Variations in the price and quality of English grain, 1750-1914: quantitative evidence and empirical implications.

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Abstract[1]

Interpretation of historic grain price data may be hazardous owing to systematic grain quality variation – both cross sectionally and over varying time horizons (intra-year, inter-year, long run). We use the English wheat market, 1750-1914, as an example to quantify this issue. First, we show that bushel weight approximates grain quality. Then we show that cross sectional and intra-year variation are substantial and problematic, generating erroneous inference regarding market integration. Long run variation is significant, due to sharply declining international quality differentials, and this impacts estimated cost of living changes. By contrast, inter-year variation is smaller and controlled for more easily.

JEL Codes: N01, N50, Q13.

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1. Introduction

We address the issue of quality variation, which we shall quantify for wheat, the primary Western European food grain since 1800 (Collins, 1993). We discuss consequences of quality variation for both market participants and historians interpreting price and quantity data, focusing on the issue of interpretation by historians.

As a widely available historical source, grain prices have been used to quantify living standards (Phelps Brown and Hopkins, 1956), market integration (Shiue and Keller, 2007) demand elasticity (Fogel, 1992), interest rates (McCloskey and Nash, 1984) and even cognitive ability (Baten, Crayen and Voth, 2014). These studies rely on the fact that wheat used to contribute a large share of household budgets and caloric intake (Feinstein, 1998) and shortages of grain led to famine as recently as 1891-2 in Russia. With so many wheat prices being used, it is important to know how much quality variation matters, e.g. Brunt and Cannon (2013) argue substantial and systematic pre-1914 wheat quality variation makes price movement interpretation difficult.

Quality variation is frequently acknowledged in economic history but rarely studied explicitly. Olmstead and Rhode (2003) study post-1920 US cotton quality improvements, particularly via the quality metric of staple length. But they really focus on governmental and economic institutions to facilitate raising quality, rather than implications of quality measurement and implications for price variation. Olmstead and Rhode (2002) study exhaustively US wheat seed variety ("cultivar") changes, 1840-1940, showing how changing cultivars enabled wheat production to spread to harsher US climates and maintained yields in the face of crop pests. Again, this differs from our focus on interpreting historical data.

Within the English market, merchants determined quality by inspection, at purchase and delivery. Increasing mid-19th century international trade required organizations (Chicago Board of Trade, London Corn Trade Association) enabled traders to establish quality remotely (Velkar, 2012). Reliable long-distance transmission of quality information was crucial for modern milling techniques. But wheat quality information remained problematic for some imports even in the late 19th century – notably Indian, as evidenced by the Secretary of State of India's 1885-90 enquiry (BPP, 1894).

In this study of English quality variation 1750-1914, we begin with definitions and contemporary information on domestic wheat in different locations (section 2) and of different types (section 3). In section 4 we discuss trends in quality of imported wheat. Section 5 uses our estimates of quality variation and simulation analysis to see the effects on time-series analyses of prices. Section 6 looks at the inter-year variation and section 7 discusses the within-year variation. Overall, we find substantial spatial and long-run quality variation; measurable but modest inter-year variation; little *systematic* intra-year quality variation for wheat (rather more for barley and oats).

2. Grain quality

Although we focus on England, we provide an historical benchmark where quality is directly measured – late 19th century USA. The Chicago Board of Trade developed a wheat grading system to facilitate exports, culminating in the 1916 US Grain Standards Act (Hill, 1990). Long distance trade (Chicago to New York, thence Europe) necessitated explicit grain quality measures to create homogeneity and transparency (Henry and Kettlewell, 1996). Each wheat type was subdivided into six grades (Grade 1 at the top, down to Grade 5, to "Sample Grade" at the bottom). Grades were based on bushel weight, moisture content, percentage of damaged kernels, purity, cleanliness and condition (Ball *et al*., 1921).

US price data for this period are constant-quality, sometimes available for several grades. With some variation, Grade 2 wheat traded at a 5% discount to Grade 1, a 12% premium to Grade 3. Proportions of each grade shipped Chicago-New York show great year-on-year variation: 1% was Grade 1 in 1879, 11% in 1878 (Chicago Board of Trade annual reports – see appendix A1). Using prices and proportions of each quality, we construct an average-quality index to quantify annual quality volatility for 31 years (1875-1912, 7 years missing).

