British GDP per capita in the second half of the 17th century. The Malthusian argument is incomplete, it would only explain about half of the increase.

From this central message (energy as a key element) come other issues that should be studied in the future. Some of these issues are as follows. Economic transformations occur everywhere, in the countryside and in the city. We can connect physical energy with the economy through subsistence wages and productivity. Egalitarian farms respond by maintaining population and increasing yields. Capitalist farms respond by reducing the number of workers per acre and improving incomes. This leads to involuntary and voluntary unemployment. Some communal farms have difficulty retaining some workers, given the relationship between the effort they must make and the income they earn. Women and children reallocate their energy consumption more efficiently by working in manufacturing. There is a liberation of labour in manufacturing and services. Non-agricultural wages began to differ from agricultural wages. The structural change of the second half of the 17th century marks the path of the origin of the British economic revolution.

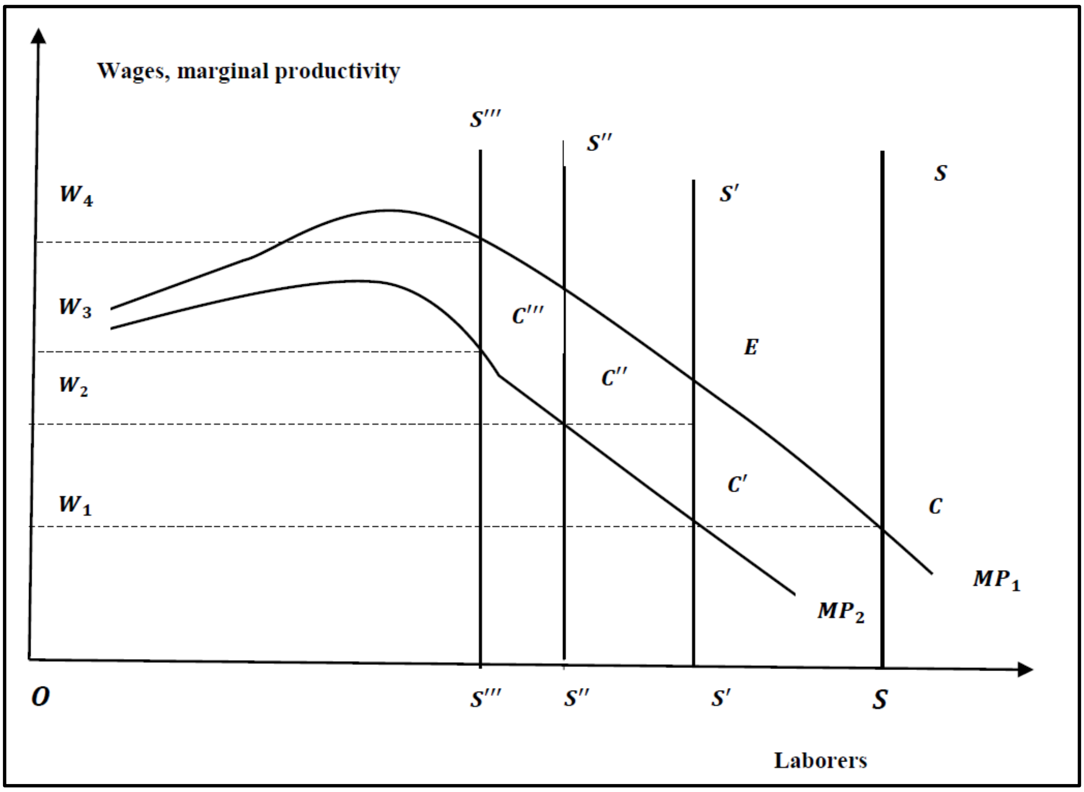
5. Appendix.

Figure 5.1. Climate effects on labor productivity



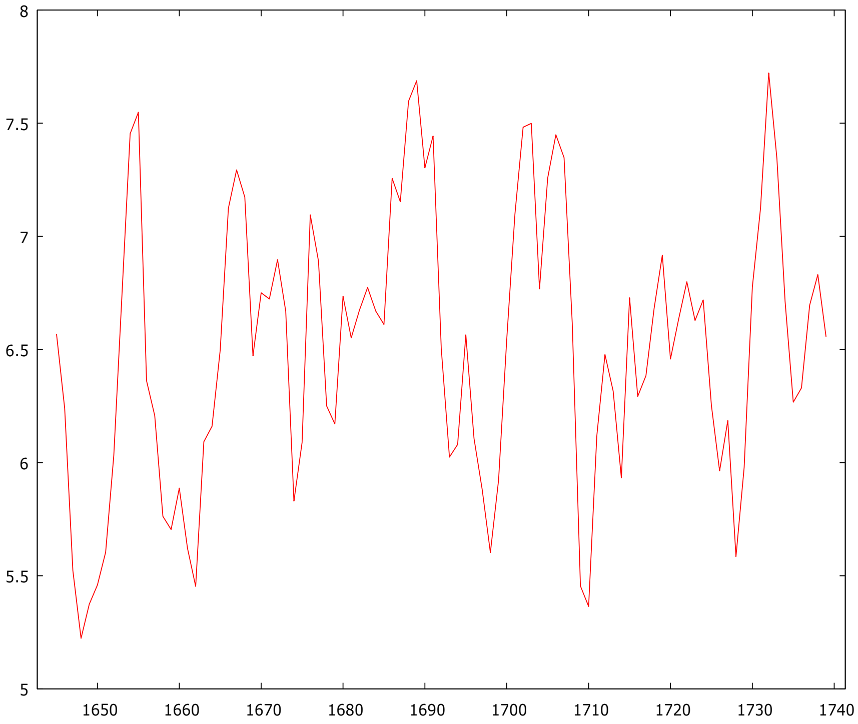
Own elaboration

Figure 5.2. Variations in energy consumption, productivity, and wages



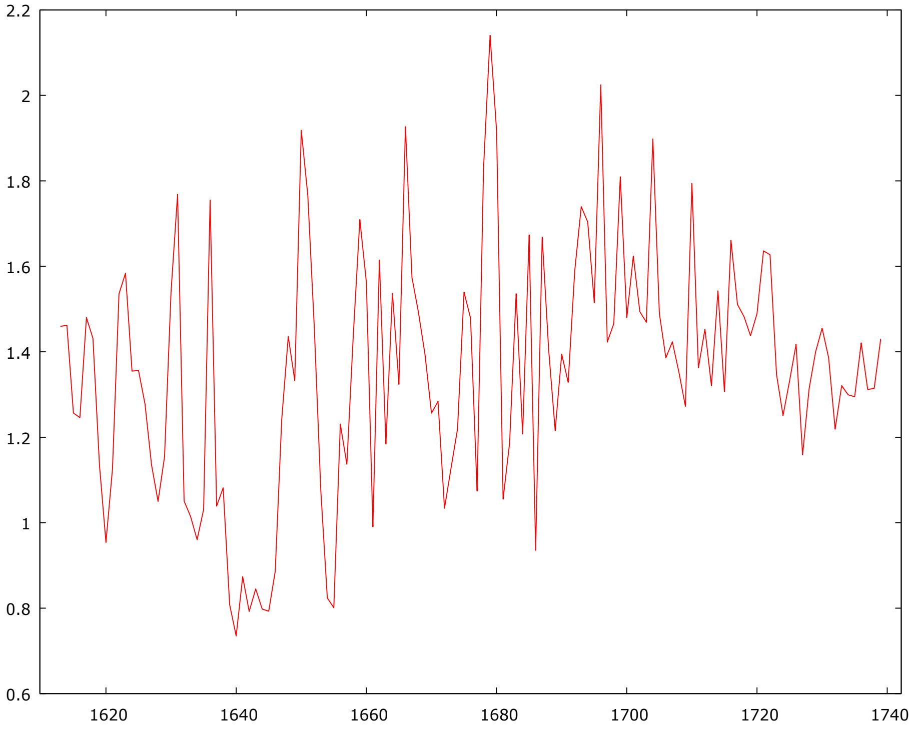
Own elaboration

Figures 5.3. Gross wheat per head in bushels. England and Wales, 1645-1740.



Own elaboration from Martínez-González et al- 2019 wheat estimates and Wrigley et al. 1981 population estimates.

Figure 5. 4. Relative prices between wheat and rye. England and Wales, 1645-1740.



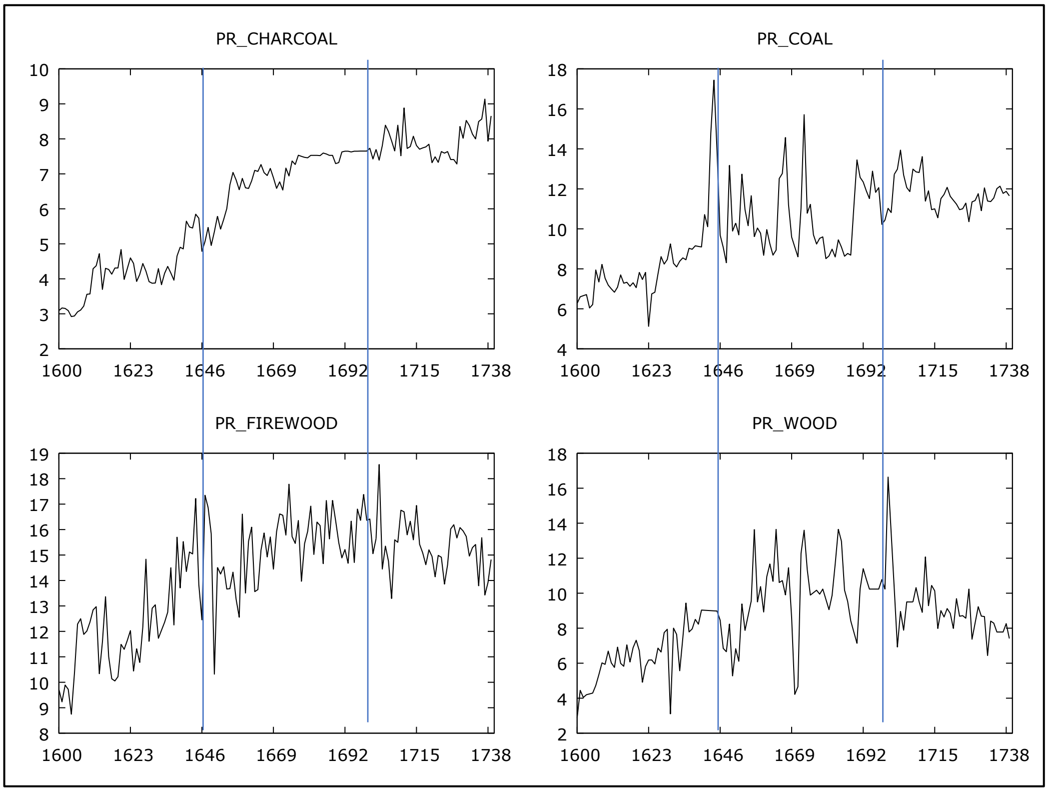
Own elaboration with Clark prices

Table 5.1. Testing the relationship between the demand for food energy and climate variables, in the short and long term. England and Wales.

Dependent variable	GROSS_WHEAT_ PER_HEAD 1645-1739	PR_RYE 1645-1739	PR_OATS 1645-1739	
Constant	6.12*** (0.0001)	5.60*** (0.0002)	2.44*** (0.0001)	SHORT TERM
TEMP		−0.24*** (0.0060)		
TEMP (-2)	0.14** (0.0184)			
TEMP (-3)	0.14** (0.0387)		−0.06** (0.0422)	
TEMP (-4)			−0.05* (0.0868)	
TEMP (-6)	-0.16** (0.0114)	0.20** (0.0329)		LONG TERM
TEMP (-7)	−0.019*** (0.0017)		0.06** (0.0374)	
TEMP (-10)		0.31*** (0.0014)		
SUMMER RAIN	−0.002*** (0.0027)			
SUMMER RAIN (-1)	−0.002*** (0.0013)			
SUMMER RAIN (-3)	0.001** (0.0451)	−0.002** (0.0476)		SHORT
SUMMER RAIN (-4)	0.001* (0.0700)	−0.004*** (<0.0001)		
SUMMER RAIN (-5)	0.002*** (0.0015)	−0.002* (0.0727)	−0.001*** (0.0024)	
SUMMER RAIN (-6)			−0.0006* (0.0541)	LONG TERM
SUMMER RAIN (-7)		−0.002** (0.0202)		
SUMMER RAIN (-8)		−0.004*** (0.0002)		
SUMMER RAIN (-9)			−0.0008** (0.0106)	
SUMMER RAIN (-10)	0.002*** (0.0010)		−0.0005* (0.0761)	
SPRING RAIN (-1)	−0.004*** (<0.0001)	0.004** (0.0201)		SHORT T.
SPRING RAIN (-2)			0.0014*** (0.0054)	
SPRING RAIN (-6)	0.003*** (0.0008)		−0.001** (0.0304)	LONG TERM
SPRING RAIN (-9)	0.003*** (0.0017)	−0.005*** (0.0024)		
SPRING RAIN (-10)		−0.006*** (0.0013)		
N	95	95	95	
$adj\ R^2$	0.54	0.48	0.28	
F	9.61	8.91	4.93	

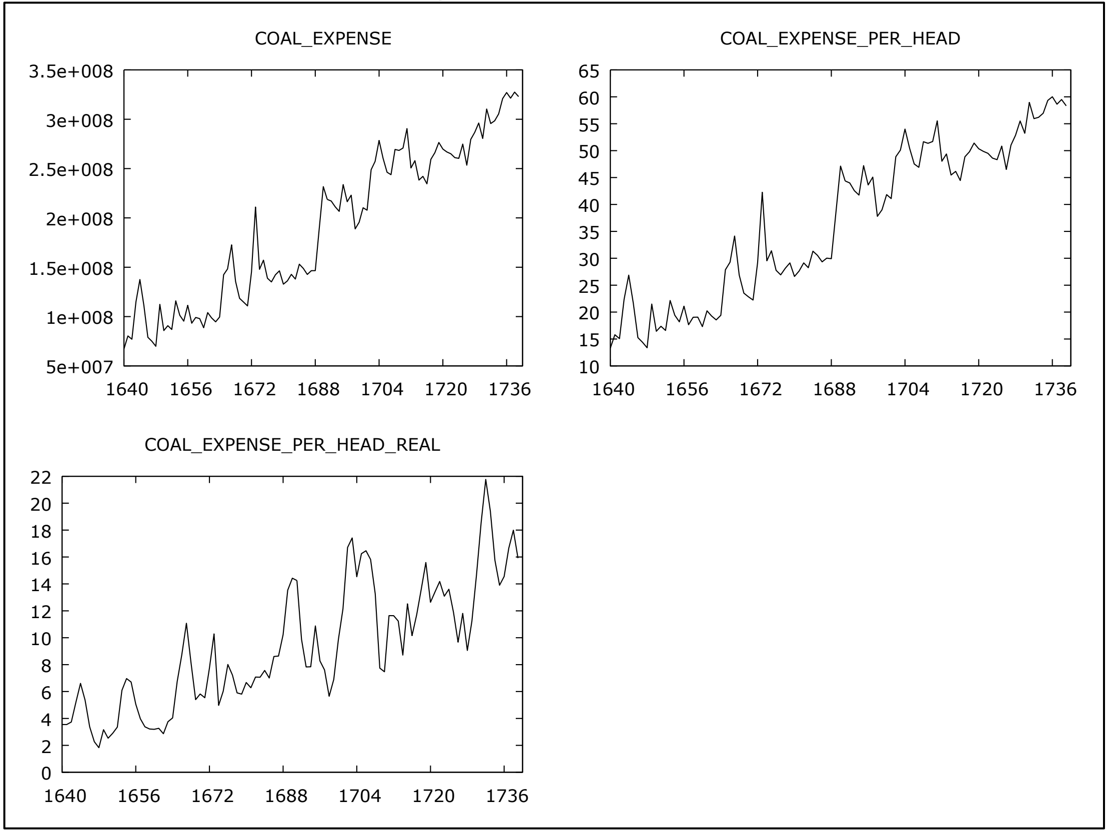
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Figures 5.5., 5.6., 5.7, 5.8. Prices of charcoal, coal, firewood and wood. England and Wales, 1600-1740.



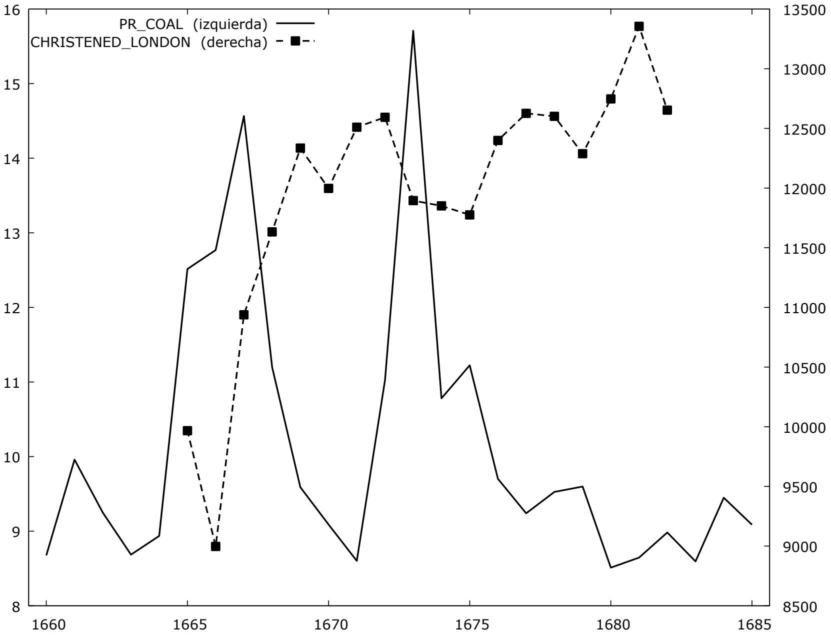
Own elaboration with Clark prices.

Figures 5.9., 5.10., 5.11. Coal expense, coal expense per head, real coal expense per head. England and Wales, 1640-1740.



Own elaboration with Clark prices.

Figure 5.12. Coal prices and baptisms, London, 1665-1682.



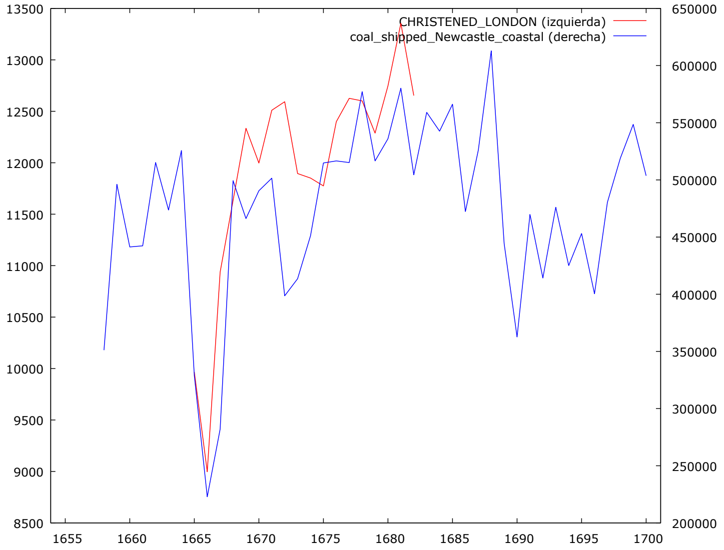
Own elaboration with Clark prices and Petty baptisms data.

