Building an annual series of English wheat production in an intriguing era (1645-1761): methodology, challenges and results

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KEYWORDS: **wheat production, England, Davenant's Law, agricultural revolution.**

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This article presents a method for estimating an annual series of English wheat production in physical units during the intriguing period of 1645-1761, when the English Agricultural Revolution began. It is based on Davenant's Law and the assumption of a decrease in long-term crop variability, taking into account the yields obtained from probate inventories and farm accounts. The exercise confirms the idea that the King-Davenant accounting of the inverse variation of prices and quantities through price elasticity was indeed a common rule at that time, whereas income elasticity did not become a decisive factor until the mid-18th century. From then on it gained momentum, as can be observed by lengthening the series until 1884. The new series of English wheat production presented here also shows that, from a physical and environmental perspective, the Agricultural Revolution began before 1750 and resumed after 1800. The results are consistent with recent estimates of agricultural GDP put forward in the literature on English economic history.

Construyendo una serie anual de producción de trigo inglesa en una etapa fascinante (1645-1761): metodología, desafíos y resultados

PALABRAS CLAVE: **producción de trigo, Inglaterra, ley de Davenant, revolución agraria.**

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Este artículo presenta un método para estimar una serie inglesa de producción de trigo en unidades físicas durante el período 1645-1761, cuando empezó la revolución agrícola. Este método se basa en el supuesto de un descenso a largo plazo de la variabilidad de las cosechas, teniendo en cuenta los rendimientos agrícolas estimados por diversos autores a partir de los inventarios testamentarios y las contabilidades agrarias. El ejercicio confirma la idea de que la ley de King-Davenant fue una regla común en la época, y la elasticidad renta no fue un factor decisivo hasta mediados del siglo XVIII, cuando empezó a ganar impulso, como se puede observar alargando la serie hasta 1884. La nueva serie inglesa de producción de trigo presentada aquí también muestra que, desde una perspectiva física y ambiental, la revolución agrícola fue un fenómeno que comenzó antes de 1750 y se reanudó después de 1800. Los resultados encontrados son consistentes con las recientes estimaciones del PIB agrícola presentadas por la historiografía económica.

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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 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 precapitalist 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, *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, 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.

TABLE 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: 116-49). 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 $-0.6 < \varepsilon_p < -0.8$. 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 article 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:

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

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 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 8 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 $D_{\text{wheat}} = P^{\propto}_{\text{wheat}} I^{\beta}$, where D_{wheat} stands for the national annual wheat demand in bushels, $P^{\propto}_{\text{wheat}}$ 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 Graphs 1 and 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 2 to 6).

GRAPHS 1 AND 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 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 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 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 5 and 6). On the other hand, income elasticity is nearly zero in I and III, and 0.6/0.7 in II and IV.

TABLE 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 6
Price elasticity of English wheat consumption obtained through differences and logarithms, 1645-1761

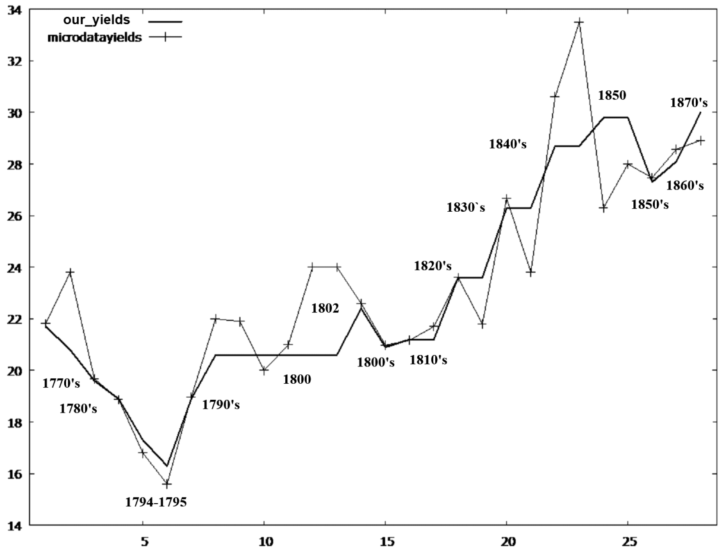
SERIES	Price elasticity
BROAD_POP (I)	-0.38
BROAD_POP_RENT (II)	-0.39
DEANE_POP (III)	-0.46
DEANE_POP_RENT (IV)	-0.47

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.