To fix concepts and notation, consider the following price model, where the quality traded changes over time. At time *t*, observed average market price is P_t, dependent on the average quality traded at time *t*. Define P_t^* as the market price if average quality at time *t* were actually constant over the whole time sample: notice that P_t^* changes over time due to shifts in supply and demand. Then

(1) $$P_t = P_t^* H_t \Rightarrow \ln P_t = \ln P_t^* + \eta_t$$

where $\eta_t \equiv \ln H_t$ is the effect of quality on price. Throughout this paper we use the standard deviation of log variables (similar to the coefficient of variation) as our volatility measure. For US wheat, 1871-96, where we observe both prices and quantities of different qualities, the standard deviation of η_t was 0.034 (i.e. 3.4%), with no trend. The corresponding standard deviation of changes prices for a constant quality wheat was 14.6%. So annual quality volatility was a quarter of the magnitude of (constant-quality) price volatility.

Explicit quality data are unavailable for England, or elsewhere, pre-1914, but very occasionally we can make inferences from within-market variation. Figure 1 illustrates Bristol prices taken from the corn inspector's notes on individual transactions used to calculate the 1790 London Gazette Corn Returns average (BRO, 04531/1). Bristol's corn market opened only once per week in the late eighteenth century, so the within-week prices we observe must be contemporaneous and price variation is thus due to quality variation. In 38 weeks there was more than one transaction and hence more than one price. For example, the week ending 2 January 1790 had seven transactions, with prices from 51/0 per quarter to 61/4 (weighted average of 56/0): about half total trade was a single transaction at 58/4. The estimated quality variation from the standard error of the weighted mean price is 1.86% of average price. The standard deviation of the average weekly price from these data is 6.2% (similar to the corresponding figure of 5.9% in the 1820s when the Bristol average price was first published in the London Gazette). So for these weekly data, the ratio of quality variation to constant-quality price variation is about a quarter, similar to the ratio for the annual US data discussed above.

Figure 1 here.

How can we measure quality variation, absent explicit quality data or contemporaneous prices? A key source of pre-1914 grain price variation derives from prices being quoted by volume in most countries; many quantitative studies are based on volumetric prices (e.g. Keller and Shiue, 2014). Mass is a superior basis because grain mass primarily determines the flour mass produced. Since flour has always been sold by mass – and since grain value is determined by flour value produced – it makes sense to value grain on the basis of its mass (note that English flour sacks had a standard weight of 240lbs, so were really a mass measure.)

Weighing bulk grain was more difficult and costly than establishing volume pre-1914, so trading grain by mass was less popular (Velkar, 2012). The 1834 Corn Inspectors' returns (BPP 1834) reveal that, of 148 monitored markets, 90 used volume alone; 28 used mass alone; about 10 used both; the remainder are hard to classify (appendix A2). Regardless of local custom, the London Gazette published data based on volume: a proposal by the Select Committee on the Sale of Corn (BPP 1834) for official returns to include information on both volume and density was never implemented. The Select Committee's primary conclusion was that significant density variation primarily determined grain quality variation. Most corn inspectors gave no detailed comments, but eighteen inspectors explicitly linked quality to density in 1834. (The Sheffield Corn Inspector explicitly linked measurement problems to density and quality: "the weight per load is often mentioned by the seller in confirmation of the quality of the corn; frequently the small farmers have not the means of ascertaining the weight at home, and then recourse is sometimes had to the scales at the weighhouse in the market." BPP 1834, 252). Thus grain density is the main focus of our discussion in this section.

We model cross sectional quality variation using the following decomposition:

(2) $$\underbrace{P^V}_{\text{shillings per bushel}} = \underbrace{P^*}_{\text{shillings per quality-adjusted lb}} \times \underbrace{\theta}_{\text{quality adjustment}} \times \underbrace{B}_{\text{lb per bushel}} \Leftrightarrow \ln P^V = \ln P^* + \ln\theta + \ln B$$

P^V is price by volume; B grain density; θ any quality not incorporated into density; P^* the price by mass with constant quality. Supply and demand changes generate P^* variation.