Table 5.2. Testing the relationship between baptisms and coal prices, London, 1665-1682.

Dependent variable	CHRISTENED LONDON 1665-1682
Constant	15400.4*** (0.0001)
PR_COAL	−324.39*** (0.0042)
N	18
adj R^2	0.37
F	11.13

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

Figure 5.13. Coal shipments and baptisms, London, 1665-1682.



Own elaboration with Petty baptisms and Hatcher coal shipments data.

Table 5.3. Testing the relationship between baptisms, coal shipments from Newcastle plus seasonal temperatures. London.

Dependent variable	CHRISTENED_LONDON 1665-168
Constant	7639.47*** (<0.001)
COAL_SHIPPED	0.00933767*** (<0.001)
N	18
R^2	0.73
F	48.25

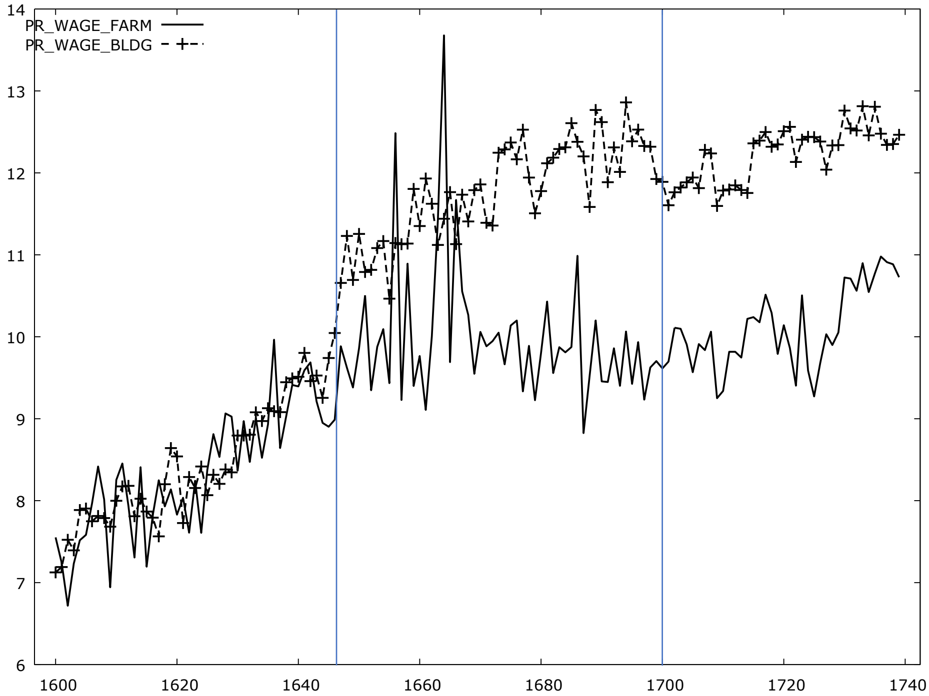
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

Table 5.4. Testing the relationship between Clark's London coal prices, and coal shipments from Newcastle plus seasonal temperatures, 1661-1700.

Dependent variable	PR_COAL_LOND 1661-1700 (1)
Constant	47.4083*** (<0.001)
WINTER_TEMPERAT	−0.400246* (0.0517)
WINTER_TEMPERAT (-1)	−0.454780** (0.0281)
AUTUMN_TEMPERAT	−1.28203*** (<0.001)
COAL_SHIPPED	-2.4983*** (<0.001)
COAL_SHIPPED (-1)	-1.4555*** (0.0016)
N	40
R^2	0.72
F	21.26

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets. Prices of firewood, charcoal, salt or bricks are not statistically significant.

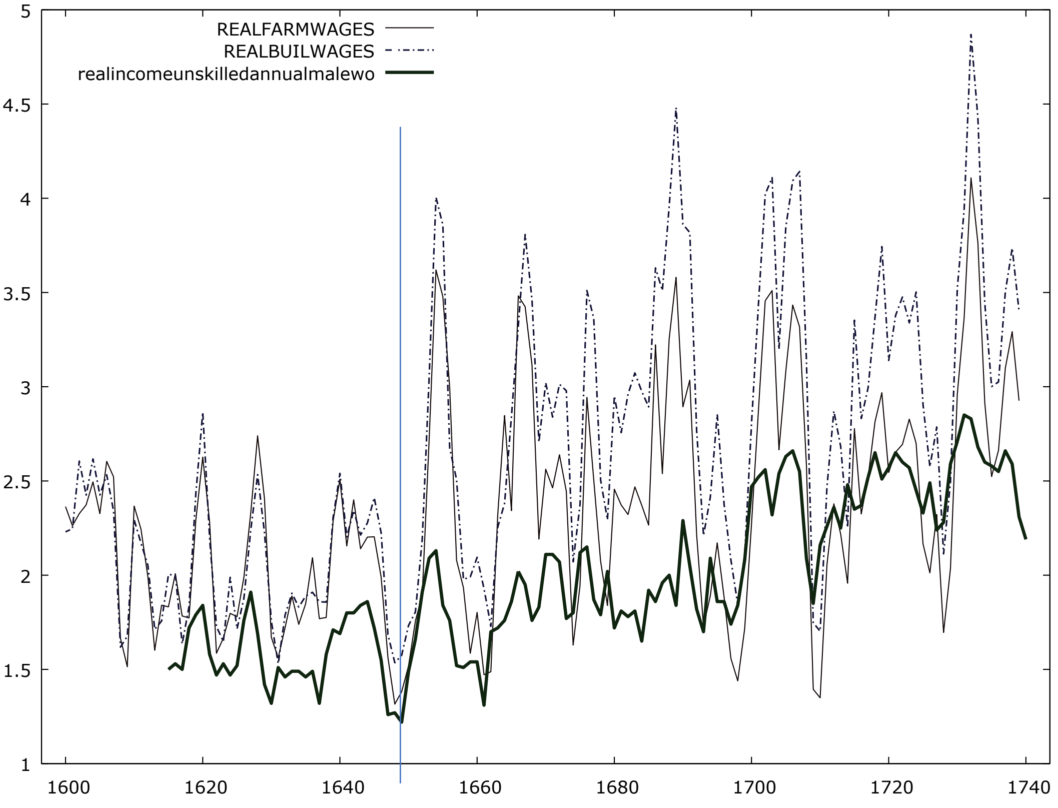
Figure 5.14. The divergence between the two wage sectors originated by climate crisis. England and Wales, 1600-1740.



Own

Elaboration with Clark wages

Figure 5.15. The divergence between the two wage sectors and annual incomes. England and Wales, 1600-1740.



Own elaboration with Clark wages and Humphries & Weisdorff estimates of unskilled real incomes

Table 5.5. Testing the relationship between temperature and wages. England and Wales, 1645-1700.

Dependent variable	REALFARMWAGES (1645-1700)	WAGE_CRAFT (1645-1700)	WAGE_BLDG (1645-1700)
Constant	1.26742	18.9480***	10.8484***
	0.5582	<0.0001	<0.0001
TEMP	0.210329**		
	0.0197		
TEMP (-1)	0.231077**	−0.281945**	−0.141323**
	0.0112	0.0104	0.0196
TEMP (-2)	0.303928***	−0.182646*	−0.173806***
	0.0013	0.0998	0.0049
TEMP (-5)		−0.220804*	
		0.0616	
TEMP (-7)	−0.210621**		
	0.0452		
TEMP (-8)	−0.206879**		
	0.0486		
TEMP (-9)	−0.198464**		
	0.0639*		
HOUSING_PRICES (-1)		0.207280***	0.165621***
		(<0.0001)	<0.0001
N	56	56	56
R^2	0.36	0.60	0.73
F	4.66	19.41	46.6

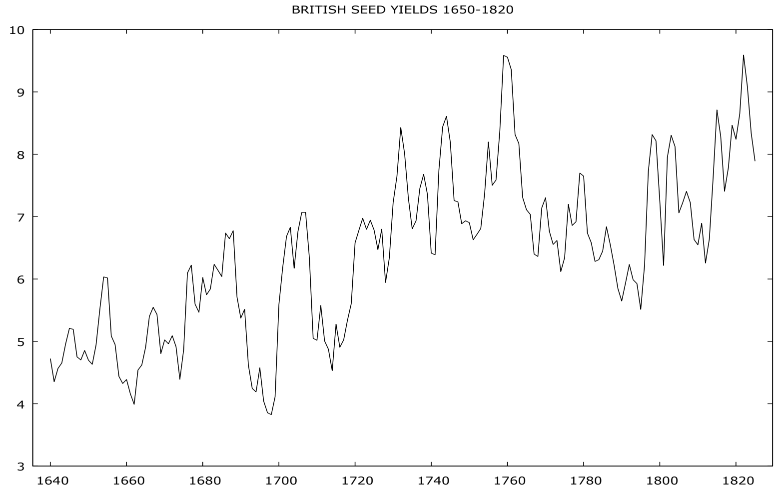
*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Table 5.6. Testing the relationship between animal work and temperature. England and Wales, 1645-1700.

Dependent variable	HORSES 1645-1700	PIGS 1645-1700	COWS 1645-1700	BULLOCKS 1645-1700
Constant	694.556***	34.3079***	140.235***	−47.6391
	<0.0001	<0.0001	<0.0001	0.1963
TEMP	−12.5748**		−2.08483**	5.88391***
	0.0478		0.0105	0.0093
TEMP (-1)	−17.0555***	−0.936031*	−2.60439***	6.26005***
	0.0089	0.0767	0.0019	0.0064
TEMP (-2)	−14.8932**	−1.37797**	−2.32712***	4.79468**
	0.0208	0.0108	0.0048	0.0333
N	56	56	56	56
R^2	0.21	0.15	0.29	0.24
F	4.74	4.5	7.31	5.58

*= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%. p-value between brackets.

Figure 5.16. British seed yields, 1650-1820.



Own elaboration with estimates of wheat production by Martínez-González et al 2019

Chapter VI. Conclusions.

Los capítulos de esta Tesis Doctoral proporcionan argumentos teóricos y evidencias empíricas de que las variaciones climáticas y económicas acontecidas en Inglaterra entre 1645 y 1740 estuvieron muy relacionadas. No hay duda de que las instituciones, los mercados y las estructuras sociales jugaron un papel fundamental en el desarrollo económico y social británico de aquel período. Sin embargo, aun corriendo el riesgo ser etiquetados por la corriente *mainstream* de "determinismo medioambiental", esta Tesis Doctoral proporciona nuevas evidencias acerca de la influencia de este factor climático-ambiental sobre la trayectoria de la sociedad y la economía inglesa, siendo mucho más relevante de lo que se ha creído hasta ahora. Algunas de las implicaciones más importantes de esta evidencia las hemos desarrollado en los capítulos anteriores, donde mostramos que las interrelaciones iban mucho más allá de una simple causación mecánica y unidireccional entre factores determinantes y consecuencias.

El Capítulo II ha tratado de establecer si existían relaciones estadísticas estrechas entre el cambio climático y/o las variaciones meteorológicas del tiempo atmosférico y la trayectoria de la economía inglesa. Dada la información disponible y los métodos de los que disponemos, es muy difícil establecer con precisión la intensidad y duración de sus efectos sobre el conjunto de la economía. Sin embargo, las aproximaciones efectuadas sobre los principales componentes del crecimiento económico de aquella economía agraria, esto es, la tierra cultivada, la energía y el trabajo invertidos, presentan unos primeros resultados de interés. La producción agrícola de trigo y cebada se vio afectada por el enfriamiento climático ocurrido durante la segunda mitad del siglo XVII. Una situación parecida observamos en dos de las variables demográficas que el profesor Edward Anthony Wrigley destacó como indicadores clave: los matrimonios, que se incrementaban en número con el buen tiempo, y la mortalidad, que empeoraba con el frío. El crecimiento de la demanda y consumo de carbón también se hallaban claramente vinculados a dicho fenómeno. En el mercado de trabajo agrario, *ceteris paribus*, la productividad del trabajo y los jornales agrícolas diarios se también movieron en función de las temperaturas. En la industria, la construcción y la economía global, la variación climática estimuló de forma significativa el alza de los salarios diarios y el PIB.

No parece que los impactos fueran permanentes. Se produjeron una serie de procesos adaptativos derivados de un factor fundamental para la vida: la necesidad de energía. El descenso de las temperaturas y el aumento de las precipitaciones, estuvieron ligados al aumento sustancial y general de la demanda de energía per cápita, imprescindible para mantener el metabolismo basal y un estado de salud mínimo para subsistir. Asimismo, también aumentó el consumo de la energía necesaria para trabajar. En el campo, los agricultores ingleses bregaron con más intensidad para garantizar las necesidades de energía de sus propias familias y de sus comunidades, y también para responder a las crecientes demandas del comercio, los mercados urbanos y los incentivos del Parlamento. De esta manera, buscaron técnicas eficientes para extraer "más energía" del suelo cultivado mediante la mejora de su fertilización, contrarrestando el reconocido efecto que la disminución de las temperaturas tiene sobre los rendimientos.

Los Capítulos III y IV tienen como objetivo profundizar en las interacciones clima/tiempo atmosférico producidas en el ámbito más sensible: la agricultura. Para ello, en el Capítulo I se ha confeccionado una serie anual de producción de trigo a partir de la regla de elasticidad precio calculada por primera vez por Charles Davenant en su ensayo de1699 *An Essay on the probable means of making the people gainers in the balance of Trade*, añadiéndole dos variables de tendencia, la evolución de la población y de la renta. La serie estimada se ajusta razonablemente bien a la información recogida en las *Farm Accounts*, los *Probate Inventorie*s y la cronología de las cosechas propuestas por Bowden (1967), Hoskins (1968) y Turner et al. (2001). El grado de precisión de la serie se confirma cuando la comparamos con la secuencia de los hechos ofrecida por Joan Thirsk (1990: 128-129) para el período 1646-1656: "*Bad weather ruined the harvest of corn and hay for five years from de autumn of 1646 onwards, and every succeeding year until the harvest of 1651 exacerbated the problems left by previous one* (…)". Pero después, "*food supplies in the mid 1650's were thought so secure that the Protectorate government finally passed in act in November 1656 permitting, and, indeed, encouraging their export*". Además, nuestra serie se ajusta bien o incluso mejor a las propuestas por otros autores, y muy especialmente, a las primeras mediciones del producto físico realizadas en el siglo XIX.

Figure 6.1. Producción de trigo en bruto en Inglaterra, millones de bushels, 1645-1656.

Fuente: elaboración propia. Obsérvese cómo el período de crisis de 1646-1651, y de recuperación en 1655, coinciden con los hechos presentados por Joan Thirsk (1990).

Los resultados del Capítulo I permiten también plantear algunas ideas y posibilidades que no forman parte de la pregunta troncal de esta Tesis Doctoral, pero que resumimos a continuación. Primera, la segunda parte del siglo XVIII fue un periodo de crisis productiva de la agricultura inglesa que no se superó hasta el fuerte despegue acontecido durante el siglo XIX. Según nuestras estimaciones, la revolución agraria inglesa tuvo dos momentos destacados: antes de 1750 y después de 1800. Segunda, la metodología aplicada se puede extender, con la debida precaución, para estimar una serie de cebada y otra de centeno. Tercera, esta serie de la producción física de trigo puede ayudar a reconstruir los balances comerciales trigueros y avanzar en la cuantificación de diversas ratios de variación anuales. Cuarta, puede ayudar a valorar la evolución productiva de cada condado o municipio en relación con la tendencia general de la producción triguera, y su importancia respectiva. Quinta, podría ser un primer paso para desagregar esta producción por variedades de trigo, algo que nos permitiría valorar las características cualitativas nutricionales de cada una de ellas. Sospechamos incluso que los cambios en la composición de nutrientes en las nuevas y resistentes variedades como las *Lammas*, y su mayor capacidad inmunológica, ayudan a explicar la sorprendente desaparición o gran reducción de las epidemias urbanas.

A partir de las estimaciones obtenidas en ese primer capítulo, las relaciones entre presiones climáticas, innovaciones agrarias y rendimientos de la tierra se discuten en el Capítulo IV (*Revisiting Allen's nitrogen hyphotesis from a climate perspective, 1645-1740)*, que a su vez se basa empíricamente en el documento de trabajo "*Did Climate Change Influence English Agricultural Development? (1645-1740)"*, sito en el anexo, y en los artículos posteriores. En éste se avanzaba ya una reinterpretación de la hipótesis del Nitrógeno expuesta por Robert Allen, sugiriendo una respuesta adaptativa de los agricultores a los impactos agroclimáticos de la última fase de la Pequeña Edad de Hielo. El clima más frío y húmedo de la segunda mitad del siglo XVII afectó negativamente el rendimiento de la tierra, pero también aceleró el cambio en el sector agrario. Los agricultores invirtieron parte de sus esfuerzos en enriquecer la reserva de nutrientes del suelo, logrando disminuir en parte el impacto del enfriamiento climático. La mejora del clima durante la primera parte del siglo XVIII, los avances agrícolas (aumento del stock de nitrógeno de origen orgánico del suelo), el crecimiento de la población, y un marco institucional más favorable impulsaron un aumento significativo de la producción y los rendimientos del trigo durante la primera mitad del siglo XVIII.

Las mejoras agrícolas se concentraron en una serie de prácticas que buscaron evitar la reducción de la tasa de mineralización del nitrógeno procedente de la biomasa a través de la descomposición de la materia orgánica del suelo. Algunas de las más destacables fueron las siguientes. Primera, mediante más rotaciones de leguminosas con el fin de fijar nitrógeno orgánico en el suelo. Segunda, frenando el largo proceso que se estaba dando previamente, de conversión de las tierras en barbecho a tierras en cultivo, que luego se reemprendió. Tercera, ralentizando el proceso secular de aumento de la superficie cultivada. Cuarta, manteniendo una separación permanente entre cultivos y pastos dentro de un sistema de agricultura convertible. Quinta, incrementando la tendencia secular de convertir en pastos los cultivos de las pesadas tierras arcillosas del centro de Inglaterra, y la de suprimir bosques en favor de cultivos y pastos causada por el cambio del modelo energético de la madera al carbón y la creciente demanda urbana. Sexta, mediante **e**l perfeccionamiento de las técnicas aplicadas a los pastos, como la reducción progresiva de las tierras comunales, el incremento de los cercamientos y la eliminación de las piedras del suelo. Séptima, con el mejor uso de las *water meadows*, una de las grandes innovaciones en la gestión de los pastos ingleses, que permitió reducir el efecto de las heladas en invierno, promoviendo el crecimiento temprano del pasto y una mayor producción de heno en verano, permitiendo luchar contra las adversidades climáticas mediante la gestión de la canalización con tiza y su cobertura para proteger el agua contra las heladas.