GRAPH 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, Graphs 3 and 5, Table 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 $D_{\text{wheat}} = P_{\text{wheat}}^{-0,65}\, P_{\text{agric}}^{0,8}\, I^{0,6}$, 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,

TABLE 7
Comparison of different estimates of English wheat yields, 1760-1879

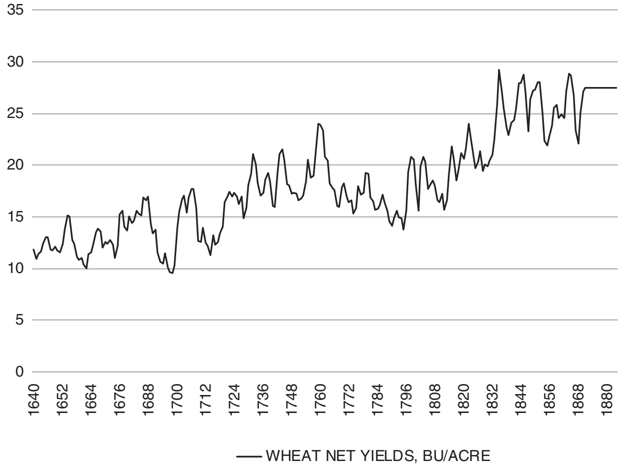
Years	Our estimates (gross, bu/acre)	Other authors (gross, bu/acre)	Deviation	Authors
1760-69	21.7	21.82	0.5%	Turner *et al.* (2001)
1770	20.8	23.80	12.6%	Artur Young (John, 1986)
1770-79	19.6	19.68	0.4%	Turner *et al.* (2001)
1780-89	18.9	18.88	-0.1%	Turner *et al.* (2001)
1794	17.3	16.8	-3.0%	Harvest 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, 1991)
1800	20.6	24	14.2%	Herts (Glennie, 1991)
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)
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.

1655, 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 8).

GRAPH 4

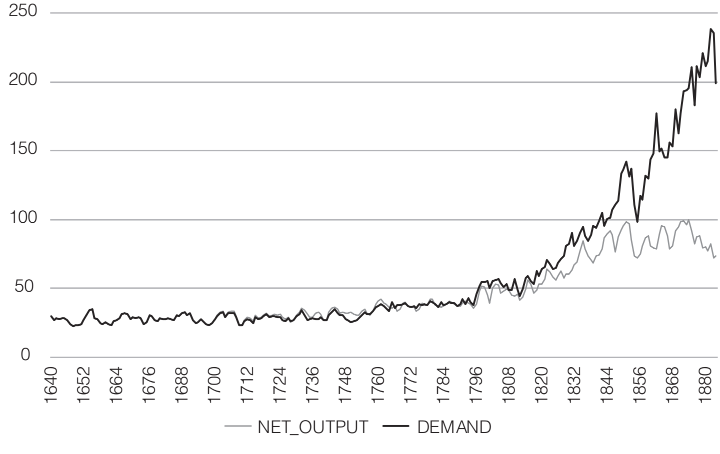
Long-term evolution of English wheat yields in bu/acre, from 1645 to 1850



Source: our own calculation.

GRAPH 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 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	29,696,256
	1656-63	30,491,192
	1695-99	29,886,137
Good crops	1664-72	34,251,154
	1685-91	35,718,380
	1714-24	34,976,126
	1741-49	37,842,623

Source: our own calculation.

This verification can be completed by comparing Table 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 article 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 article 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.

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APPENDIX

YEAR	WHEAT GROSS OUTPUT (BROAD_POP, SERIES I) Million bushels	YEAR	WHEAT GROSS OUTPUT (BROAD_POP, SERIES I) Million bushels
1640	34.5	1674	29.2
1641	32.2	1675	30.5
1642	33.5	1676	35.5
1643	32.9	1677	34.6
1644	33.5	1678	31.6
1645	33.7	1679	31.0
1646	32.3	1680	33.6
1647	28.8	1681	32.3
1648	27.3	1682	32.7
1649	28.1	1683	33.1
1650	28.5	1684	32.6
1651	29.3	1685	32.2
1652	31.6	1686	35.3
1653	35.3	1687	34.9
1654	38.9	1688	37.2
1655	39.6	1689	37.8
1656	33.6	1690	35.9
1657	32.8	1691	36.7
1658	30.0	1692	32.1
1659	29.3	1693	29.9
1660	30.2	1694	30.1
1661	28.9	1695	32.5
1662	27.9	1696	30.3
1663	31.1	1697	29.1
1664	31.6	1698	28.0
1665	33.2	1699	29.7
1666	36.1	1700	32.9
1667	36.9	1701	35.9
1668	36.2	1702	38.1
1669	32.6	1703	38.5
1670	33.9	1704	34.9
1671	33.5	1705	37.5
1672	34.3	1706	38.6
1673	33.3	1707	38.2

YEAR	WHEAT GROSS OUTPUT (BROAD_POP, SERIES I) Million bushels
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