Federico (2008) proposes log-price variance as the best market integration measure. From (3)

(3) $$\begin{aligned}\operatorname{var}\left[\ln P^V\right] &= \operatorname{var}\left[\ln P^*\right] + \operatorname{var}\left[\ln\theta\right] + \operatorname{var}\left[\ln B\right] \\ &\quad +2\left\{\operatorname{cov}\left[\ln P^*, \ln\theta\right] + \operatorname{cov}\left[\ln P^*, \ln B\right] + \operatorname{cov}\left[\theta, \ln B\right]\right\}\end{aligned}$$

Successful market integration measured by the arbitrage condition (i.e. in markets i and j, $P_i^* = P_j^*$) would suggest a low value of $\operatorname{var}\left[\ln P^*\right]$: in practice nearly all empirical studies are based on $\operatorname{var}\left[\ln P^V\right]$. We discuss some further consequences of this measurement error in appendix A2.

Many 1834 Corn Inspector returns contain bushel weights (see table 1), offering two quality variation measures. 18 inspectors give bushel weight ranges – typically 6% of average bushel weight – showing how much bushel weights varied locally. This number is only indicative, as it is unclear precisely what inspectors meant by this range: it could be between-farmer or inter-year variation. The between market variation is best measured by the coefficient of variation of typical or average bushel weights, which is 2.8%

Table 1 here.

Table 2 shows the relationship between inspectors' reported average bushel weights and London Gazette average bushel prices. Attenuation bias pushes the estimated elasticity of price with respect to bushel weight below unity (though not statistically significantly): not surprising, as bushel weight data are low quality and we cannot control for other quality factors.

Table 2 here.

Region or county dummies have little effect on coefficient estimates, though precision falls. Estimated elasticities are consistent with contemporary analysis. In his evidence to the Select Committee of 1834 (BPP 1834, 348), Page gave the example of high-quality wheat (61.25 lbs/bushel) being worth 11% more than low-quality (57.25 lbs/bushel). Two-thirds of the price differential derived simply from differential grain weights. If sellers overfilled sacks of low-quality grain to make them weigh the same as sacks of heavier grain, this would cost 8% of the low-quality bushel. A 3% price difference would remain, arising from low-quality grain having less valuable flour. Two experimenters (Hillyard, 1840; Barclay, 1845) grew different cultivars and measured bushel weights; they asked local corn factors the price each would fetch. Differentials between the most and least expensive samples suggest elasticities of 0.53 and 0.84 respectively (appendix A5). All the results suggest bushel weight correlates with quality; elasticities in cross sectional data are consistently around two-thirds.

How important is this for price analysis? The unadjusted r-squared in the first regression in table 2 is 0.153, suggesting that $\text{st.dev.}\left[\ln B\right]/\text{st.dev.}\left[\ln P^*\right] = 0.43$ (calculations in appendix A4). So quality variation may have been slightly greater in 1830s England than in the US at the end of the century (which we estimated above as about one quarter).

Density is the primary quality indicator. Wheat type (red/white, hard/soft, winter/spring) was also important and affected price. Spring wheat contains more starch; "hard" wheat contains more gluten, necessary for good bread but not biscuit (Jago, 1886). So would density be a sufficient statistic to enable dealers to judge quality? To what extent is density important for quality *per se*, and to what extent correlated with other quality characteristics?

The 1834 Select Committee (BPP 1834) found evidence of density as a sufficient statistic. Cooke, Chairman of the Committee of Agriculture in the London Society of Arts:

> "A considerable dealer in corn called upon me this morning ...: I stated to him that there was an idea of adding weight to measure [volume]; he said, then if that is the case, then skill would be of no value; anyone might buy corn as well as ourselves."

Were other quality characteristics correlated with density? Jago (1895) provides an 1881 cross section of English and imported wheats. We regressed price/bushel on bushel weight alone, and on bushel weight and other quality determinants (table 3, full results in appendix A5).

Table 3 here.

Bushel weight evidently correlates with other quality determinants: additional explanators (gluten, impurities) reduce the estimated coefficient on density. The price elasticity of density is higher than our earlier estimates; presumably international wheat variation exceeded English.

18th century English commentators discussed price effects of grain characteristics (density, cleanliness, kernel soundness). A fundamental part of grain trading was sampling parcels for these characteristics to determine market price. High impurities made grain unsalable even in the 18th century (Ellis, 1744); Palmer (BPP, 1834, 256-60) speaks of wheat being "too hot" (starting to ferment) from being stored damp, and it being brought "into condition" by turning and aerating. Jago (236-37) notes that damp wheat was disadvantageous because it effectively meant purchasing water and resulted in mustiness. In 1814-33, the volume lost by 690,000 quarters of stored wheat coming into condition averaged 2% (appendix A5). Henry and Kettlewell (1996, 430-1) offer a modern analysis. Absent systematic evidence on these grain quality dimensions, we can say only that wet harvests resulted in more grain that was "too hot" being brought into granaries.