Estas innovaciones se mencionaron explícitamente en los debates de la Cámara de los Comunes a partir de cartas o informes remitidos a los parlamentarios desde la sociedad inglesa, tal como recogió Joan Thirsk (1990) en la obra antes citada: "*Discussions outside parliament that were deliberated directed at members of parliament were lively and stimulating, especially in the years 1649-56. Walter Blith addressed both houses of parliament in the introduction to his new book of husbandry in 1649, and in pointing out the main obstacles to agricultural improvement he bought the argument down to an unusual level of detail. In his view, they were: the absence of compensation to tenants for improvement...; contentions about water supplies between farmers and millers, which hindered the floating of meadows; the intermixture of land in common fields, which discouraged individual improvers; the grazing of common pastures without stint, which ruined the grass and which, once in every four or five years, caused outbreaks of sheep rot; men's failure to search for mineral fertilizers, like lime and chalk; their failure to eradicate moles, to plough up mossy, neglected land, to straighten water courses, and to preserve timber*" (1990:131-132). En aquellas circunstancias climáticamente adversas la capacidad de iniciativa de los agricultores ingleses fue un aspecto crucial que les distinguió de muchas otras partes del continente europeo. De nuevo en palabras de Joan Thirsk: "*The principal message of Blith's book was to urge all men to make the most of all their lands, whether arable, meadow, pasture, or woodland, and especially to promote tillage, for he held to the traditional view that this was the most profitable use of land both to landlords and tenants. To achieve this, he favoured leaving men complete freedom to use their best land as they wished.*[...] *Blith's book of 1649 inaugurated prolonged discussions on ways of improving agricultural output* [...] *Until good season return in 1652 parliament was preoccupied with curbing excessive food prices, preventing the waste of grain, prosecuting boarders, and curbing secret dealings; it gave little thought to positive measures for increasing food production. Six months after the first good harvest in many years, in autumn 1651, men began to take the full measure of national food production...*" (1990:131-132).

El Capítulo IV se centra también en darle otra 'vuelta de tuerca' al argumento de Robert Allen sobre la importancia del esfuerzo de los campesinos y propietarios ingleses para incrementar la incorporación de materia orgánica en el suelo, y la dificultad de establecer los incentivos económicos para hacerlo cuando sus efectos sobre los rendimientos sólo se producirían años después cuando aquel N orgánico hubiera sido mineralizado por los procesos biológicos que tienen lugar en el suelo. En este caso partimos de un modelo teórico donde se establece que la tasa de crecimiento del nitrógeno per cápita disponible en el suelo para el crecimiento de los cultivos es igual a la tasa de mineralización del nitrógeno orgánico (la variable tecnológica señalada por Allen) más la tasa de variación del parámetro climático (la variable omitida). En ese supuesto, el crecimiento se produce si la tasa de mineralización con la consiguiente absorción por las plantas y el clima mejoran, a través de su impacto conjunto en la tasa de variación del nitrógeno mineral disponible en el suelo per cápita. Si el segundo término es positivo, el crecimiento de la producción de trigo será aún mayor que si sólo observamos el cambio del manejo técnico que incrementa la materia orgánica incorporada en el suelo como humus.

A continuación, testamos empíricamente el modelo empleando la serie de temperaturas Engelen propuesta por algunos autores críticos con la serie CET, utilizada en los estudios anteriores. Además, se ha transformado la ecuación agronómica y estática de Allen en un modelo más multidimensional y dinámico que combina tanto variables biofísicas como económicas. Los resultados muestran que las variaciones climáticas importaban, pero a la vez se refuerzan algunas de las conclusiones de Robert Allen: las adiciones de nitrógeno en el suelo derivadas del cultivo de granos de primavera alternados con el trigo tuvieron un impacto significativo en los rendimientos, mientras que el efecto de las leguminosas fue importante pero mucho más lento. Las variaciones climáticas afectaban a los rendimientos tanto directamente como por sus efectos en los niveles de nitrógeno disponible en el suelo.

Sabemos que ese modelo es demasiado simple para recoger todas las complejas relaciones no lineales existentes en los procesos de descomposición que tienen lugar en la biota del suelo manteniendo o incrementando su fertilidad, tal como se ha explicado en detalle en el Capítulo III. Sin embargo, adaptarlo para ponerlo en relación con las principales hipótesis de esta Tesis Doctoral para poder comprobar empíricamente su capacidad explicativa con los datos disponibles ha demostrado ser un ejercicio útil con resultados relevantes. Esos resultados corroboran la intuición básica del artículo seminal que Robert Allen publicó en el *Journal of Economic History* en 2008 sobre la importancia de aquellos procesos de mineralización del nitrógeno en el suelo para entender la Revolución Agrícola Inglesa como innovación agroecológica. Y también ofrecen una respuesta clara a la pregunta sobre los incentivos que indujeron a los campesinos y terratenientes ingleses a buscar y encontrar maneras de reintroducir mayores dosis de nitrógeno orgánico en los suelos cultivados intensificando la recirculación de biomasa a través de nuevas formas de integración entre cultivos, pastos, bosques y ganado, al considerarlas una respuesta adaptativa a los impactos del enfriamiento climático en la producción agropecuaria.

El clima más frío y húmedo que caracterizó el período 1645-1715 afectó negativamente los rendimientos al reducir la actividad bacteriana y biológica del suelo y, consiguientemente la tasa de mineralización del nitrógeno orgánico, obligando así a los agricultores a compensar mediante mayores inversiones en plantas fijadoras de nitrógeno, mejores cultivos y semillas mejoradas. En cambio, el clima más suave que comenzó alrededor de 1715 mejoró los rendimientos independientemente de los esfuerzos de los agricultores, al mineralizar más rápidamente el stock de nitrógeno orgánico previamente acumulado. Por consiguiente, nuestros resultados ponen de relieve que la producción agrícola (trigo, cebada, centeno) aguantó mejor que en otros lugares de Europa la presión de la fase fría gracias a reintroducir más nitrógeno y materia orgánica en los suelos agrícolas, permitiendo un despegue productivo superior cuando el clima mejoró durante la primera mitad del siglo XVIII. Ese resultado no sólo permite explicar mejor los inicios de la Revolución Agrícola inglesa, també concuerda históricamente con los datos comparativos entre Inglaterra y Francia reunidos por Axel Michaelowa (2001).

Cuando sus iniciativas ya no tuvieron que compensar tanto los efectos negativos del enfriamiento sobre la mineralización del nitrógeno orgánico del suelo y la duración de la temporada de cultivo, los campesinos y agricultores ingleses encontraron que los nuevos métodos de la agricultura mixta agroganadera adoptados temporalmente como respuesta al enfriamiento climático previo eran más productivos y rentables que los antiguos. Las interacciones entre clima y población abrieron la puerta a un lento cambio estructural durante la segunda mitad del siglo XVII, fortaleciendo y promoviendo las adaptaciones del sector agrario. Esto nos lleva a concluir que los rendimientos observados por la literatura previa subestiman (en el período frío) y sobreestiman (en el periodo cálido posterior) las prácticas agrícolas en relación con las influencias ambientales durante aquellos dos períodos respectivamente. La incorporación de las variables ambientales contribuye a una explicación más completa de la precocidad de la Revolución Agrícola Inglesa durante un periodo de condiciones climáticas más duras, que pudieron ser enfrentadas gracias a unas innovaciones que se después de convirtieron en una importantísima herencia biocultural de los campesinos ingleses.

El Capítulo III muestra que las interacciones clima/agricultura no eran siempre directas, sino que estaban mediatizadas por otros factores sociales y ambientales. En el artículo publicado por el equipo liderado por Enric Tello en el *Journal of Interdisciplinary History* mostramos como entre el enfriamiento y los rendimientos mediaban las innovaciones de los agricultores ingleses. A partir de la hipótesis del nitrógeno de Allen, de los modelos utilizados en la ciencia del suelo y un conjunto de pruebas cualitativas, deducimos que los agricultores ingleses diversificaron sus cultivos en la segunda mitad del siglo XVII, probando nuevos métodos de fertilización, para adaptar su agricultura tanto a un cambio climático como a cambios en el mercado. Cuando sus iniciativas ya no tuvieron que compensar los efectos del enfriamiento de la mineralización del nitrógeno del suelo y la duración de la temporada de cultivo, descubrieron fortuitamente que los nuevos métodos de agricultura mixta que habían adoptado de manera contingente eran más productivos y rentables que los anteriores.

No es casualidad que estos hechos arrancaran después de 1645, ni que muchas de las variables socioeconómicas del periodo estuvieran asociadas al suceso climático. A corto plazo, los impactos fueron generalmente adversos. En el ámbito agrario, como ya hemos visto, el descenso de las temperaturas y la alteración de los regímenes pluviométricos locales afectaron las cosechas y los rendimientos del suelo alterando los niveles de nitrógeno y el ciclo de nutrientes del suelo. Pero también afectó al consumo rural, una cuestión dejada al margen por las corrientes interpretativas predominantes, que han estado centradas hasta ahora en la fuerza tractora de la creciente demanda urbana. La necesidad de disponer de más energía en forma de comida, fuera para el propio consumo familiar, la comunidad rural campesina o para el mercado, empujó a los agricultores a experimentar mejoras mediante el "método prueba-y-error", con plantas fijadoras de nitrógeno, mejores cultivos y semillas mejoradas. Un buen ejemplo de esto último fueron las variedades de trigo *Lammas*, más resistentes y con un buen contenido en gluten y otros nutrientes.

El Capítulo V se centra en analizar el problema desde el punto de vista de la energía y el trabajo, y en como estos elementos condicionaron el sistema económico preindustrial británico. El flujo de la energía externa e interna de la Tierra se transforma en temperatura, precipitación y otras variables climatológicas. El sistema biofísico proporciona servicios ecosistémicos de apoyo vital en energía a la economía, a través de plantas, animales y minerales (transformados en alimentos, leña, carbón mineral, fuerza animal y abonos). En este ámbito, encontramos una relación teórica muy sólida entre los efectos del enfriamiento sobre el esfuerzo humano/trabajo y el incremento del consumo calórico endosomático (alimentos) o exosomático (leña, vestido, carbón mineral).

A partir de la teoría del salario natural en función del nivel de subsistencia de David Ricardo y Robert Malthus, mejorada por autores posteriores como Harvey Leibenstein (1957), Christopher Bliss & Nicholas Stern (1978) o Joseph Stiglitz (1976), desarrollamos un modelo teórico que relaciona el aspecto más físico de la energía con la esfera económica del trabajo. El aumento de la necesidad per cápita de energía implicaba, primero, un desplazamiento hacia arriba de los salarios de subsistencia (ingresos) en toda la economía; segundo, un aumento de la probabilidad de divergencia creciente entre la productividad y los salarios de los sectores rural y urbano; tercero, una divergencia evolutiva entre las fincas comunales y las capitalistas, incrementándose la productividad en las fincas comunales, y por contra subiendo los salarios de eficiencia y reduciéndose la fuerza de trabajo por acre en las granjas capitalistas; y, cuarto efecto, generando una mayor percepción social del desempleo y subempleo. Estas predicciones parecen confirmarse mediante modelos econométricos, así como analizando los trabajos y estimaciones ofrecidos por algunos de los autores principales que han escrito sobre la materia, y un repaso de la literatura existente y de la historia del pensamiento económico.

La población inglesa era en su mayoría pobre y con salarios de subsistencia concentrados en alimentos, ropa, vivienda y energía para quemar y calentarse. Así que, para gastar un poco más en más energía que antes, necesitaban que sus ingresos de subsistencia mejoraran. Los salarios (o ingresos) de los dos sectores (agrícola y no agrícola) comenzaron a crecer, pero a diferentes velocidades, abriéndose una divergencia a favor del sector no agrícola. Pero, en cualquier caso, el aumento del fondo salarial agregado fue uno de los factores que conformaron el notable crecimiento del PIB per cápita británico en la segunda mitad del siglo XVII. El argumento malthusiano explicaría alrededor de la mitad del aumento, y nos planteamos si la otra mitad podría ser explicado por razones energéticas derivadas de los cambios ambientales. Nuestros resultados nos llevan a sugerir que el aumento de la ingesta calórica procedente de los cereales estimado por Broadberry et al. (2015) es insuficiente. Según los datos que manejamos, la cesta de la compra básica británica se volvió "más energética" (es decir, contenía mayor ingesta calórica) como respuesta adaptativa al cambio climático en curso y la creciente demanda de trabajo.

La novedad importante que este estudio plantea es que las transformaciones económicas que tuvieron lugar durante aquella etapa ocurrieron por doquier, en el campo y en la ciudad. La innovación no vino solo por la demanda urbana, sino también por la demanda rural, ya que todas las personas necesitaban consumir más energía en diferentes modalidades (alimentos, calefacción y transporte) per cápita. Esto es importante, porque se ha tendido a considerar la aportación del mundo rural como algo secundario, solo destacando sus innovaciones desde la faceta productiva pero no desde el consumo rural como elemento tractor. En los albores de la Revolución Agrícola Inglesa puede que el factor clave no fuera únicamente la demanda urbana ni la comercial, sino simplemente algo mucho más sencillo: un aumento general de las necesidades de energía per cápita.

Ésta es la hipótesis principal con la que se cierra el Capítulo V, donde se efectúan algunos primeros contrastes estadísticos con la información que está más fácilmente disponible que han obtenidos resultados prometedores. Reconociendo que esa hipótesis requiere de análisis más profundos, también se convierte en uno de los avances que se espera poder desarrollar a partir de esta Tesis Doctoral. Estudiar los vínculos entre los salarios agrarios y no agrarios desde una perspectiva de la energía, y de forma comparativa entre las *villages* de los *open fields* y las fincas capitalistas conectando su evolución con el conjunto de innovaciones agrarias incluyendo el recurso a nuevas variedades y productos puede abrir nuevas perspectivas a temas muy clásicos de la Historia Económica que distan mucho de estar ya cerrados.

En resumen, las investigaciones aquí presentadas sobre el período 1645-1740 en Inglaterra muestran claras evidencias de una serie de relaciones significativas entre las variaciones climáticas y económicas. Esto nos lleva a concluir que el clima importaba en la historia económica preindustrial inglesa. Sospechamos además que fue un factor importante, uno más, en el despegue económico británico y el inicio de la doble divergencia: la pequeña, entre las economías de Holanda e Inglaterra con respecto al resto de Europa; y la Gran Divergencia, entre aquel núcleo de la nueva economía Atlántica respecto de Asia y el resto del mundo. En este sentido, el punto cero de los inicios del crecimiento económico moderno lo situamos alrededor de las décadas centrales del siglo XVII. Los efectos principales de aquellas relaciones entre economía, clima y medio ambiente se canalizaron a través de los vínculos principales que conectan los procesos biológicos con el sistema social: las plantas, las personas, y la energía. De todos los factores de crecimiento, estos conectores estaban especialmente centrados en la Tierra y el Trabajo, es decir, en la agricultura y el trabajo físico y mental que requiere. Nos equivocamos si la historia económica o la economía se enrocan fuera del sistema ecológico de la Tierra, como tan bien demuestra la presente crisis del Covid-19.

Esperamos que este trabajo abra algunas perspectivas interesantes, que ayuden a impulsar contenidos y métodos más innovadores y menos cerrados en una sola ciencia, más transdisciplinares, compartidos y cooperativos. Que permitan el desarrollo de nuevos modelos mixtos, combinando variables biofísicas y económicas, y adoptando además un enfoque dinámico. Que permitan capturar las adaptaciones y que, a través de su desarrollo futuro, permitan simular escenarios más próximos a la realidad. Todos esos avances permitirían profundizar en cuestiones de gran relevancia para nuestra sociedad actual, y abordar nuevos trabajos similares o mejor elaborados que esta Tesis Doctoral con una visión más amplia y evolutiva de la economía.

También pensamos que los modelos y resultados de esta Tesis Doctoral pueden ayudar a que se realicen estudios similares en otras regiones del mundo que nos permitan responder la pregunta sobre "por qué ocurrió lo que ocurrió y como ocurrió" en Inglaterra y no en otros lugares. Creemos también que esa nueva mirada, con la energía y el medio ambiente como hilo conductor interaccionando con los procesos económicos, puede ser un ejercicio transformador para la propia economía y la historia económica que ayuden a reconsiderar muy seriamente el papel del mundo rural. El autor de esta Tesis Doctoral cree que fue más importante de lo que generalmente se piensa como tractor del desarrollo económico británico. Y también que está llamado a jugar nuevamente un papel de gran importancia para lograr una prosperidad sostenible en el siglo XXI.

Final Appendix. Did climate change influence English agricultural development? (1645-1740)[106]

1 Background

So far, the impact of climate on English agriculture has been little studied. We have a few references on its dynamics in the short and long term, but there is little research linking the LIA (the Little Ice Age) or Maunder Minimum (1645-1715) to the Agrarian Revolution and the possible adaptive response from the farmers[107].

It is well known that during the 17th century the weather in England generally worsened. This phenomenon has been related to a long fall in the solar activity, the Maunder Minimum[108], but this solar minimum is likely to have coincided with other adverse climatic forces[109]. In any case, average temperature fell but rainfall variability and humidity increased[110]. Production of dry materials from crops decreased more, in proportion to reduced solar radiation absorbed by plants[111]. The energy balance between the heat latent in the soil and the evotranspiration levels of the plants, as well as photosynthesis processes and respiration became more unstable.

A past generation of agrarian historians has ably examined the issue of climate. In their pioneering works, W.G. Hoskins (1964, 1968), E. L. Jones (1964, 1965b: 155-156), Kerridge (1967) and Bowden (1967: 617-620-623) demonstrated the role of climatic anomalies during 1680-1730 in 'breaking' the cycles of good crops, spreading epizootics amongst livestock, and promoting changes in soil management. Since the decade of 1980, a second generation of historians has followed (Overton, 1989, 1996; Turner *et al*, 2001, 2003); and other authors have studied the relationship between climate and demography (Galloway, 1985, 1986; Appleby, 1979, 1980). Recently, a third group of studies have appeared, which have tried to measure the relationships between climate and agriculture using econometric methods during that period, including recent studies published by Michaelowa (2001), Brunt (2004, 2014) and Waldinger (2014).

The first and second generations of agrarian historians identified excess water in summer and frost in spring, not drought, as the main threats to crops. Moreover, they inferred

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[106] José L. Martínez-González, 2015. "Did Climate Change Influence English Agricultural Development? (1645-1740)", *Working Papers 0075, European Historical Economics Society* (EHES).

[107] Adam Smith (1778: 253, 256, 259), W.H. Beverigde (1921), G. Stanhill (1976:2), Kelly and O'Grada (2014a), L. Brunt (2004, 2014), W. G. Hoskins (1964, 1968), G. Utterström (1955), E. L. Jones (1964), A. B. Appleby (1978, 1979, 1980), P. Bowden (1967), M. Overton (1989), A. Michaelowa (2001), R.W. Hoyle (2013) and M. Waldinger (2014).

[108] The astronomer Jack Eddy published in the magazine *Science* (1976; 1189-1202) a famous article in which he provided scientific evidence of the existence of this solar minimum, named after the English astronomer who discovered it, E. W. Maunder (1851-1928). See also Parker, 2013.