Return to the primary quality determinant, bushel weight, where we can say something well founded and rigorous. Table 4 reports "average" or "representative" bushel weights for wheat, barley and oats (additional grains in appendix A4), mainly from official sources (Corn Returns Act, trade and navigation accounts, etc.). They trend upwards, especially for wheat and barley; bushel weights increased by perhaps 7% between 1791 and 1902.

Table 4 here.

Consider within-harvest and between-harvest variation around these averages (table 5). An average year was around 59lbs (consistent with the Corn Returns Act), good years being around 2lbs heavier and bad years around 2lbs lighter. Within-year quality variation was larger, with high or low quality wheats weighing perhaps 5lbs more or less than average.

Table 5 here.

We charted long run bushel weight changes, year-to-year differences and within-year variation. How much flour, and what type, did a pound of wheat produce? Flour content ultimately defines grain quality. Variations in flour quantity, or quality, may explain grain quality variation not due to bushel weight. Details vary slightly, but English flour was generally assigned to one of five or six categories. "Household" – best quality, for white bread commonly eaten in London. "Seconds" – mixed with Household, or used by bakers selling bread below the maximum price. "Thirds" – shipped out of London, for brown bread in the provinces. "Fourths" (sometimes divided into "Fine middlings" and "Coarse middlings") – to Liverpool or Newcastle for ships' biscuit. Pollards and bran – not used for human consumption (Bennett and Elton, 1898). Component proportions varied significantly across wheat parcels, greatly affecting value. Dimsdale, a corn factor, was asked by a Parliamentary Committee (British Parliamentary Papers (1826-7), "Report", 674): "What proportion do you reckon that a sack of flour compares to a quarter of wheat, generally speaking?" He answered:

> "It depends so entirely upon the quality of the wheat, that I should mislead your Lordships by giving an answer. Flour, if good, will make more loaves per sack than if indifferent."

Table 6 reports how much flour, of each type, derived from bushels of different weights.

Table 6 here.

The 1841 data are based on 13 grain samples. A regression of flour extraction rate on bushel weight (appendix A5) reveals the elasticity of flour with respect to bushel weight is 1.4 (t-statistic = 2.29.

Table 3's extraction rates are higher than other sources. Elliott's 1903 Cabinet Memorandum suggests flour extraction rates of 72% (El-Husseini, 2002); Petersen (1995) suggests 70-75%; Feinstein used 75% (personal communication). Although our rates are high, the sources are consistent with one another and generate a plausible pattern. Panels B and C show heavier bushels contained higher proportions of farinaceous material. Heavier bushels have larger mass, by definition, so two effects pushed up high quality bushels' flour content – larger mass, and higher farinaceous proportion. This correlation is useful because bushel weight captures not only variation in grain mass, but also variation in flour mass – the fundamental determinant of bushel value – and makes bushel weight closer to being a sufficient statistic for quality variation. The outlier is Panel A, having light bushels but high extraction rates. Those data are drawn from London's Albion Mill, England's first steam-powered mill; perhaps the powerful, new machinery was better able to separate farinaceous material from bran, pollard and waste, giving higher extraction rates. It is also consistent with contemporary Parliamentary enquiries: Kingsford, a miller, gives typical flour extractions rates of 81.25% (BPP 1813-14, 292). Fire destroyed the Albion Mill in 1791, but the 19th century switch to steam milling possibly pushed up flour extraction rates.

How did grain quality affect price? Table 7 reports Stead's 1834 evidence to the Select Committee. Prices *per pound of grain* are similar for grains of all qualities: first quality sells for around 5%

more per pound than third quality, in both good and bad years (consistent with heavier bushels having proportionately more flour). Obviously, bushels weighing 10% more would sell for 10% more: more grain mass generates more flour mass. But bushels weighing 10% more actually sold for 15% more, owing to higher proportions of farinaceous material. Hence *price per pound of grain* was 5% higher for heavier bushels. Thus around two-thirds of grain quality variation arose from density variation.

Table 7 here.