[109] Increase of clouds, volcanic dust and fluctuation in the North Atlantic. See Lean *et al* (1995), Luterbacher *et al* (2001, 2010), Guiot *el al* (2010), Yasuhiko *et al* (2010). Büntgen *et al* (2013).

[110] Luterbacher *et al* (2001); Büntgen and Hellmann (2014); S. White (2014); G. Parker (2013).

[111] According to the mechanism reasoned by Monteith, (1977:279).

some connection between certain agricultural techniques and the worsening of climatic conditions (Jones, 1965; Bowden, 1967). They related the spreading of water meadows and the enclosure of pastures to offer additional fodder in place of open fields[112]. Second, cold in spring and too much rain in summer damaged wheat more than cheaper cereals or pulses, which became an alternative to wheat. Not only could they be substitutes in case of a bad crop, but they also allowed greater cattle-raising which would also contribute to crop improvement increasing manure (Jones, 1965; Bowden, 1967; Overton, 1989; Turner *et al,* 2003; Hoyley, 2013). In fact, studies show evidence that farmers were aware that the spread of such agrarian techniques were aimed at overcoming climate disturbances (Jones, 1965b; Overton, 1989; Appleby, 1979, 1980; Hoyley, 2013).

The latest econometric studies started by A. Michaelowa (2001) have shown a clear relationship between climate trends and economic growth, proving that the climatic amelioration between 1700 and 1740 stimulated British population growth and agrarian production. Following Pfister's works in Switzerland (1988), he found a clear link between climate change (the Maunder minimum) and cereal prices[113]. The fall in prices during the second half of the18th century encouraged investment and innovation, and since the prices of meat remained stable, a combination of cattle-raising and grain crops was favored. Therefore, the consumption of food helped the middle and lower classes grow, although the hotter summers kept mortality high. L. Brunt (2004) also proved that the main driving forces of British wheat production in 1770 were climatic and technological[114]. Waldinger (2014), by means of panel statistical techniques, connected rising temperatures with falling wheat prices in northern cities and rising prices in the south. This pattern of results suggests that temperature changes are related to changes in agrarian production (2013:3)[115].

There are also complex issues of agrarian social change. The traditional historiography focused on enclosures, the size of the farms and the leadership of "learned pioneers" during the 18th and 19th centuries. However, the historiographical focus shifted to the study of open fields and to an earlier period, 1650 to 1750[116]. This started with E. L Jones (1965a), who proposed some important ideas: first, improvements were carried out between 1660-1750; second, these improvements were applied both in open fields and enclosures (an integrated position, very close to the results in my research); third, the different types of soil (light or heavy) had an influence on these improvements; fourth, there is an apparent contradiction between the fall in the relative prices (fall in the prices of wheat and the rise or stability of cattle prices), and the low demand (caused by a population decrease or stagnation in spite of incipient urban growth). Jones's originality, not overcome yet, lies in his hypothesis claiming that agrarian investment had different

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[112] E. L. Jones (1965b:155-156). Jones would deal with this issue in 1981, when he connected warm weather with advantages in agricultural techniques and innovations (Dell *et al,* 2013).

[113] Michaelowa (2001:5).

[114] L. Brunt, (2004:219).

[115] In the same way, the changes generated by temperatures in small towns were bigger than those generated in big cities, and much more diversified.

[116] Allen (1988, 1989, 1991, 1992, 2005); E. L. Jones (1964, 1965); J. Thirsk (1967, 1984, 1985, 1997).

speeds and its protagonists were changing, i.e. there were different waves of innovation, an idea which will be dealt with later on in this work. According to Jones, tenants were the first to increase their investments when landowners were doing just the opposite, and later the efforts of landowners increased whereas those of the tenants fell. All this taking into account that the types of investment were different: tenants invested in land management and cattle, whereas landowners invested in infrastructures and facilities (Jones, 1965a).

This debate was revived in the works of Robert Allen (1992) and Mark Overton (1996) amongst others (Campbell and Overton, 1992). Whilst the former agreed with Jones's thesis emphasizing the leading role of the yeomen in the spread of agrarian innovations, especially during the period 1650-1750 (Thirsk, 1967, 1984, 1985, 1997), Overton followed the tradition that linked agrarian innovation and enclosure processes (Chambers and Mingay, 1966), placing the period of increase in yields in the second half of 18th century and giving more importance to the landowners' investment (Overton, 1996).

Robert Allen was one of the economic historians who related the exceptional growth of labour productivity between 1600 and 1800 to the rise in the yield of cereals and the merger of little fields into great capitalist country estates, reducing the employment rate per acre[117]. In his search for the "Holy Grail" of yields he stated that the improvement of the yield of the land was due both to the increase of nitrogen stock (convertible agriculture, growing of pulses, sainfoin) and higher efficiency in its use, thanks to the changes in the way of growing and working the land (new tools and seeds, better labour). According to Allen, the word "revolution" needs qualifying: the process of change to higher yields was gradual, due to the slow growth of the stock of nitrogen in the land[118].

Allen suggested the Standard Model of Nitrogen as a starting point[119]. However, he did not take into account the temporal variability of the stock of nitrogen **(N)** or its mineralization rate **(r)**. This variability can be explained, directly or indirectly by changes in temperature, rainfall, solar radiation and volcanic aerosols. For example, it is difficult to accept a constant ***r*** in long periods, since it decreases during climatic cooling[120]. Ceteris paribus, lower temperatures and shorter growing seasons lead to a lower mineralization rate and a slower loss of the stock of organic matter in the soil (OM) and humus[121].

It is well known that after 1645-46 the climate of England became colder and wetter, a fact that reduced ***r*** and the decomposition speed of OM. There seems to be historical evidence that farmers struggled to avoid this. Farmers engaged in the following practices in order to maintain or increase OM: (1) including more pulse rotations in order to fix

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[117] Allen (1988:62).

[118] Allen (2008). See also the argument of Mark Overton (1996), who considers the period after 1750 as the one showing the greatest changes.

[119] Allen (2008:188).

[120] Loomis *et al* (2002:190-191).

[121] H. Jenny (1930). As Loomis *et al* stated, "the sensitivity of the balance level of humus to temperature and rainfall means that many changes may occur in the CC" (2002:191).

nitrogen in the soil; (2) slowing down the conversion of fallow land to crops[122]; (3) slowing down the increase of the cultivated area[123]; (4) maintaining permanent separation crop-pastures[124] within a convertible system, the results of which were brief and which was used out of necessity or interest[125]; (5) replacing crops with pastures, in both uplands[126] and lowlands[127]; (6) opening new pastures; (7) with improvements of the techniques applied to pastures, such as the progressive reduction of common lands, enclosures and stone removal and finally use of water meadows. To Allen, one of the most impressive aspects of agrarian change was the increase of pasture and the reduction of communal tenure[128]. Besides the strong increase in surface (from 4 to 9 million acres between 1600 and 1700, and from 9 to 12 million between 1700 and 1750), two other relevant changes occurred; one related to communal pasture enclosures and the other related to the technological improvement. In the highlands of England and Wales enclosing pastures increased their productivity, since enclosures were made with the stones from the pastures and their removal from the surface improved yield. In short, Allen draws our attention to some key developments in English agriculture, such as changes in pastures management and the improvement of their yield. This could have begun an increase of the OM stock.

Another great qualitative advance was the better use of water meadows. During the period 1645-50 the "difficult" technique of floating started to become relevant, even giving rise to professional floaters. Although it was not new, this system was considered to be one of the great innovations in the management of English pastures by J. Thirsk and E.L. Jones[129]. There were "water" pastures placed next to rivers or streams of water, driven to produce rich hay crops and stimulate grazing, with canalizations that allowed a continuous water flow at particular times. Through floating, mud rich in nutrients settled and a beneficial oxidation of the soil occurred. This technique also allowed a reduction of the effect of frost in winter, promoting early grass growth and higher hay production

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[122] This process became stagnant during the 1650-1700 period: 3.24 million acres in 1500, 2.16 in 1600, 1.88 in 1650, 1.91 in 1700, 1.59 in 1750, 1.28 in 1800 (Broadberry *et al,* 2011b:30, table 10).

[123] The data show a decrease in the total cultivated land from 7.74 to 7.64 million acres between 1650 and 1700, in contrast to its long-term rise since 1450 (Broadberry *et al*, 2011b:30, table 10).

[124] See Overton (1989: 291) or A.Smith (1778:286). Despite the generation of manure in barns (winter), the division system between pastures and crops was relatively inefficient (Shiel, 1989:666-67). On the contrary, it was a OM reserve: with the increase in the new rotation systems, the "night manure", the new ploughs and the changes in agrarian constructions, this reserve allowed higher productivity.

[125] Although Kerridge focused the agrarian revolution on the up and down or convertible agriculture (rotation of pastures into crops and vice versa), E.L. Jones (1965a:156) and Shiel considered it of little importance during the 17th century (Overton, 1989:293-294). Despite the important release of nitrogen through the ploughing of these pastures, in a few years the situation became the same or even worse (soil acidification). Overton even pointed out that there was scarce written proof of its feasibility in the probate inventories. Neither did Kerridge provide enough proof, so this issue had to be further researched into.

[126] Broadberry *et al,* quoting Grove, 2004, and admitting the *LIA* (2011a:9).

[127] Because of the long trend to turn crops from the heavy claylands in the centre of England into pastures (Bowden, 1985: 47-48, 55-56, 61-62). According to Broadberry *et al*, the importance of pastures in England was increasing, including permanent pastures. There was a process of elimination of forests in favor of crops and pastures with the change of the energy model from wood to coal. The increasing urban demand also stood in need of more permanent pastures to the detriment of permanent crops.

[128] Allen (2005:6).

[129] J. Thirsk (1985, pp. 180-181, E.L. Jones (1965a, pp. 155-156).

in summer. Water meadows yielded up to four times the usual quantity and density of hay, which enable the year-round feeding and early breeding of livestock. Water meadows allowed one to struggle against climatic adversity by the management of canalization with chalk and covering to protect water against frost. This water was later drained and many essential nutrients for plants were collected. With all this the quantity of sheep and cattle could be kept and even increased in winter and summer as well, producing much more manure, OM, and nitrogen. If it were not for this system, the impact of the climate change on livestock would have been more intense.

But the quantity of mineral nitrogen (in Allen's model, F is the level of free nitrogen) does not only depend on **r** and **OM** variability. First, there is a direct input flow (rainfalls and free, non-symbiotic fixation) and output (denitrification, volatilization and leaching), which also depend on the climate, besides other factors[130]. Allen assumed that this input and output were balanced, but in colder and wetter periods this balance could be uneven. We must remember that the microbiological processes of the soil depend on temperature, water and pH. Microbial activity slows down at low temperatures, affecting the speed of decomposition of OM. One of the processes of mineralization, ammonification, generated by microbial matter, is also very sensitive to temperature. The increase of humidity promotes denitrification, so that N returns to the atmosphere as gas in a greater quantity. On the other hand, there are some factors which affect the performance of pulses and the N quantities yearly fixed. The assimilation and fixing of N is proportional to biomass production, so that if biomass declines in colder weather, N fixing also declines[131].

Besides N content, climate influenced fertility in other ways, including the content of phosphorus, potassium, and acidity in the soil, and the germination and growth of plants. In the case of phosphorus, although its function has been historically minimized[132], Newman and Harvey pointed out that it could have been the main soil fertility factor until the 19th century[133]. Phosphorus generation (from OM mineralization) is usually deficient during cold periods. That would mean that during the LIA (in the long term) its replacement management had to be improved. Climate change also affected the development phases of plants. The flowering period of the winter variety of wheat was critical and frost or a deep temperature fall could ruin the crops. The wet and cold springs, typical of the second half of the 17th century, would therefore affect agrarian production, forcing farmers to introduce new seeds such as Red-Stalked Wheat in 1670 (Oxfordshire), or White-Eared Red Wheat in 1650. As for barley, early varieties such as narrow-eared barley became predominant in the 17th century. These varieties were planted in May "better than in March" and stored in the barn in two months or less, becoming very

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[130] The increase in humidity and soil reflectiveness generates greater denitrification; the increase of urine in the soil generates greater ammonium volatilization and a greater humidity index together with higher nitrate levels from manure or urine cause higher lixiviation. (Loomis, 2002:225-229).

[131] Loomis *et al*, 2002, pp.209, 222, 230.

[132] Allen, 2008.

[133] Newman y Harvey (1997:136). On the other hand, pH seems to be affected by temperatures in the very long term. However, historiography indicates that farmers, in their struggle, increased their OM contributions, but they did it in a rather much wetter soil, which meant more acidification.

valuable in wet and cold springs typical of the climatic downturn, and were very well-known in Cornwall and widely planted in Oxfordshire[134]. Another variety which was widely spread was a spring barley, planted in Lincolnshire and typical northern species were successfully adopted in the south. All this makes me think that climate was an influential factor in seed selection, an issue still to be resolved[135].

Since this balance of factors was so weak, when crops grew in less than ideal conditions, slight variations in the environment could cause great variation in the yield and in the harvest index HI[136]. This fact explains part of the nitrogen variation in wheat output between 1660 and 1740 (graphic 1 in the appendix). For example, in the pre-industrial era, the nitrogen available to crops from rainfall and free nitrogen was as little as 6kg per ha per year. With a harvest index HI of 0.4 (at that time it must have been lower than today) and 0.02 kilograms of N/ha per kilogram of grain, it equalled about 120 kilograms of wheat on an average crop of 900 kilograms, that is 13.3 per cent of the total. With an elasticity of price for the demand of -0.4, this implied price variations of about 33 per cent. Consequently, slight variation of N caused by weather changes affected prices considerably[137]. This conclusion seems to be confirmed with the works by Liam Brunt (2014): not including climate in the calculation of yield distorts the agrarian historical series.

This revision of Allen's model allows us to see in more detail how climate change could affect agriculture, and to gather historical information about some of the adaptive measures adopted by the rural world[138]. However, apart from climate, there was another driving force, population. The stagnation of English population has been pointed out as one of the causes of the depression in prices of wheat in late 17th-century England and Europe, favouring cattle-raising and the diversification of consumption (Slicher von Bath, 1959; W. Abel, 1978). It is also known that wheat supply was higher than demand between 1650 and 1750. So, why did it continue to increase?[139]

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[134] Thirsk, 1984:68-169.

[135] Mark Overton, 1989, p. 90.

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

[137] I have supposed elasticity of 0.4 but some authors place to the figure as low as 0.1 (Fogel). This means that prices would be even more sensitive (133 per cent). A 900-1000 kg production of wheat was somewhat common in those times. R. S. Loomis (1978) estimated the N cycle on an English farm of the 14th century where 16.1 kilograms/ha of N were yearly produced. Rainfalls, free N2 and fixing with peas was 8 kilograms/ha of N, higher than that of the seed (2.5 kilos/ha), straw waste (2.5 kilos/ha) or manure (3.1 kilos/ha). If the direct contribution of N was already relevant by then, it is reinforced by the indirect effect of climate, catalyzing changes in almost all the processes that affected the yield of the crops as the ones mentioned above (fixing, waste, manure).

[138] For a critical review of Allen model, see E. Tello, J.L. Martínez, G. Jover, J. R Olarieta, R. García-Ruiz, M. González de Molina, M. Badia-Miró, V. Winiwarter and Nikola Koepke (forthcoming).

[139] Already in 1965, Jones rightly observed that offer was ahead of demand. Production improved in spite of stagnant demand, innovation and price deflation. In his article, Jones deeply studied the different ways adopted according to the different types of soil or farm activity (E. L. Jones, 1965a).

2 Models and methods

In an effort to explain these issues I consider three approaches: production, relative prices, and the Ricardian rent approach (R. Mendelsohn, D. W. Nordhaus, D. Shaw, 1992). First, we analyse the physical relationship climate-output in the short term. Then, we identify the driving forces of the agrarian market. Next, we infer the existence of adaptations. Finally, we try to understand the relationship between these driving forces and the different adaptive periods from at historical point of view. Since this is an analysis at the country level, econometrics is the main tool used, but also local research from primary sources would be necessary.

The starting point is a wheat production function (dependent variable) depending on land, labour and capital. In this research the main inputs are land and labour. A novelty, besides presenting the series of wheat, is including the "climatic box" as an explanatory variable. The objectives of this first approach are threefold: 1), since it seems obvious that the climate affects crops and land yield, if a relationship is detected, that means that the data are valid and we can continue to research; 2), this function includes climate as the main force in the short term, a fact that allows us to qualify Allen's model of nitrogen and lets us correct slants in the traditional estimates of the yield of the land; 3), it opens new possibilities in the research for evidence of long-term effects and adaptive processes.

Next, I try to integrate the supply and demand by inserting physical production into the market by means of the mechanism of relative prices. This way I try to determine the driving force of agrarian change. My proposal is to determine whether climate was a significant factor, together with population levels and agrarian improvements. The third step – and probably the most difficult one – goes into the relationship between climate and adaptations, by means of the production approach (analyzing separately the depressive and expansionary periods) and the Ricardian rent approach. Next, I try to consolidate my results from a double perspective, theoretical and historical. In order to do so, I analyze the combinations climate-population and I compare them to what really could have happened, i.e. what Economic History says.

3 Data

Climatic Data

Although the pre-industrial figures are scarce, as far as climate is concerned we have temperatures, solar radiation, volcanic dust and rainfalls (graphics 2, 3, 4, 5, 6, 7 in the appendix). We have a series of monthly records of temperatures which start in 1659, from several towns in the Midlands (G. Manley, 1974, series *TEMP*). Although there are other temperature series, they do not come from direct measurements of the soil, but rather recent reconstructions[140]. I have chosen Manley's series for various reasons: first, it offers monthly information; secondly, it is the only one coming from measurements on the ground, even when it is likely to contain biased calibration; the third reason is that they are temperatures from England; and the fourth is that, although I do not agree with it, it avoids the criticism by Kelly and O'Gràda (2014) and McShane et al (2011) about the reliability of proxy reconstructions of temperatures. Manley's series presents some limitations: One is that it starts in 1659, that is, after the phase of accelerated cooling began (approximately in 1645), so many years of analysis are missing (when we combine this series with other containing data prior to 1659, these data cannot be used). Another one is that it does not represent the whole country but only a few specific points of it, which makes us remember that we must never lose our perspective.

As for solar radiation and volcanic activity, we have the series *SOLAR_IRRAD* and *DVI_VOLCANIC_INDEX*, both present in Mann et *al* (2000). According to Lean *et al*, irradiation explains 74 per cent of temperature variations in the pre-industrial phase[141]. To J.L. Monteith and C.J. Moss, solar radiation falls on England in a nearly uniform way[142] and the different distribution of rainfalls determines the potential evaporation. The same Monteith established a positive relationship between dry material from the crops and the radiation intercepted. This could justify the use of radiation as an influencing datum. According to the author, most of the cultivated lands are in +/- 10% of 9MJ/m2 daily average per year. This means that the regional differences would have been caused by other factors, such as rainfall.[143]

Nevertheless, we do not have direct humidity, rainfall or weather instability records in the 17th century apart from the references written at the time by A. Smith (1778), Comber (1808) or T.Tooke (1838). However, some recent academic works are beginning to throw some light on this issue through May-August (summer) rainfall reconstruction in the south of England (Rinne *et al*, 2013, *RINN* series), rainfalls between March and July (spring-summer) in the east of England (Cooper *et al*, 2012, *RICH* series) and rainfalls between March and July (spring-summer) in the south and centre of England (Wilson *et al*, 2012, *WILS* series). I will use this series because I do not have any others. However, we must take into account that: a) they are reconstructions; b) measurements come from trees located in specific territories, when I am going to analyse the whole country; and c) it seems that rainfalls have a more local and diverse incidence than temperatures, depending upon many geographical factors[144].