3. Cross-sectional quality variation

Many factors generated grain quality variation across England (e.g. different storage conditions). But cultivar was probably the most important systematic grain quality variation determinant. Cultivar could vary due to supply or demand. Consider supply. Some cultivars are better suited to certain climate and soil conditions: so cultivars grown in the drier east differ from those in the wetter west. Also, there was a possible trade-off between grain and straw production: farmers located further from grain markets, producing relatively more animals, had relatively higher values for straw and might rationally choose lower-yielding cultivars. Finally, we assume nowadays innovations spread rapidly: less obviously true in the 18th century, superior cultivars might take years to diffuse. Parliamentary enquiries reveal significant systematic wheat supply quality variation. Coupland was asked: "As a corn factor, if you knew that the price of wheat in the Lincoln market was 60 shillings, would you, in giving an order for foreign corn, calculate upon an importing price of 60 shillings or above it?" He answered (British Parliamentary Papers 1826-7, "Report", 738):

> "I certainly should not expect to receive 60 shillings for what I imported. I should conceive that the average of the Lincoln market is much above the average of the country. The wheats in the Lincoln market are much better than the average quality; they are better by several shillings than the average quality."

Consider demand. Different places value seed characteristics differently: high-yield cultivars are valued in potential food shortage areas, but high-quality cultivars where people consume fancy goods (London). Hodgson, Liverpool corn merchant, was asked: "Were those [two] wheats of nearly the same quality?" And he replied (British Parliamentary Papers 1826-7, "Report", 753):

> "There is considerable difference in the quality; the quality of wheat imported into Liverpool is generally much inferior to the qualities imported into London; the wheats in

> question were 6 shillings to 8 shillings inferior to the quality of that which is sent to London; the consumption of Liverpool being generally of an inferior description of wheat; to place Liverpool and London qualities on a par, fully 6 shillings [20%] must be added to the Liverpool prices."

Systematic quality variation prevents prices equalizing across markets, affecting market integration measures.

Few historians have analyzed cultivar role in English agriculture. Walton's (1999) treatment of temporal change is largely descriptive. Anecdotal evidence reveals different cultivars being grown across regions, but systematic evidence is unavailable. An author may state Rivet is popularly grown in Lincolnshire, being better suited to the climate and soil. But we do not know *all* farmers were growing it; whether cultivation extended *throughout* Lincolnshire; or whether its use was *exclusive* to Lincolnshire. In fact, farmers often sowed several cultivars to suit different conditions around the farm (Ellis, 1744, 33-4; Trowell, 1750, 9); this also provided weather insurance and staggered harvest dates, spreading peak labour demand. Heterogeneity makes it difficult to quantify cultivar effects on yield differentials between Lincolnshire and elsewhere. However, presenting the available data puts bounds on the problem: how much *could* yields have varied around England from cultivar differences?

Rothamsted cultivar experiments, 1871-81, quantified yield differentials and tested if newer cultivars gave higher yields than traditional ones. This agenda is key because we must consider how traditional cultivars impacted regional yields and quality in the 18th and early 19th centuries. Absent contemporary experiments, our best approach is to examine later experiments based on the same seed stock. This measure is imperfect because quality of a given cultivar may have improved. 18th century farmers employed "in-breeding" – taking the best kernels from their current crop, and sowing only those, to propagate strains with desirable attributes. In 1601, Maxey lauded high yields from "well-dunged land sown with choicely picked seed"; in 1788, Marshall recommended using the best ears as special seed stock; the Romans used "mass selection" of the best ears, whilst "pedigree selection" (in-breeding) was used in the 19th century Percival (1934, 43, 75, 83-4). Possible quality improvement makes it hazardous to take 19th century cultivar data and project it back to the 18th century. However, we pursue this approach because we have little alternative (no systematic 18th century data exist) and we are careful to adduce corroborating qualitative evidence.

The *Journal of the Royal Agricultural Society of England (JRASE)* contains cultivar data from around 1841. The Society's motto – *Science with practice* – was implemented from the outset by organizing cultivar trials across England. Members sought to establish the best cultivars and raise average yields by popularizing them. The trials were less systematic than Rothamsted, taking place on private, working farms. This reveals how cultivars performed in a range of realistic farming conditions (unlike Rothamsted trials); but trial heterogeneity makes it difficult to assess whether results were driven by farming practices or cultivar characteristics. Farms differed in soil, climate, manuring, crop rotation and sowing practice (drill, dibble or broadcast; sow thick or thin; early or late in the season). Large samples might balance out such variation but most trials involved few cultivars and we typically have only a few trial observations for each cultivar. We analyze data from the seven largest trials (each testing 5-17 cultivars).