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[140] One of them corresponds to those of J. Luterbacher's *et al* (2006), which presents the average European temperatures organized by seasons. A second reconstruction is the one developed by Guiot *et al* (2010), with annual temperatures April-September organized by latitude and longitude of the earth every 50º, being the most suitable in the case of England TAS_2_5W_52_5N (west of England, near Birmingham) y TAS_2_5E_52_5N (east of England, but near the sea), and reconstructed from 117 different intermediate indicators (including tree rings, historical documents, pollen and ice records).

[141] Global data, geographically speaking.

[142] J.L. Monteith and C.J. Moss (1977:277-278).

[143] Monteith (1977:280).

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

There is also another important issue. If we draw an individual graphic analysis, it is rather difficult to interpret trends as a whole. An innovative solution is to integrate the series in the same graph, standardizing them from their means and standard deviations, making them comparable. That makes me consider two ‘quantitative’ ways; the first is the one I use in this paper (by means of the original series); the second is an index that I call Climate Index of the Productivity of the Land (CIPL). Changing the weightings of each climatic input, several alternative CIPL series can be calculated (graphics 8, 9, 10, 11, 12, 13). In these series a climate worsening can be observed until the early 18th century. I have also tested how all the climatic indices have predictive capacity in the production of wheat (chart 2). However, it is essential to have the support of soil scientists and agrarian biologists available so as to be able to use these series.

Production Data; Wheat Annual Series in bushels

Since there are no monthly/annual physical measures of the output (volume and weight), I estimate the English production in bushels and kilograms[145]. To do this, I will use the influential equation Davenant-Jevons-Bouniatian (Wrigley, 1992), adjusted by means of the most reliable trend indicator: population[146]. Graphics 14, 15 and 16 in the appendix show the resulting series (wheat supply, moving average wheat supply and wheat production). We must distinguish wheat supply from wheat production. After the harvest, one part of the cereal is used as seeds for the land or food for livestock (there is even a part kept for other uses such as personal consumption or as a means for payment/exchange in kind). The resulting offer faces demand and the farmers’ expectations, so new factors come into play[147]. Underlying all these considerations, I obtain series of gross production OUTPUT_BUS, the one I use in the econometric modelling. We can see how the wheat

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[145] As an example, among more than 1500 “farm inventories” in Hampshire only two country estates offered this type of information punctually, so yield had to be calculated by using indirect procedures and period grouping. (M. Overton, 1989; P. Glennie, 1989:27, 257). Undoubtedly, thanks to the works by economists and historians we are closer to obtaining series of physical production, but the data is still fragmented in time and among counties. These figures were obtained through indirect calculations (Clark, Broadberry *et al*) or through works carried out from primary sources, in country state records or probate inventories. (Allen, Overton, Glennie, Yelling, Turner *et al*, Theobald) and also in specific regions. G. Clark’s series (2002) offers decennial information about the real output-based 100=1860 between 1550 and 1910. A series of Broadberry *et al* (2011b:31) presents an agrarian GDP based 100=1700 with annual information. The problem of this series is that, even with constant prices, the agrarian GDP in monetary units does not reflect the climate’s physical impacts properly. If adverse weather reduces crops 50 per cent but prices increase, let us say, about 100 per cent, the fall of the physical production is not visible in monetary values.

[146] The equation is $\boldsymbol{y = 0,757/(x - 0,13)^2},$ (Wrigley, 1992:139), where y stands for the price of wheat (G. Clark (2004, 2005, 2007), and x represents the proportion between the real quantity and the usual quantity. As the usual quantity we take the one supplied by Broadberry *et al* (2011b, 31) in 1700. The price of 1700 takes the unity. We deflate prices according to the population growth rate (taking Broadberry’s POP_INDEX to use data in a harmonic way) because it is the most consistent trend variable in wheat demand. I dismiss the use of the GDP deflator and other price indexes because of their lack of independence from the price of wheat. As for the controversial issue of the role of silver in prices, in this first estimate I have assumed its influence as neutral. Its inclusion is left for the future.

[147] Demographic pressure, urbanization, substitute product prices, imports, storage, inflation, production costs and social dynamics.

supply increases slowly and gradually, settling at over 30 million bushels. That means a progressive, soft growth; and consequently, as Allen states, the Agrarian Revolution was a long and slow process where farmers were able to adapt to changes.

When I put the series to different tests, its strength is surprising. First, I combine the series with gross climate data, without adding any other factors, using multiple regression models. If any relationship were detected, it could mean that the route is correct. Secondly, I check the crops chronology to see if it matches my series. Third, I contrast the results of the series with the figures partially obtained by historians and economists. If my series stays within reasonable intervals, my approach could be right, although there is still much to do. In all the tests, the results are acceptable, which means a lot, taking into account the fragility of the figures and the initial assumptions.

As for the econometric test, an explanatory capacity of 41 per cent is obtained (table 4 in the appendix), with only the temperature, rainfall, volcanic dust and radiation. Regarding the second test, the series proves what historiography says from price movements. Bowden suggested the existence of bad crops during the second half of the 17th century, from 1645-51, 1656-63, 1695-99, and good crops in 1664-72, 1685-91, 1714-24, and 1741-49[148]. Additionally, Hoskins qualified as deficient the crops from the years 1646, 1657, 1710,1711, bad or very bad those from the years 1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728, 1729 (workhouses for the poor appeared in the last decade of the 17th century and the government blocked all kinds of exports during the most critical periods); "average" years were 1699, 1718, 1719, 1720; and good years 1652, 1653, 1654, 1655, 1665-72, together with the 80s, generally good, and the periods 1700-1707 o 1721-23[149]. Finally, we have the sequence of the food riots, most of which occurred during the years of production fall[150]. All these data match my series.

A third proof of the reliability of the calculated series is that it matches the physical data provided by Broadberry *et al* in the decades 1650 and 1750 (table 3)[151]: around 1650 they give a figure of 27.01 million bushels with respect to the 27.12 that I obtain. By the mid 18th century, this comparison is also reliable: 31.48 against 31.89 million bushels[152]. Additionally, keeping the wheat surface constant (only as a first test), I obtain an average figure of 12.6 bushels/acre for the whole country in 1660, 14.8 in 1720 and 15.35 in 1730. Although it is difficult to compare with the research carried out using probate inventories or indirect estimates, given the regional differences, we find that Wrigley points out an average of 10 bushels of wheat per acre in the Davenant era, or from 13 bushels/acre in 1660 to 15 in the decades 1720 and 1730, according to Overton[153]. All this suggests that,

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[148] Bowden, 1984, p.56.
[149] Hoskins, 1968, pp. 20-22.
[150] B. Bohnstedt, 2010, pp. 33-54.
[151] Net output of seeds to grow or animal feeding.
[152] Broadberry *et al* (2011b:31)
[153] Wrigley (1992:140-141).

once again, the series seems to match. Overton himself provides the data of 14.5 in 1660-1679 [13.8-18.8], 15.9 in 1680-1709 [14.39-19.39] and 19.2 in 1710-1739 [14.86-19.86] for Norfolk and Suffolk (gross data)[154]. As for Lincolnshire he gives a figure of 15.1 between 1650 and 1674 [13.85-18.85], 14.7 between 1675 and 1699 [13.88-18.88], 16.5 between 1700 and 1724 [14.88-19.88], and 18.7 between 1725 and 1749 [15.56-20.56][155]. In Woodland and High Suffolk Theobald estimated 15.5 in 1660 [12.6-17.6], 17.5 in 1690 [15.44-20.44], 19.60 in 1720 [14.80-19.80] and 20.1 in 1750 [16.26-21.26][156]. Bowden obtained 10 bushels/acre in St. Horsham in 1682 [13.86-18.86] and 17.4 in Arreton in 1732 [17.91-22.91][157]. Finally, Allen provided the figure of 19 gross bushels/acre in England, in 1700 [13.97-18.97]. This last datum matches nearly completely my 18.97 bushels/acre[158].

4 Results and discussion

Production approach and climate

In this first contrast (chart 4), the function of wheat production in bushels (endogenous variable) is well-explained by the climatic parameters. Model 1 only includes the average temperature of the year, volcanic activity, solar radiation from last year and rainfalls from the present year and last. It can be claimed, then, that the series used are reasonably valid, since they prove the obviousness that climate (and not other factors) influences the wheat crops (41 per cent). The variables show the expected signs: more temperature and radiation increase wheat production, more volcanic aerosols and summer rainfall generate worse crops. A decrease in temperature by 1ºC and an increase of the summer rainfall by 50 per 100 (over the global average) resulted in a fall in wheat production of about two million bushels. If we add a reduction of 0.073 per 100 of solar radiation, which reduces production by another 1.4 million bushels, plus the increase of volcanic aerosols and the summer rainfall from the previous year, the effect accumulated on production is still larger. Besides being a solid result, it matches some works already mentioned (Brunt, Michaelowa) or those of Chmielewski and Potts, who proved the explanatory aspect of weather between 33 (grain) and 50 per cent (straw)[159]. In model 2 I add the two production

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[154] Between square brackets I include my estimates of the net and gross yields for that year.
[155] M. Overton (1989b:302-304).
[156] Theobald (2002:9).
[157] Bowden (1967:882-883).
[158] Allen (2005:32).
[159] Chmielewski & Potts (1995:43).

factors: the labour-energy factor[160] (graphic 17 in the appendix) and the land factor[161]. The level of global significance of this model goes from 41 percent to 68.6 percent and the signs of the climatic parameters remain the same, especially those regarding temperatures and rainfalls. Labour supply is not a significant variable, and that means that abundance or scarcity of crops may determine labour demand. Previous agronomic practice (land factor) shows wheat production from a previous year with a positive sign, i.e. a good crop led to another good crop and a bad crop led to a bad one; confirming Hoskins's wheat-price series theory[162]. Model 3 is a variation of model 2. The labour force variable has been removed and a fictitious variable has been included (EXP), which shows an institutional measure, the English mercantilist policy of protecting the national wheat market and exports incentives. This mercantilist policy is quite significant: the incentives helped increase wheat production but, globally, they don't carry much weight (about 3 percent), which leads one to think that excessive importance has been attached to it in literature[163].

One of the key forces in the relative prices, the climate

Models 4, 5, and 6 (chart 5) explore the statistical causes of the movements in the relative prices of wheat/cattle, wheat/pig production and wheat/milk production. Three main forces have been analyzed: climate (temperatures, rainfalls, volcanic activity and solar radiation), demography (annual population, annual birth rate, and annual death rate) and adaptation (mineral nitrogen of the current and previous years, experience and expectations)[164]. The good news is that the group of climatic, demographic and adaptation

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[160] This series is part of a second hypothesis which is not dealt with in this document. We know that the daily energy expenditure (DEE) depends on the basal metabolic rate BMR (the necessary energy to maintain the body inactive and without digesting) the physical activity level PAL. That makes $DEE = BMR \times PAL$ and in men $BMR = (14.7 \cdot M) - (5.6 \cdot TMEAN) + 735$, where M stands for the body mass index in kilograms and $TMEAN$ stands for the average annual temperature in grades centigrade (Froehle, A. W., Churchill, S. E., 2009, pp.96−116). According to the WHO, the PAL are between 1.55 and 1.77 (light activity), 1.78 y 2.09 (moderate activity) and 2.09-1.81 (heavy activity). Supposing a PAL of 1.71 and that *M* depends on the environment influence of the 13 previous years (TEMP), we obtain an estimated series of the male individual's daily gross availability in kilocalories which was 2,569 kilocalories in 1700. Broadberry's calculations show 2,162 in 1705, Allen's were 3,255 kilocalories in 1700, and 3,579 kilocalories according to Muldrew (quoted in Kelly, M. and Ó Gráda, 2012). Taking next Clark's agrarian labour force weight (2001:40) on population (datum by Wrigley *et al*, 1983) we obtain a second series with the number of workers and if we combine the two series we obtain a first approximation to the total gross availability of daily work-energy in England, adjusted with the increase of the worked days.

[161] This second factor is quantified by means of the proxy "wheat production of the previous years in bushels", which collects the previous agrarian experiences globally: harvest indexes, seed management and their content in nitrogen as well as the farmers' expectations.

[162] Hoskins (1968:17-19).

[163] Observing the three models, we can see that summer temperatures and rainfalls are solid variables, but volcanic activity and radiation are not. In model 2 they stop being significant and in model 3 only volcanic activity is. When we complete model 1 with agrarian or institutional variables, as the model becomes more explanatory, these two variables lose strength. In model 3, the result is apparently surprising. Although the wheat production of the previous year has the same sign as the current year, the one from two years before has the opposite sign; that is, a higher production two years before affected production in the opposite way. All this suggests that there were alternating cycles in the crops of 2-3 years.

[164] As temperature indicators I use TEMP (average temperature of the year), TEMP_1 (average temperature of the previous year) and TEMP_SQUAR or TEMP_SQUAR_1 (average squared temperatures of the

variables seem to offer a good and reliable explanation about the relative prices, although we must be very careful about the results and continue to investigate. In the case of PR_WHEAT_ PR_BEEF, the climate variables TEMP, TEMP_SQUAR and TEMP_SQUAR_1, RAIN_WILS_1, DVI_VOLCANIC_INDEX_1 and SOLAR_IRRAD seem significant. However, even if the temperature and volcanic activity signs are the ones expected (higher temperatures/less volcanic activity caused a decrease in the relative prices in favour of cattle, since wheat crops improved and their prices went down), the signs of rainfalls and solar radiation required another type of reasoning. Rainfalls and solar radiation, even if they are usually good for wheat production, are likely to have been even better for hay production, which lowered the cost of livestock. As for demographic variables (population, birth and death rates), they are significant and with the expected signs (more population or higher birth rate the previous year means higher production during the year and lower prices indicating adaptive adjustments on the offer, whilst the pressure of the demand during the same year pushes up prices). The rate of the global model determination might be too high (nearly 90 per cent), inviting its adjustment. Even if all the conditions of the OLS estimate occurred, we must take into account that the nitrogen content series IC_VAR_N_0_02 has been calculated on the basis of harvest indexes conditioned by temperatures. Besides, the source-series for its calculation, wheat output, has been estimated from a population index of Broadberry *et al*. All this indicates a certain degree of colinearity. The subsequent question is: what other series can we choose as indicators of agrarian improvements? So far and as a conclusion, three relevant explanatory forces for the relative price variations have been identified: climate, demography and adaptation. However, the statistical work must be strengthened. More research on the relative strength of each force is needed to develop a simpler and stronger model.

Long term impacts and adaptation

We find causality in the long term between temperature and wheat production at about 14 percent (chart 6)[165]. This leads us to research the relationship between climate change and adaptation from two approaches: the production and the land rent approach (Ricardian). Through the production approach it is possible to find out whether there was an agrarian adaptation or not regarding the influence of climate by dividing the period 1645-1740 into two parts, the first being the cooling phase and the second the phase of climate recovery, *but accepting instability in the degree of influence of each weather variable*. In each of the two parts the best model is selected, even if the influential climatic variables are not always the same. Using this strategy, the first results (chart 7) confirm

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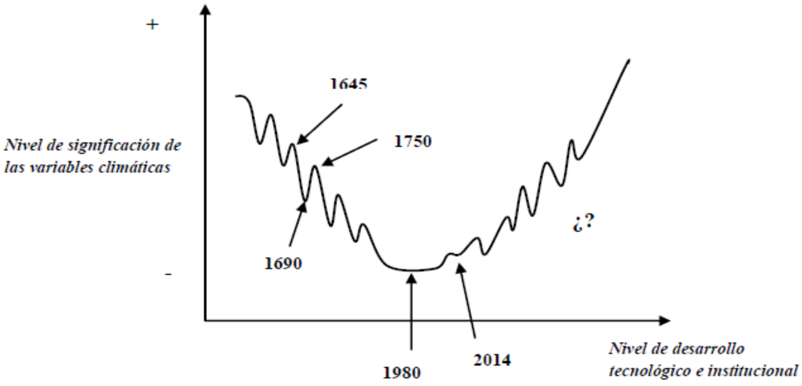
current and previous year). As rainfall indicators I use RAIN_RINN (summer rainfalls) and RAIN_WILS_1 (spring rainfalls of the previous year). DVI_VOLCANIC_INDEX_1 indicates the volcanic activity of the previous year and SOLAR_IRRAD indicates volcanic radiation. The use of squared terms is due to the possible non-linearity of the variables, and the lagged variables are used because this is economic history and the dynamic series contain relevant information in their past.

[165] Taking both series, we verify that they are stationary (augmented Dickey-Fuller test under a lagged variable and with a constant), as well as the cointegrated regression residuals.

that in the first period the climatic variables have less effect on wheat production[166]. That means that there were great efforts to lessen the climatic shock from 1640 to 1660, at the beginning of the Maunder Minimum[167]. This conclusion can be supported by means of direct contrast with dummy variables[168] (chart 6b) or with the endogenous Bai-Perron test (chart 6c), avoiding the division of the series and the resulting reduction in the number of observations[169]. The detected breakpoints are 1664, 1700 and 1730. From a far more general point of view, the British case shows us how, even if the long-term trend of the global significance of climate on the economic system is decreasing, during shorter periods the paradox of phases during which the climate recovers its explanatory capacity may occur (graphic 22).

Graphic 22. Level of influence of climate in the very long term



Source: compiled by the author

An alternative approach is that of the land rent (Ricardian Approach), developed by Robert Mendelsohn, William D. Nordhaus y Daigee Shaw (1992), frequently applied in current studies on climate impact on agriculture. It is based on the idea that the function of production does not measure agrarian adaptations correctly and overestimates damage (or at the most it equals it). On the other hand, the function-rent (or soil value) measures improvements and innovations in a better way. According to Clark's decennial rents (2001), there seems to be a long-term relationship between climate change and land rent,

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[166] I chose three breakpoints: 1689, 1700 and 1715.

[167] There are three aspects to be taken into account: first, that the climate impact is asymmetric. When it harms us we react more dramatically; when it benefits us we relax. This means that during the cold period farmers worked hard to overcome the difficulties, increasing the content of nitrogen, cushioning the environmental impact of the climatic variables. On the other hand, when the weather improved they did not need to struggle so much, so *the explanatory capacity of the climatic variables was higher*. Secondly, the relationship climate-agrarian production is a reflection of human activity and must not be considered an input, on the same level as those supplied by the farmer. Therefore, the agrarian improvements boosted the positive effect or climate in the short term. Third, since 1700 the critical episodes were more isolated (although hard) as in 1709, 1714, 1727 and 1739, catching farmers off their guard. This leads to a major explanatory capacity of the climatic variables, since the previous phase, more changeable, cold and wet, allowed the farmer to be more prudent.