18th century information derives from Ellis – a well-informed practical farmer, agricultural writer and seedsman who gives considerable detail on numerous cultivars of wheat and other crops. The evidence is not quantitative but permits us to trace the history of different cultivars and get qualitative descriptions – such as Red Lammas being superior for bread making in 1750, just as in 1850. Appendix A4 reports yields and bushel weights for all identifiable cultivars in 1750, 1841, 1871 and 1914. Here we summarize the most striking features.

Rivet, said to be the oldest English wheat still cultivated in the late 19th century, gave heavy yields on strong land but had coarse straw and low quality grain. Walton (1999, 49) notes Rivet's exceptionally low gluten content, making it inferior for bread. Rothamsted results confirm Rivet's high yields – 21% more bushels/acre than Nursery Red (one of the lower yielding cultivars). But Rivet's quality was low, bushels weighing 7% less. So, controlling for bushel weight, Rivet was only 14% more productive. Yield and quality are strongly and significantly *inversely* correlated across Rothamsted cultivars (-0.6, p=0.01). Farmers could choose high yields and low quality, or vice versa, but not have both; contemporaries noted this (Percival, 1934). It may explain persistence of so many cultivars: one cultivar was not superior, but offered a different quantity-quality trade-off. Pooling the two largest *JRASE* trials, the yield-bushel weight correlation is -0.4 (p=0.08, N=21). These two trials were carried out in different years – one in wet Gloucestershire, the other in dry Lincolnshire – so we find it remarkable that results are so similar to Rothamsted.

The average yield across all cultivars 1871-8 was 42.5 bushels/acre, but for three known 18th century cultivars (Rivet, Red Lammas, Golden Drop) it was 46.7 bushels/acre. New cultivars generated no obvious yield increase, 1750-1871, although post-1750 disappearances – White

Cone, Red Pirkey, etc. – may have raised the average. But the distribution's upper tail was surely unchanged.

Table 8 below compares Rothamsted and *JRASE* data, reporting all cultivar matches. Yields are predictably different (Rothamsted averaging 17% higher, and a correlation between the two yield samples of 0.5, p=0.32). But bushel weights are almost identical (Rothamsted averaging 0.2% higher, and a correlation between the two sets of bushel weights of 0.7, p=0.15). Take two cultivar data sets, 30 years and hundreds of miles apart. You cannot easily predict yield levels – but you can predict yield rankings well, and bushel weights with extraordinary precision. Bushel weights in 1914 were also similar to 1871. This characteristic is very robust.

Table 8 here.

Persistent quality variation impacts market integration measurement. The literature presumes Law of One Price (LOOP) holds when transport costs are zero. But LOOP will *never* hold: with zero Kent-Lincolnshire transport cost, wheat would not trade at the same price because quality differed. How large was English cross sectional quality variation? Take average wheat prices for 1886-1914 for each county – long enough to smooth out random fluctuations, and so truly capturing equilibrium county prices. The coefficient of price variation is 2%. The coefficient of quality variation, *c*.1871, is also 2% (appendix A4). So quality variation *could* explain observed price variation. We matched seven cultivars to particular counties, based on qualitative literature: Cumberland (Fenton), Essex (Essex Brown), Gloucestershire (Bristol Red), Middlesex (London Red), Northumberland (Hopetown), Somersetshire (Bristol Red), Surrey (Surrey White). The quality-price correlation is 0.6 (p=0.16). Again, the evidence is weak – owing to few observations – but consistent with quality determining long run price variation.

International comparisons are very problematic. Persson (2004) and Hynes *et al.* (2012) tackle this by restricting their analysis to a particular product (such as "Manitoba No. 2 Red Wheat"); this is feasible for late 19th century Atlantic trade, but not earlier or for less developed markets, with less tightly defined products. Price dispersion estimates (favoured in Federico, 2008) are notably problematic. We considered quality variation in England – a small and relatively homogenous locality. The quality problem increases for larger regions (India, China) and international markets; it may also be larger for other commodities (rice?); and geographical quality trends can generate price convergence unrelated to market integration, as we show next.

4. Long-run quality variation

Although English and foreign wheat differed in quality, table 9 shows that bushel weights from different international sources both increased and converged in the period 1825-1900, showing wheat imports became more homogeneous.

Table 9 here.