[168] The influence of temperatures on wheat production becomes stronger by 18 per 100 from 1700, and the negative impact of summer rainfalls, comparing their rates, decreases by 41.3 per 100, also from 1700.

[169] J. Bai and P. Perron (2003).

i.e. the existence of agrarian adaptation (chart 8). Higher temperatures and more abundant spring rainfalls seem to increase the rents in the long term. When the climate favoured cereal production, prices were brought down and so were the rents. Therefore, the fact that the rents increased (or remained the same) in the long term means that landowners were able to keep their income or increase it, either innovating and diversifying their activity towards cattle production or pressing tenants further[170].

The last step is to compare what is expected to occur when the two main forces, climate and population, are combined (the theory, Schema 2), to what history says (Schema 1)[171]. From this comparative analysis four phases appear: first, unfavourable climate and increasing population (1645-63); second, alternating climate and stagnant or decreasing population (1664-1691); third, unfavourable climate and initial stagnant population increasing later (1692-1700, 1708-14); fourth, favourable climate and increasing population (1715-1750, especially from 1730)[172]. It is observed that, after the climate shock at the end of the 1640s, farmers managed to maintain wheat production and even increased it gradually when the temperatures or the rainfalls were more favourable (since 1664). This, together with a period of demographic stagnation and lower demand, led to a medium-term decrease in the price of wheat. Meanwhile, there was also a climate impact on cattle breeding, which stagnated, and so there was a process of diversification towards sheep. Since demand was depressed, livestock prices tended to remain relatively stable or increased (except mutton prices, which fell). Therefore, the balance of prices wheat/livestock products favoured the second. That makes me think that climate, population, and the agrarian capacity to adapt were key forces for relative prices, as long as the institutional environment was favourable, since it was a key element which made England different from the European continent. Finally, this first analysis allows us to understand better the consecutive innovative waves carried out by Yeomen and Landlords and also what the socioeconomic dynamics were (Schema 2). During the climatic shock (1645-1663), the mineralization rate of nitrogen and the harvest index fell. Wheat production decreased when the population was growing. All this led to a period of high prices, a stagnating demand for goods and agricultural labour, with a consequent decrease in real salaries, higher rural unemployment, a rise in land rents and more inequality. Neither did institutions help, given the existence of wage ceilings and migration controls in the counties. The number of landless would increase, the diets and life conditions of the tenants and workers would worsen, leading to social and political unrest. It is likely that the first wave of innovation came from yeomen and small farmers. It was necessary to maintain the prosperity of the community, expanding the areas of arable land and marginal plowing. The area of land devoted to cattle-raising had to be reduced. Farmers

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[170] However, although the model is valid, the sample is too small. It would be very interesting to have an annual rent series or to do future research using primary sources to guarantee these results.

[171] All this is proved by means of the econometric analysis of the structural break points detected with the production approach (charts 6b and 6c), specifically the years 1664, 1700, 1715 and 1730.

[172] It is important to point out that within the period 1664-1691, there is a period of bad crops, during the 70s.

resorted to convertible agriculture. Seed management made a huge leap forward. According to E. L. Jones (1965), innovation was spread faster among light soils.

When climate conditions improved (1664-1691), it was the landowners' turn. The previous reaction by the farmers increased organic matter supply. On the other hand, milder weather made the flow of nitrogen into the soil easier. All this helped to improve production and the wheat harvest index. In the meantime, the human and animal population stagnated and even fell, leading to a decrease in cattle yield, although urban growth was unchanged. The prices of wheat and mutton fell, whereas the rest of cattle products rose or remained stable. This way, the well-known process of a descent in relative prices started. Real salaries rose or remained stable but the opposite happened to land rents. Institutions became more favorable, stimulating both new written works on agriculture and gardening and a new moral vision of labour, together with mercantilist policies which encouraged domestic production. The number of landless decreased and diets improved, as well as the situation of tenants and workers. During this period, then, the landowners acted: the area or arable land decreased and the area devoted to cattle-raising increased. Yeomen went back to permanent division in the open fields, but not the landlords, who increased pastures, the rotation of lands and water meadows. Forest areas were substituted by cattle-raising, increasing clovers and turnips. Investment in rural construction increased.[173]

The third phase, again a climatic shock, was so intense that this time it affected the whole of the agrarian sector (1692-1700, 1708-1714). The rate of mineralization of nitrogen fell again and cold and humidity damaged the crops. Wheat production fell sharply, as did the harvest index. Population and demand remained depressed, although poised to recover. Prices started to rise, and consumption and demand for labour started to decline. Real wages fell and unemployment increased. Neither did the land rents escape the crisis (i.e., there was a global crisis in the agrarian sector). The government stopped restrictions on wheat imports. The arable area increased, but so did that of pastures or grasslands and marginal lands. The farmers resorted to convertible agriculture, intensified improvements of seeds, and converted production from wheat to barley or oats, avoiding new famines.

The next phase was the warm period (1700-1707, 1715-1750). Temperatures and solar radiation increased, and rainfall became more favorable. As a result of the farmers' previous efforts, more organic matter and nitrogen were available (more TM) leading to an increase in cereal production. Population grew again. Sheep, animal work and the

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[173] The growing diversity of agrarian practice and climatic pressure modified some patterns in agrarian constructions. Different adaptations were carried out because of the heavy rains in the high lands of the west or because of the cold winds in the eastern counties in order to minimize the exposure of men and animals to the most extreme weather. The storage of grain and fodder was combined with the shelter and feeding of horses and cattle. In the Penine counties cold and wet winters determined cattle management originating a practice which became very popular since 1650: a barn, away from the house, which also sheltered the cattle. These barns with cowsheds also extended in pastoral areas, were used to store grain but also fodder and hay (M.W. Barley, 1985: 667-671). In some cases, the cattle sheltered from the elements produced higher quantities of manure and urine-containing straw than before, to be distributed on the land.

yield of livestock products also recovered. All this led to a growth in rural and urban demand together with the development of industrial demand. Agrarian prices fell, cattle prices remained stable or rose and the price of mutton fell. Labour force supply and demand both increased, whereas real wages remained higher than in the rest of Europe.[174] Land rents remained stable. The use of the soil started to diversify in an environment of growing protection of property rights. Enclosures increased property fragmentation in some cases and concentration in others. The number of wage-earners grew, diet remained stable but the number of landless continued to grow.

I provisionally conclude that agrarian communities and great landowners innovated at different moments and using different methods (according to their resources), following these driving forces (environmental pressure, human and animal population, innovation, institutional framework). However, a deeper study is needed in this respect to totally or partially confirm or refute these conclusions.

5 Preliminary conclusions

The provisional results of this research suggest that the interactions between climate and population opened the door to a slow structural change during the second half of the 17th century, strengthening and promoting adaptations from the agrarian sector. Farmers invested part of their efforts in enriching the nutrient pool, succeeding in lessening the impact of climatic cooling. According to incentives, these adaptive measures were carried out by different social sectors, but in general there was an increase in the production of wheat in the long term and a decrease in relative prices, due to demographic stagnation during the second half of the 17th century. The union of climate recovery and agrarian efforts (the increase in nitrogen stock) and the increase in population within a favourable institutional framework led to a significant increase in production and yield during the first half of the 18th century. The final reading suggests that climate was a positive force in the long British Agrarian Revolution, answering the question of the missing link of nitrogen and solving the problem of the divergence between wheat supply and demand. In the framework of organic agriculture and little technology or resources, the rural sector was able to adapt to natural climate change. Now will current agriculture be able to adapt to the challenge of the global change to come?

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[174] Despite the depressed cycled mentioned, between 1660 and 1740 the real agrarian and urban wages tended to increase in general (Clark, 2007; Overton, 1996). Also, the incomes of wage-earners (wages and number of worked days) increased during that long period (De Vries, 2008).

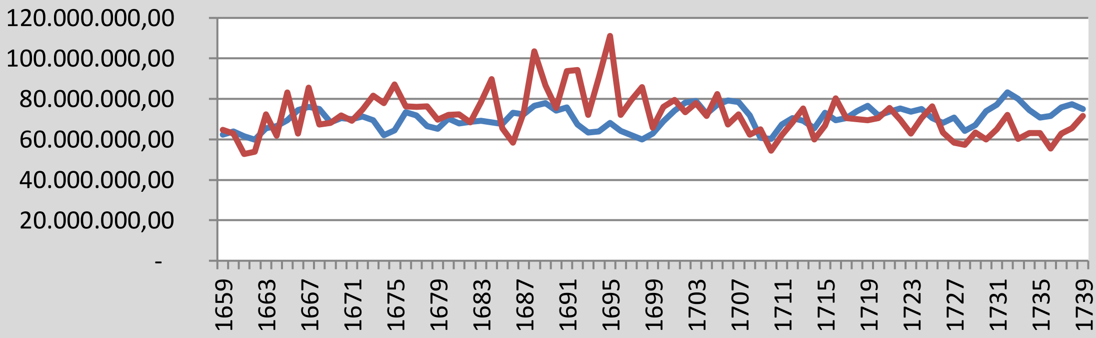
Tables and Figures

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

Year	Temp averag	m
1660-1664	9,2	15,84
1665-1669	9,0	15,07
1670-1674	8,6	13,79
1675-1679	8,5	13,38
1680-1684	8,6	13,66
1685-1689	8,9	14,74
1690-1694	8,2	12,28
1695-1699	8,0	11,80
1700-1704	8,9	14,80
1705-1709	9,3	15,85
1710-1714	9,2	15,70
1715-1719	9,1	15,36
1720-1724	9,3	15,92
1725-1729	9,3	16,16
1730-1734	10,0	18,25
1735-1739	9,8	17,53

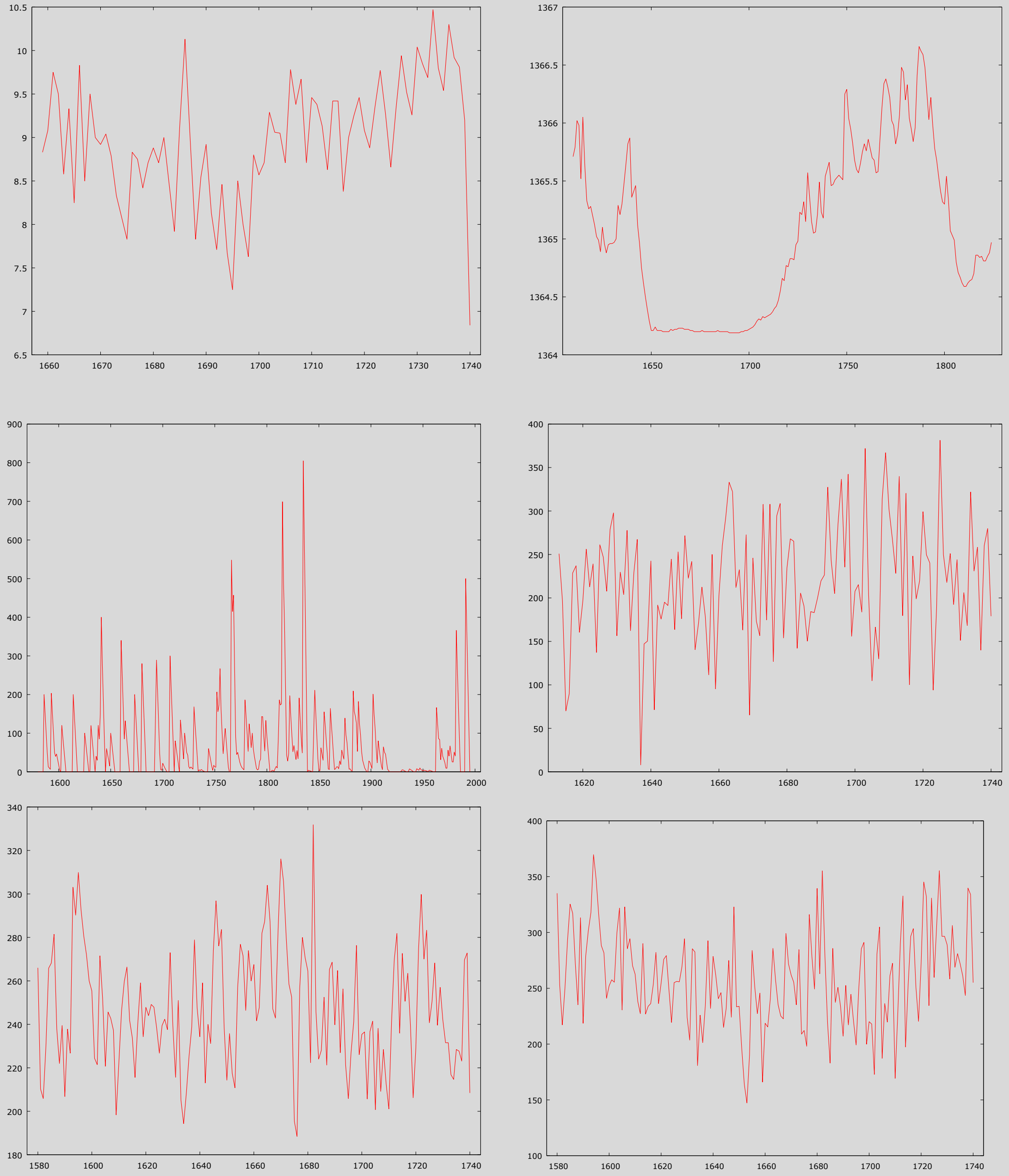
Source: Compiled by the author. In Allen's equation, Y is grain yield and F is the level of mineralized nitrogen. Taking Loomis's modified formula (total production variation * N content in the grain (0.02 kg of N/Kg of grain)/(Harvest Index HI)= total variation of N**, we calculate a proxy of F. The grain production series is estimated as explained in the data section. The novelty is that here the HI depends on temperatures. This variability is calculated giving HI=0.03 for 9ºC and modifying the HI proportionally according to temperature deviations from 9ºC (Loomis, 2002:67).**

Graphic 1. Total nitrogen (kg) in wheat production. England, 1659-1740.



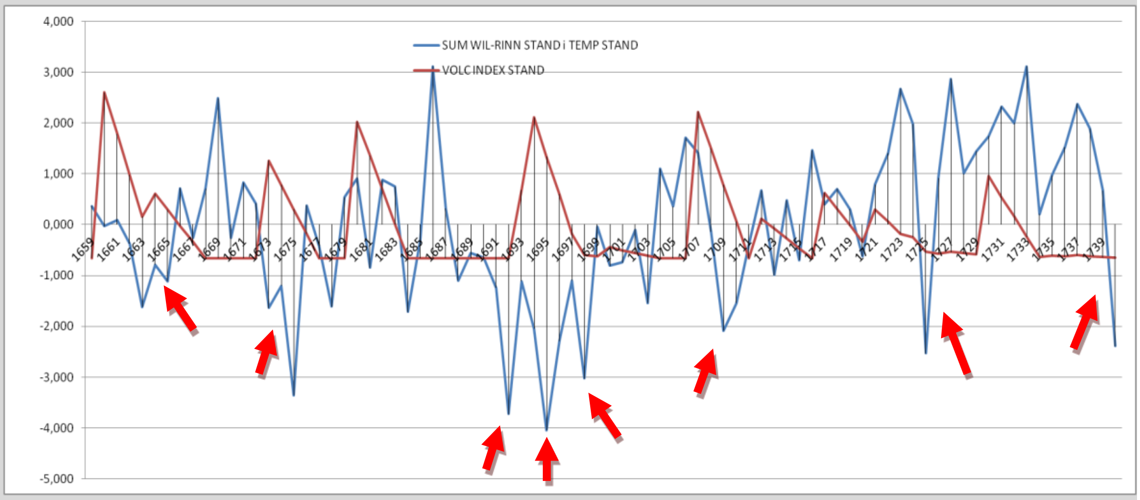
Source: Compiled by the author. The blue line shows total variations of N maintaining HI constant (0.3) and N content in the grain (0.02 kg of N/ha per kg of grain). The red line shows, with a variable HI (between 0.2 and 0.4) according to temperature. An increase in N is observed during the cooling phase (Maunder Minimum). The calculation of N variations (F) is explained in chart 1.

Climate graphics 2, 3, 4, 5, 6, 7: Temperature in degrees (TEMP); radiation in W/m2 (SOLAR_IRRAD); volcanic activity index (DVI_VOLCANIC_INDEX); rainfalls in mm. May-August (summer) in the south of England (RAIN_RINN); rainfalls en mm. between March and July (spring-summer) in the east of England (RAIN_RICH) and rainfalls in mm. between March and July (spring-summer) in the south and centre of England (RAIN_WILS).



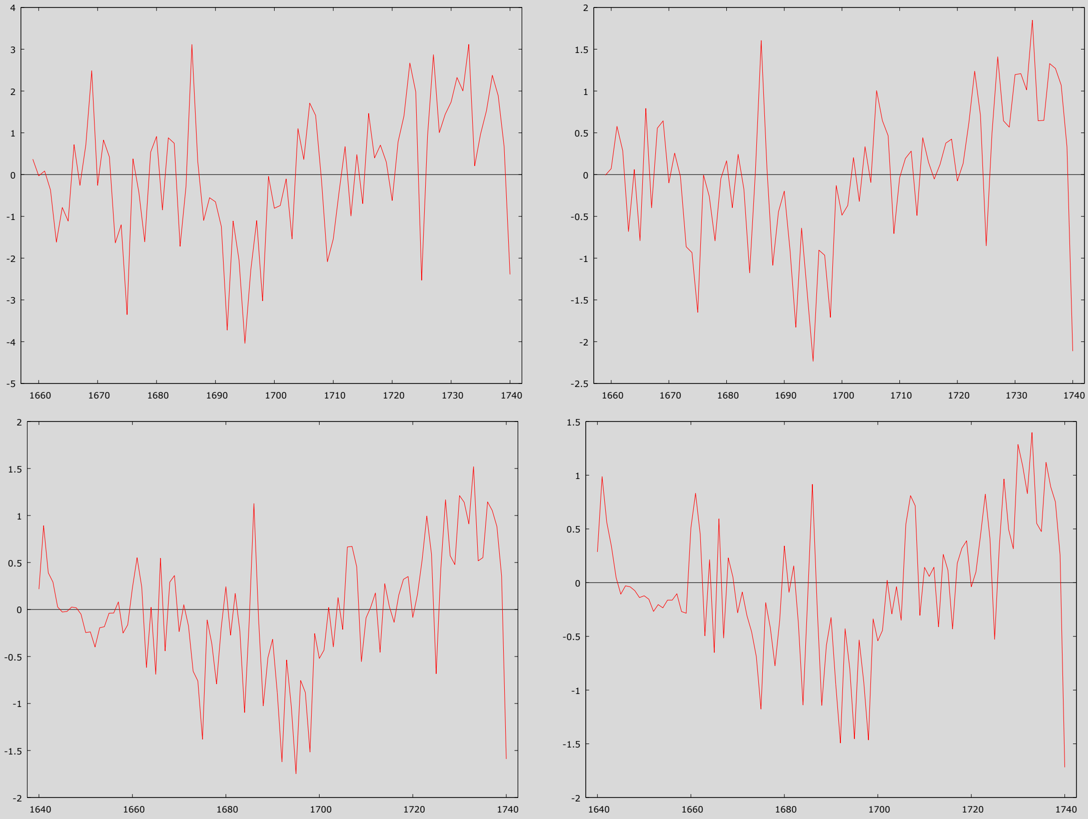
Source: compiled by the author. Temperatures, series TEMP, G. Manley's data (1974); volcanic aerosols, DVI_VOLCANIC_INDEX series, data by Mann *et al*, (2000); solar radiation, SOLAR_IRRAD series, data by Lean *et al*, (1995); *WILS series*, rainfalls between March and July (spring-summer) in the south and centre of England, data by Wilson *et al* (2012); RICH series, rainfalls between March and July (spring-summer) in the east of England, data by Cooper *et al*, 2012; RINN series, rainfalls between May and August (summer) in the south of England, data by Rinne *et al*, 2013.