How did bushel weight affect market value? Johnson (1902, 2) states explicitly grain parcels are entered into trade ledgers pro-rated. A trader accepts 100 bushels weighing 62lbs/bu, rather than the normal 63lbs/bu. This enters the ledger as a stock of 98.4 bushels (=100×62/63), while the bushel price is reflated by 63/62. This implies the elasticity of price to bushel weight was 1 (bushels 10% lighter valued 10% less and *vice versa*). Weeks (1871) suggests this was standard accounting practice by 1871, at the latest. This supports evidence above suggesting an approximate one-to-one relationship between bushel weight and market value.

Consider earlier years. Weighted average prices of foreign grains traded in England are reported in table 10. These prices are net of freight and import duties (i.e. the prices paid at Mark Lane) and so are likely to reflect quality variation alone. Data were reported in bushels to 1863 and so are directly comparable to English Corn Returns data. North American wheat quality equalled English; German was a bit better; western European was a bit worse; southeastern Europe and eastern Mediterranean – especially Egypt – were significantly worse.

Table 10 here.

Post-1863 trade accounts claim to report quantities in cwt., which is almost certainly wrong: apart from occasional use of the "cental" (100 lb) in Liverpool in the 1880s, grain usually traded in England in bushels and the government is unlikely to have had detailed bushelweight information to convert imported grain from bushels to cwt. Also, most quality variation arises from bushel weight variation: reporting prices per cwt should reduce price variation, but the variation does not fall after 1863 (compare columns 2 and 4 of table 10); correlation between the two cross sections of country average prices is 0.89 ($p<0.01$). How did the Government generate the cwt. data? We are not told but can infer it. An 1887 account reports imports back to 1866 in quarters, noting they have been converted from cwt. at 4.5 cwt./quarter (63lbs/bushel) (BPP 1887, 300). Converting country cwt. data back into bushels at 63lbs/bushel, gives prices in table 10, column 4. Prices are a bit lower in 1864-74 than 1855-63, but differentials are very similar. Egypt is exceptional, its quality converging to the Eastern Mediterranean mean.

The conversion saga has several implications. First, suppose the Government were correct that imports averaged 63lbs/bu. Total import estimates, expressed in cwt. from 1864 onwards, would be correct. But individual country figures would be wrong: accurate country figures require country-specific bushel weights. Second, reversing Government calculations enables inference of number of bushels imported from each country, and then prices per bushel (given total import value from each country). We can thus infer quality changes over time using the ratio of European wheat prices to English wheat prices, shown in figure 2. Third, weighting prices by trade volumes enables calculation of changes in average English wheat consumption prices.

Figure 2 here.

All series are flat (trendless compared to English wheat). Danish and French wheats were consistently slightly lower quality, German and Spanish wheats consistently slightly higher. Danzig furnished much German wheat sent to London, and was renowned for high quality (Scott, corn factor, BPP 1795, 26; Lander, Maltese Government Agent, BPP 1826-7, 649; and Birkett, corn factor, BPP 1826-7, 657-8 and 660; Capper, 1862, 230-1).The half-dozen very low values typically involve small quantities – maybe small loads of very low quality grain (perhaps damaged in transit), or maybe data recording errors at the customs house. There is some suggestion English wheat quality fell after 1885 (Biffen, 1905-6, 4-5; Percival, 1934, 70-1). If so, quality of other European wheats fell similarly, which is plausible because western European nations bought English seed (Humphries and Biffen, 1907-8, 2-3).

Figure 3 charts New World wheat quality. There is clear upward movement, from a price relative of 1 to 1.1, with a discrete jump around 1878. Australian wheat was significantly higher quality than others; Indian wheat started lower but converged by 1914.

Figure 3 here.

Figure 4 is most dynamic, trending strongly upward from 0.8 to 1.1, 1855-1914. Egyptian wheat started lowest but gained most; Persian wheat was highest. Eastern Mediterranean wheat was long known in England for low quality (Wilson, corn factor, BPP 1813-14, 273; Lander, Maltese Government Agent, BPP 1826-7, 652). A key problem was poor threshing technique (livestock treading); it added impurities to grain, which was not cleaned and lost condition faster (Bosanquet, Governor of the Turkey Company, BPP 1795, 26; Baldwin of Alexandria, BPP 1795, 183; Dimsdale, corn factor, BPP 1826-7, 666, 676; and Schneider, Russia merchant, BPP 1826-7, 730). Processing improvements in the late 19th century eastern Mediterranean likely increased quality and market value in London. Expansion to virgin soils on the Great Plains likely raised average

American grain quality (in North America and Argentina). Western and central European soils – cultivated for 1 000 years and already well managed in 1855 – saw no quality improvement to 1914.