Graphic 8. Net Index of Rainfalls and Temperatures (*CIPL*-1), England, 1659-1740 compared to the volcanic aerosols index DVI_VOLCAN_ESTAND. Standardized data.



Source: Compiled by the author. In red, the moments of highest social unrest and food raising, detailed by B. Bohstedt (2010:33-54). The correlation with the main aerosol movements until the 18th century is observable.

Graphics 9, 10, 11, 12 and 13. Climatic Indices of the Productivity of the Land (CIPL-1, CIPL-2, CIPL-3, CIPL-4).



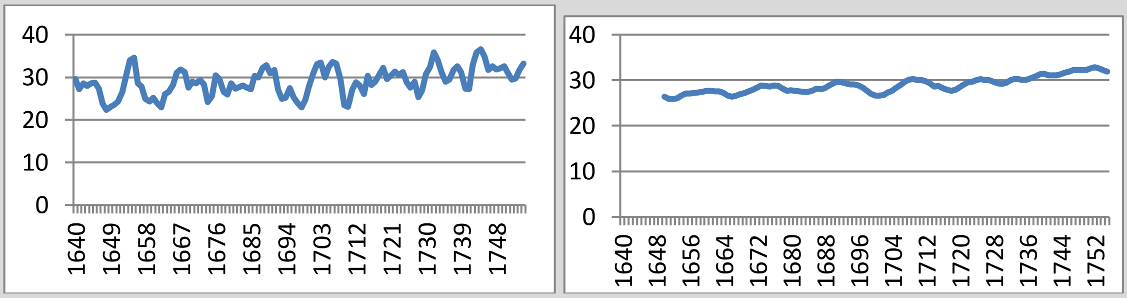
Source: Compiled by the author. CIPL-1: balance 50% temperatures, 50% net rainfalls (the difference between spring rainfalls WILS and summer RINN); CIPL-2: 75% temperatures and 25% net rainfalls; CIPL-3: 60% temperatures, 20% net rainfalls, 10% volcanic dust, 10% solar radiation; CIPL-4: 60% temperatures, 10% net rainfalls, 20% volcanic dust, 10% solar radiation.

Chart 2. Contrast tests with productivity climatic índices, England.

Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS (2)	Wheat production in bushels (OUTPUT_BUS) (3)	Wheat production in bushels (OUTPUT_BUS) (4)
Sample size	1659-1740 (T = 82)	1659-1740 (T = 82)	1642-1740 (T = 99)	1642-1740 (T = 99)
Constant	1.93298e+07*** (<0.00001)	1.94513e+07*** (<0.00001)	1.61218e+07*** (<0.00001)	1.54837e+07*** (<0.00001)
DVI_VOLCANIC_INDEX_1	-4850.62* (0.06289)	-5746.41** (0.02512)		
CIPL-1	447345*** (0.00232)			
CIPL-2		822610*** (0.00194)		
CIPL-3			942067*** (0.00334)	
CIPL-4				865060*** (0.00956)
OUTPUT_BUS_1 (value p)	0.8129*** (<0.00001)	0.814352*** (<0.00001)	0.916804*** (<0.00001)	0.931651*** (<0.00001)
OUTPUT_BUS_2	-0.30331*** (0.00326)	-0.306404*** (0.00288)	-0.334388*** (0.00053)	-0.332628*** (0.00064)
R-square adjusted	0.609662	0.611318	0.604776	0.596777
F	32.62818	32.84920	50.98680	49.34731

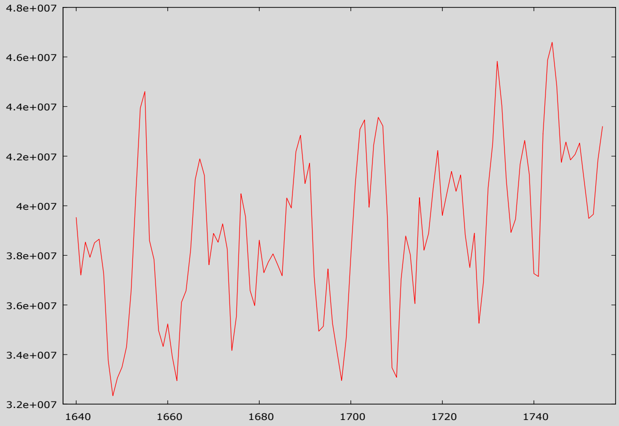
Source: compiled by the author,*=level of significance at 10%, **= level of significance at 5%, *=level of significance at 1%. P-value between brackets. DVI_VOLCANIC_INDEX_1 is the index of volcanic activity from the previous year. OUTPUT_BUS is wheat production in bushels, the calculation of which is explained in the production data section. OUTPUT_BUS_1 belongs to the previous year, and OUTPUT_BUS_2 belongs to the year before the previous one.**

Graphics 14 and 15. Wheat supply, England, in million bushels and in 11-year moving average, 1640-1750.



Source: compiled by the author. Short-term movements are well adjusted to Hoskin's calendars (1968:20-22): bad crops in 1646, 1657, 1710,1711; bad or very bad in 1647, 1648, 1649, 1658, 1661, 1662, 1673, 1674, 1678, 1692, 1693, 1695, 1696, 1696, 1697, 1698, 1708, 1709, 1714, 1727, 1728, 1729; "average" years in 1699, 1718, 1719, 1720; and good years in 1652, 1653, 1654, 1655, 1665-72, 1680s in general, between 1700-1707 and 1721-23.

Graphic 16. Wheat production series in bushels. OUTPUT_BUS, (1640-1755).



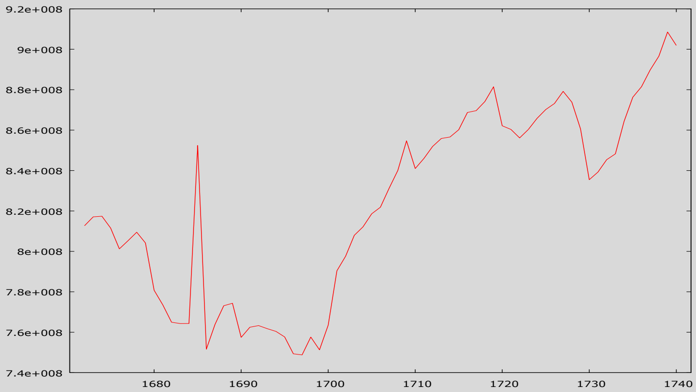
Source: compiled by the author. Short-term movements are well adjusted to Hoskin's calendars (see previous chart). The difference between this and the previous series is explained in this paper.

Chart 3. Comparison of my estimates to those of Broadberry's et al (2011b:31). In million bushels.

Period	MY AVERAGE	BROADBERRY'S AVERAGE	
Average 1645-1655	27.12	27.01	1650s
Average 1695-1705	28.39	27.94	1700s
Average 1745-1755	31.89	31.48	1750s

Source: compiled by the author.

Graphic 17. Male agrarian labour-energy series (1672-1740).



Source: compiled by the author. See calculation in footnote 54. Data in KCAL.

Chart 4. Statistic contrasts of climate impact in wheat production. England, 1659-1740.

Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS) (2)	Wheat production in bushels (OUTPUT_BUS) (3)
Sample size	1659-1740 (T = 82)	1672-1740 (T = 69).	1659-1740 (T = 82)
Constant	1.83485e+09* (0.05444)	6.54596e+08 (0.50047)	3.99448e+07 (0.95890)
TEMP	907586** (0.02743)	964089 *** (0.00452)	612634** (0.04511)
DVI_VOLCANIC_INDEX	-7712.18** (0.01415)	-1985.03 (0.44356)	-3948.96* (0.09519)
SOLAR_IRRAD_1	1.37213e+06* (0.05019)	496084 (0.48792)	45169.1 (0.93675)
RAIN_RINN	-8570.58** (0.02062)	-9951.3*** (0.00149)	-7888.01*** (0.00460)
RAIN_RINN_1	-18696*** (<0.00001)	-13987.8*** (0.00005)	-12107.6*** (0.00006)
FTM_KCAL_TOT		-0.00399085 (0.55655)	
OUTPUT_BUS_1		0.59191*** (<0.00001)	0.640781*** (<0.00001)
OUTPUT_BUS_2		-0.156753 (0.12219)	-0.233072** (0.01315)
EXP			1.09556e+06** (0.01644)
R-square adjusted	0.410784	0.686599	0.680281
F	12.29417	19.62184	22.54341

Source: compiled by the author
***= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%.**
p-value between brackets. TEMP, temperatures; DVI… volcanic activity index; SOLAR…solar radiation RAIN_RINN, summer rainfalls…; FTM…labour-energy supply; OUTPUT_BUS, wheat production in bushels. The fictitious variable EXP took value 1 when incentives were active and value 0 when they were interrupted.

Chart 5. Relative prices, climate, agrarian adaptation and population.

Dependent variable	PR_WHEAT_PR_BEEF (4)	PR_WHEAT_PR_PORK (5)	PR_WHEAT_PR_MILK (6)
Sample size	1660-1739 (T = 80)	1660-1739 (T = 80)	1660-1739 (T = 80)
Constant	-231.934** (0.04839)	-226.408* (0.05351)	7.13008*** (0.00633)
TEMP	-2.77787*** (<0.00001)	-2.8593*** (<0.00001)	-3.11101*** (<0.00001)
TEMP_1			1.71263*** (0.00039)
TEMP_SQUAR	0.12045*** (<0.00001)	0.12277*** (<0.00001)	0.144524*** (<0.00001)
TEMP_SQUAR_1	0.0102894*** (0.00215)	0.0102289*** (0.00243)	-0.0767059*** (0.00160)
RAIN_RINN		-0.000295632* (0.08628)	
RAIN_WILS_1	0.000766007*** (0.00671)	0.000623145** (0.03414)	-0.000649942** (0.01379)
DVI_VOLCANIC_INDEX_1	0.000255158* (0.06421)	0.000332575** (0.02383)	
SOLAR_IRRAD	0.184703** (0.03247)	0.180931** (0.03586)	
POPULATION		1.4876e-06** (0.01175)	2.23781e-07** (0.01826)
POPULATION_1	-3.76751e-07** (0.02207)	-1.78246e-06*** (0.00876)	
BIRTH_RATE	-0.0172331** (0.02241)	-0.0262394*** (0.00719)	
DEATH_RATE_1	-0.00905939*** (0.00640)		
CI_VAR_N_0_02	-3.70916e-08*** (<0.00001)	-3.85272e-08*** (<0.00001)	-3.12431e-08*** (<0.00001)
CI_VAR_N_0_02_1	8.47861e-09** (0.01027)	8.25456e-09** (0.01321)	2.0434e-08*** (<0.00001)
PR_WHEAT_PR_BEEF_1	0.203118*** (0.00997)		
PR_WHEAT_PR_BEEF_2	-0.152468*** (0.00322)		
PR_WHEAT_PR_PORK_1		0.184421** (0.01923)	
PR_WHEAT_PR_PORK_2		-0.152104*** (0.00377)	
PR_WHEAT_PR_MILK_1			0.764702*** (<0.00001)
PR_WHEAT_PR_MILK_2			-0.141199** (0.03704)
R-square adjusted	0.870378	0.869148	0.848339
F	41.80499	38.48114	45.18998
Durbin-h	-0.487693	0.289082	-0.993105

Source: compiled by the author.

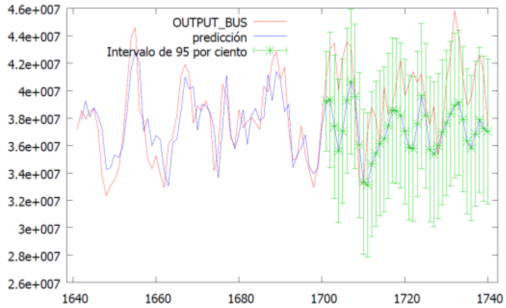
***=level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets. TEMP=annual average temperature; TEMP_1, idem previous year; TEMP_SQUAR, annual average temperature squared; TEMP_SQUAR_1, idem previous year; RAINN_RINN, annual summer rainfalls in mm.; RAIN_WILS_1, annual spring rainfalls from previous year in mm.; DVI_VOLCANIC_INDEX_1, volcanic activity index from previous year; SOLAR_IRRAD, annual solar radiation in W/m2; POPULATION, number of inhabitants of the year; POPULATION_1, inhabitants from previous year; BIRTH_DATE, English annual birth rate; DEATH_RATE_1, English annual death rate from previous year. Demographic data by Wrigley *et al*, 1981; IC_VAR_N_0_02 is F proxy explained in chart 1 and graphic 1; IC_VAR_N_0_02_1, idem from previous year. PR_WHEAT_PR_BEEF is the quotient between the prices of wheat and cattle of the year; PR_WHEAT_PR_BEEF_1 idem from previous year; PR_WHEAT_PR_PORK is the quotient between the prices of wheat and pigs; PR_WHEAT_PR_PORK_1 idem from previous year; PR_WHEAT_PR_MILK is the quotient between the prices of wheat and milk production; PR_WHEAT_PR_MILK_1 idem from previous year. All prices by G. Clark (2004, 2005, 2007).**

Chart 6. Output and temperatures in long -term growth, England.

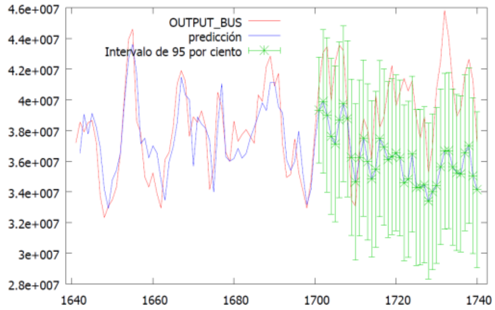
```
Estapa 1: contrastando la existencia de una raíz unitaria en OUTPUT_BUS
Contraste aumentado de Dickey-Fuller para OUTPUT_BUS incluyendo un retardo de (1-L) OUTPUT_BUS
tamaño muestral 80, hipótesis nula de raíz unitaria: a = 1, contraste con constante,
modelo: (1-L)y = b0 + (a-1)*y(-1) + ... + e
            -Coef. de autocorrelación de primer orden de e: 0.010
            -valor estimado de (a - 1): -0.39793
            -Estadístico de contraste: tau_c(1) = -4.75903
-           -valor p asintótico 6.188e-005
Etapa 2: contrastando la existencia de una raíz unitaria en TEMP
Contraste aumentado de Dickey-Fuller para TEMP incluyendo un retardo de (1-L)TEMP, tamaño muestral 80,
hipótesis nula de raíz unitaria: a = 1
contraste con constante
modelo: (1-L)y = b0 + (a-1)*y(-1) + ... + e
            -Coef. de autocorrelación de primer orden de e: -0.040 valor estimado de (a - 1): -0.423927
            -Estadístico de contraste: tau_c(1) = -3.52182
            -valor p asintótico 0.007475
Etapa 3: regresión cointegrante
Regresión cointegrante -  MCO, usando las observaciones 1659-1740 (T = 82), Variable dependiente:
OUTPUT_BUS
                  Coeficiente        Desv. Típica     Estadístico t   Valor p
  -----------------------------------------------------------------------------------------
  const          2.42726e+07      3.90329e+06      6.219            2.15e-08 ***
  TEMP           1.61659e+06      433879            3.726             0.0004   ***

Media de la vble. dep.   38772036       D.T. de la vble. dep.    2953043
Suma de cuad. residuos  6.02e+14       D.T. de la regresión     2742966
R-cuadrado                 0.147869      R-cuadrado corregido    0.137218
Log-verosimilitud         -1330.954      Criterio de Akaike      2665.907
Criterio de Schwarz        2670.721      Crit. de Hannan-Quinn   2667.840
rho                        0.634246      Durbin-Watson           0.703550
Etapa 4: contrastando la existencia de una raíz unitaria en uhat
Contraste aumentado de Dickey-Fuller para uhat incluyendo un retardo de (1-L)uhat, tamaño muestral 80
hipótesis nula de raíz unitaria: a = 1, modelo: (1-L)y = (a-1)*y(-1) + ... + e
            -Coef. de autocorrelación de primer orden de e: -0.024
            -valor estimado de (a - 1): -0.441626
            -Estadístico de contraste: tau_c(2) = -4.7146
            -valor p asintótico 0.0004988
Hay evidencia de una relación cointegrante si:
(a) La hipótesis de existencia de raíz unitaria no se rechaza para las variables individuales.
(b) La hipótesis de existencia de raíz unitaria se rechaza para los residuos (uhat) de la regresión cointegrante.
```

Source: compiled by the author

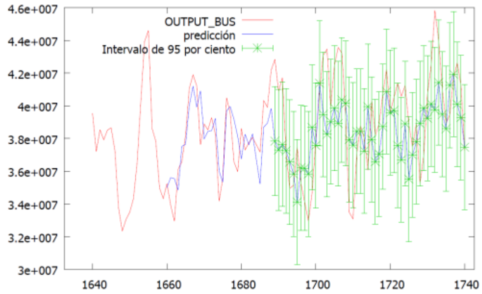
Graphics 17, 18, 19, 20 and 21. The increase of agrarian innovation could explain the gap between forecast and real wheat production.



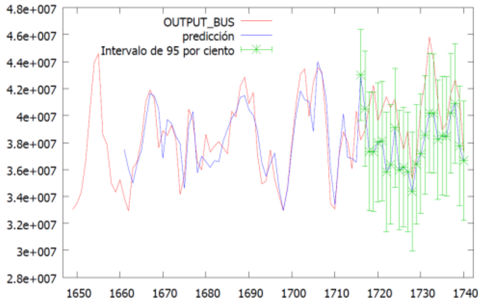
Dependent variable: OUTPUT_BUS
1642-1700 (T = 59)
RAIN_RINN
RAIN_RINN_1
OUTPUT_BUS_1
OUTPUT_BUS_2
R-square adjusted 0.613692
Durbin-h 0.455419



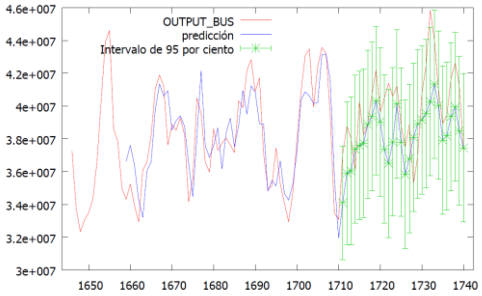
Dependent variable: OUTPUT_BUS
1642-1700 (T = 59)
RAIN_RINN
RAIN_WILS_1
OUTPUT_BUS_1
OUTPUT_BUS_2
R-square adjusted 0.650254
Durbin-h 0.903482



Dependent variable: OUTPUT_BUS
1660-1688 (T = 29)
TEMP_MAX
GRAD_SHORT
GRAD_LONG
OUTPUT_BUS_1
R-square adjusted 0.533641
Durbin-h 0.548846



Dependent variable: OUTPUT_BUS
1661-1715 (T = 55)
RAIN_RINN
RAIN_WILS_1
TEMP_2
OUTPUT_BUS_1
OUTPUT_BUS_2
R-square adjusted 0.679316
Durbin-h -0.291423



Dependent variable: OUTPUT_BUS
1659-1710 (T = 52)
RAIN_RINN
RAIN_RINN_1
TEMP_MAX
OUTPUT_BUS_1
OUTPUT_BUS_2
R-square adjusted 0.689520
Durbin-h 1.280392

Source: compiled by the author.

Chart 6b. Statistic contrasts with dummy variables to value the existence of agrarian adaptation. England, 1640-1740.

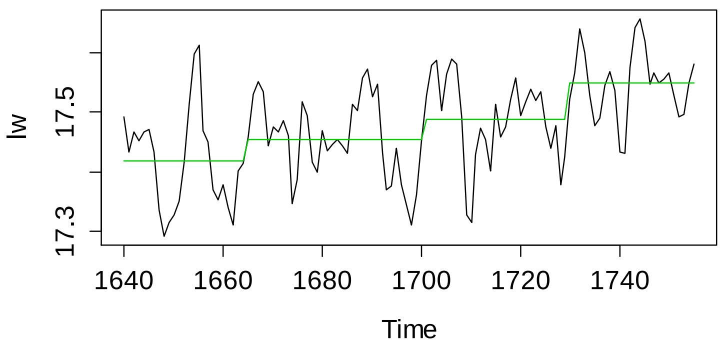
Dependent variable	Wheat production in bushels (OUTPUT_BUS) (1)	Wheat production in bushels (OUTPUT_BUS (2)	Wheat production in bushels (OUTPUT_BUS) (3)	Wheat production in bushels (OUTPUT_BUS) (4)
Sample size	1659-1739 (T = 81)	1659-1739 (T = 81)	1659-1739 (T = 81)	1640-1739 (T = 100)
Constant	2.89512e+07*** (<0.00001)	4.51652e+07*** (<0.00001)	4.4234e+07*** (<0.00001)	4.49616e+07*** (<0.00001)
F2TEMP	181315** (0.02135)			
TEMP	1.00072e+06* (0.07144)			
F2RINN		11294.4*** (<0.00001)		15804.2*** (<0.00001)
RAIN_RINN		-16888.8*** (0.00004)	-11892.7*** (0.00281)	--20898.3*** (<0.00001)
RAIN_RINN_1		-17652.8*** (<0.00001)	-16302.7*** (0.00005)	-17319.9*** (<0.00001)
F1RINN			10133.9*** (0.00019)	
D1RINN				10101.1*** (0.00033)
R-square adjusted	0.186932	0.328716	0.260381	0.408052
F	10.19641	17.15954	12.73494	18.06107

Source: compiled by the author

***= level of significance at 10%, **=level of significance at 5%, ***=level of significance at 1%.**

p-value between brackets. TEMP, temperatures; RAIN_RINN, summer rainfalls; OUTPUT_BUS, wheat production in bushels. The dummy variable F2 took value 1 from 1700 and value 0 before 1700. The dummy variable F1 took value 1 since 1715 and value 0 before 1715. The dummy variable D1 took value 1 between 1664 and 1691 and 0 in the rest. These results suggest structural changes in 1664, 1700 and 1715. There could be more break points, since this analysis has not been carried out with all the "candidate" years.

Chart 6c. Bai-Perron Test to value the existence of agrarian adaptation. England, 1640-1740.



Source: compiled by the invaluable assistance of Professor Marc Badia Miró. Lw is the wheat production logarithm in bushels. The detected breakpoints are 1664, 1700 and 1730.

Chart 7.1. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1640-1700 y 1701-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1640-1700 (T = 61)	1701-1739 (T = 39)
Constant (p-value)	4.67232e+07*** (<0.00001)	4.84412e+07*** (<0.00001)
RAIN_RINN	-10550.5** (0.04120)	-13955.8*** (0.00459)
RAIN_RINN_1	-12509** (0.02016)	-22260.3*** (0.00003)
RAIN_WILS_1	-14828.1*	
DVI_VOLCANIC_INDEX	-7264.74** (0.03115)	
R-square adjusted	0.226245	0.434050
F	5.385975	15.57189

Source: compiled by the author.
***=level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets.**
No more variables have been included in order to isolate climate effects.

Chart 7.2. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1640-1716 y 1717-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1640-1716 (T = 77)	1717-1739 (T = 23)
Constant	4.45009e+07*** (<0.00001)	3.09034e+07*** (<0.00001)
TEMP_SQUAR (valor p)		91519.1* (0.05682)
RAIN_RINN	-9130.15** (0.03786)	
RAIN_RINN_1	-17782.6*** (0.00012)	
DVI_VOLCANIC_INDEX	-7927.47** (0.01460)	
DVI_VOLCANIC_INDEX_1		25428.5*** (0.00394)
R-square adjusted	0.237144	0.373675
F	8.875212	7.562764

Source: compiled by the author.
***= level of significance at 10%, level of significance at 5%, ***= level of significance at 1%. p-values between brackets.**
No more variables have been included in order to isolate climate effects.

Tabla 7.3. Statistic contrasts to value the existence of agrarian adaptation by means of sample division into two periods (1660-1689 y 1690-1739). England.

Dependent variable	Wheat production in bushels (1)	Wheat production in bushels (2)
Sample size	1660-1689 (T = 30)	1690-1739 (T = 50)
Constant	9.23392e+010* (0.07915)	3.32712e+07*** (<0.00001)
TEMP		1.5587e+06*** (0.00130)
TEMP_1	3.44379e+07* (0.06819)	
TEMP_SQUAR_1	1.86754e+06* (0.07570)	
RAIN_RINN	-12722.1** (0.04533)	-11943.5*** (0.00978)
RAIN_RINN_1	-12632.2** (0.01884)	-22678.4*** (<0.00001)
RAIN_WILS	30698.4** (0.01166)	
DVI_VOLCANIC_INDEX	-8578.56** (0.04220)	
SOLAR_IRRAD_1 (valor p)	6.78296e+07* (0.07866)	
R-square adjusted	0.440917	0.535566
F	4.267240	19.83489

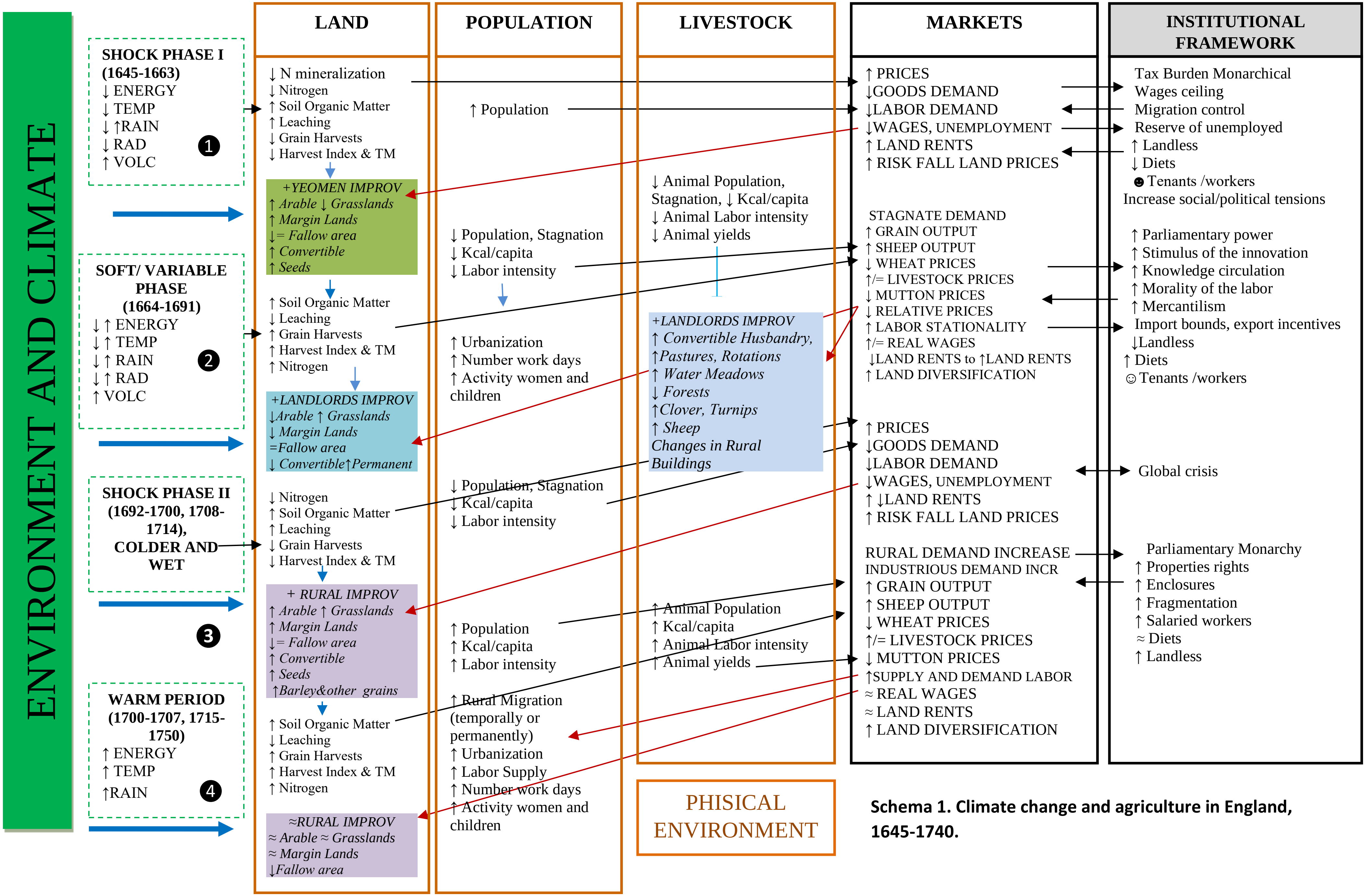
Source: compiled by the author.
***= level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%. p-values between brackets.**
No more variables have been included in order to isolate climate effects.

Chart 8. Statistic contrasts in the climate long-term impact: agrarian adaptation. Approaches of the land rent (Ricardian) and production. England, 1640-1740.

Dependent variable	Decennial rent, in m. of £. (1)	Decennial rent, in m. of £. (3)
Sample size	1640-1740 (T = 10)	1660-1740 (T = 8)
Constant	5.92199** (0.01683)	1.9334 (0.60923)
RAIN_WILS_DEC	0.029106*** (0.00541)	
TEMP_DEC		1.29526** (0.01737)
R-square adjusted	0.595794	0.578072
F	14.26588	10.59050
Durbin-Watson	1.565345	2.358401

Source: compiled by the author.
In DW, for T=10 and k=2, between ds (1,320) and 4-ds (2,68) absence autocorrelation. For T=8 and k=2, between ds (1,332) and 4-ds (2,67) absence autocorrelation. Total land rents and local taxes in m. £. by Clark (2001).
***= level of significance at 10%, **= level of significance at 5%, ***= level of significance at 1%.**
p-values between brackets.

THE CYCLE OF CLIMATE CHANGE IN AGRICULTURE: ENGLAND: 1645-1740



ENVIRONMENT AND CLIMATE

SHOCK PHASE I (1645-1663)
↓ ENERGY
↓ TEMP
↓ ↑RAIN
↓ RAD
↑ VOLC
❶

SOFT/ VARIABLE PHASE (1664-1691)
↓↑ ENERGY
↓↑ TEMP
↓↑ RAIN
↓↑ RAD
↑ VOLC
❷

SHOCK PHASE II (1692-1700, 1708-1714), COLDER AND WET
❸

WARM PERIOD (1700-1707, 1715-1750)
↑ ENERGY
↑ TEMP
↑RAIN
❹

LAND

↓ N mineralization
↓ Nitrogen
↑ Soil Organic Matter
↑ Leaching
↓ Grain Harvests
↓ Harvest Index & TM

+YEOMEN IMPROV
↑ Arable ↓ Grasslands
↑ Margin Lands
↓= Fallow area
↑ Convertible
↑ Seeds

↑ Soil Organic Matter
↓ Leaching
↑ Grain Harvests
↑ Harvest Index & TM
↑ Nitrogen

+LANDLORDS IMPROV
↓Arable ↑ Grasslands
↓ Margin Lands
=Fallow area
↓ Convertible↑Permanent

↓ Nitrogen
↑ Soil Organic Matter
↑ Leaching
↓ Grain Harvests
↓ Harvest Index & TM

+ RURAL IMPROV
↑ Arable ↑ Grasslands
↑ Margin Lands
↓= Fallow area
↑ Convertible
↑ Seeds
↑Barley&other grains

↑ Soil Organic Matter
↓ Leaching
↑ Grain Harvests
↑ Harvest Index & TM
↑ Nitrogen

≈RURAL IMPROV
≈ Arable ≈ Grasslands
≈ Margin Lands
↓Fallow area

POPULATION

↑ Population

↓ Population, Stagnation
↓ Kcal/capita
↓ Labor intensity

↑ Urbanization
↑ Number work days
↑ Activity women and children

↓ Population, Stagnation
↓ Kcal/capita
↓ Labor intensity

↑ Population
↑ Kcal/capita
↑ Labor intensity

↑ Rural Migration (temporally or permanently)
↑ Urbanization
↑ Labor Supply
↑ Number work days
↑ Activity women and children

LIVESTOCK

↓ Animal Population, Stagnation, ↓ Kcal/capita
↓ Animal Labor intensity
↓ Animal yields

+LANDLORDS IMPROV
↑ Convertible Husbandry,
↑Pastures, Rotations
↑ Water Meadows
↓ Forests
↑Clover, Turnips
↑ Sheep
Changes in Rural Buildings

↑ Animal Population
↑ Kcal/capita
↑ Animal Labor intensity
↑ Animal yields

PHISICAL ENVIRONMENT

MARKETS

↑ PRICES
↓GOODS DEMAND
↓LABOR DEMAND
↓WAGES, UNEMPLOYMENT
↑ LAND RENTS
↑ RISK FALL LAND PRICES

STAGNATE DEMAND
↑ GRAIN OUTPUT
↑ SHEEP OUTPUT
↓ WHEAT PRICES
↑/= LIVESTOCK PRICES
↓ MUTTON PRICES
↓ RELATIVE PRICES
↑ LABOR STATIONALITY
↑/= REAL WAGES
↓LAND RENTS to ↑LAND RENTS
↑ LAND DIVERSIFICATION

↑ PRICES
↓GOODS DEMAND
↓LABOR DEMAND
↓WAGES, UNEMPLOYMENT
↑ ↓LAND RENTS
↑ RISK FALL LAND PRICES

RURAL DEMAND INCREASE
INDUSTRIOUS DEMAND INCR
↑ GRAIN OUTPUT
↑ SHEEP OUTPUT
↓ WHEAT PRICES
↑/= LIVESTOCK PRICES
↓ MUTTON PRICES
↑SUPPLY AND DEMAND LABOR
≈ REAL WAGES
≈ LAND RENTS
↑ LAND DIVERSIFICATION

INSTITUTIONAL FRAMEWORK

Tax Burden Monarchical
Wages ceiling
Migration control
Reserve of unemployed
↑ Landless
↓ Diets
☻ Tenants /workers
Increase social/political tensions

↑ Parliamentary power
↑ Stimulus of the innovation
↑ Knowledge circulation
↑ Morality of the labor
↑ Mercantilism
Import bounds, export incentives
↓Landless
↑ Diets
☺ Tenants /workers

Global crisis

Parliamentary Monarchy
↑ Properties rights
↑ Enclosures
↑ Fragmentation
↑ Salaried workers
≈ Diets
↑ Landless

Schema 1. Climate change and agriculture in England, 1645-1740.

Schema 2. The economic theory between climate and population.

	GROWING POPULATION (GP)	DECREASING POPULATION (DP)
FAVORABLE CLIMATE (FC)	• Δ Subdivision farms • Δ Fragmentation farms • Δ/∇ prices if GP>FC / GP<FC • Δ/∇ land values if GP>FC / GP<FC • Δ/∇ landless if GP>FC / GP<FC • ∇/Δ employment if GP>FC / GP<FC • ∇/Δ real wages if GP>FC / GP<FC • ∇/Δ diets if GP>FC / GP<FC • ∇/Δ landlords improvements if GP>FC / GP<FC • Δ/∇ yeomen improvements if GP>FC / GP<FC • Δ/∇ arable land if GP>FC / GP<FC • ∇/Δ grasslands, grazing if GP>FC / GP<FC • Δ/∇ use marginal land if GP>FC / GP<FC *Analysis applicable to 1700-1707 and 1716-1740*	• ∇ Subdivision farms • ∇ Fragmentation farms • ∇ prices • ∇ land values • ∇ landless • Δ employment • Δ real wages • Δ diets • Δ landlords improvements • ∇ yeomen improvements • ∇ arable land • Δ grasslands, grazing • ∇ use marginal land *Analysis applicable to 1664-1691*
UNFAVORABLE CLIMATE (UC)	• Uncertain subdivision farms • Uncertain fragmentation farms • Δ prices • Δ land values • Δ landless • ∇ employment • ∇ real wages • ∇ diets • ∇ landlords improvements • Δ yeomen improvements • Δ arable land • ∇ grasslands, grazing • Δ use marginal land *Analysis applicable to 1645-1663*	• Uncertain subdivision farms • Uncertain fragmentation farms • Δ/∇ prices if UC>DP / UC<DP • Δ/∇ land values if UC>DP / UC<DP • Uncertain landless • ∇/Δ employment if UC>DP / UC<DP • ∇/Δ real wages if UC>DP / UC<DP • ∇/Δ diets if UC>DP / UC<DP • ∇/Δ landlords improvements if UC>DP / UC<DP • Δ/∇ yeomen improvements if UC>DP / UC<DP • Δ/∇ arable land if UC>DP / UC<DP • ∇/Δ grasslands, grazing if UC>DP / UC<DP • Δ/∇ use marginal land if UC>DP / UC<DP *Analysis applicable to 1692-1700 (probably* UC>DP)

Source: compiled by the author.
Analysis of the demographic impact on agriculture by D. Griggs, 1982:27-31.
Rest of analyses by the author. This schema may also be developed according to the types of soil.

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