Figure 4 here.

Finally we construct a weighted average price of foreign and domestic grain consumed in England: the "consumption price" of wheat, using the trade accounts and the cwt/bushel conversions discussed above. Figure 5 charts consumption price and weighted average English (Corn Returns) price. Although the two series track each other closely, the large overall variation disguises a significant decline in the relative price in the period 1839-1914, which is illustrated in the same figure (right-hand scale): foreign prices rose faster than the English price by 0.1% per annum, resulting in a large change over 65 years. Using price series close to the item of interest is important when constructing the index; so Feinstein's index (using bread prices) is likely more accurate than Clark's index (using English wheat prices).

Figure 5 here.

To sum up, we have documented substantial quality differentials between English and different foreign wheats and significant relative quality changes over time particularly in wheat from Egypt and eastern Mediterranean. The fall in the standard deviation of log prices in table 10 (0.117 to 0.092) is due to quality convergence rather than improved market integration. And rising foreign prices and market shares means the wheat consumption price rose significantly faster than the Corn Returns imply.

5. Measurement error effects in time series models

We now quantify the effect of quality variation on modern time-series methods. Most modern time-series studies use a cointegrating VAR framework of the form

(4) $$\Delta \mathbf{p}_t^* = \boldsymbol{\alpha\gamma}\mathbf{p}_{t-1}^* + \boldsymbol{\mu} + \boldsymbol{\varepsilon}_t \qquad \forall t \neq s : \mathrm{cov}\left[\boldsymbol{\varepsilon}_t, \boldsymbol{\varepsilon}_s\right] = 0,.$$

$\mathbf{p}_t^*$ is a vector of log-prices for constant-quality wheat, as defined in equation (1). With cointegrated prices, market efficiency (speed of return to equilibrium) is measured by $\boldsymbol{\alpha}$ (the “loadings”). These can be estimated alongside $\boldsymbol{\gamma}$ (Johansen procedure) or by imposing price homogeneity.[2]

Estimates of long-run relationships are unaffected by measurement error. But here we quantify measurement error effects on causality direction and estimated market efficiency (speed of adjustment) when observed volumetric prices $\mathbf{p}_t^V$ are affected by measurement error of form

(5) $$\mathbf{p}_t^V \equiv \mathbf{p}_t^* + \boldsymbol{\eta}_t .$$

For simplicity, consider just two prices, A and B, and long-run price homogeneity so that $\boldsymbol{\gamma} = \begin{pmatrix}1 & -1\end{pmatrix}$. Remaining simplifying assumptions about disturbances and errors are:

(6) $$\begin{array}{l} \text{corr}\left[\varepsilon_t^A, \varepsilon_t^B\right] = 0.5; \quad \text{var}\left[\varepsilon_t^A\right] = \text{var}\left[\varepsilon_t^B\right] = \sigma_\varepsilon^2 \\ \text{E}\left[\boldsymbol{\eta}_t\right] = \mathbf{0}; \quad \text{var}\left[\boldsymbol{\eta}_t\right] = \sigma_\eta^2 \mathbf{I}; \quad \text{cov}\left[\boldsymbol{\eta}_t, \boldsymbol{\eta}_{t-1}\right] = \mathbf{0} \end{array};$$

so there is some correlation between disturbances to the true price series (invariably observed in real data), and classical measurement error in both price series. Disturbances and measurement errors are assumed Normally distributed. We considered a variety of parameter values for equation (4) and the measurement error, but report results here based on:

(7) $$\boldsymbol{\alpha} \in \left\{ \begin{pmatrix} 0 \\ \alpha \end{pmatrix}, \begin{pmatrix} -\alpha/2 \\ \alpha/2 \end{pmatrix} \right\}; \quad \sigma_\eta \in \left\{ 0, \sigma_\varepsilon/4, \sigma_\varepsilon/2, \sigma_\varepsilon \right\}$$

We consider two possible configurations of α to determine causality: first, “asymmetric loadings”: price A Granger-causes price B but not vice versa (only price B adjusts to remove

[2] Two further issues are not discussed here. One can test for market integration (price cointegration) using the Johansen trace test; one can estimate the cointegrating relationship summarized by vector $\boldsymbol{\gamma}$. Hassler and Kuzin (2009) show the cointegrating vector can be estimated consistently and the Johansen test continues to be reliable (probability of making a type I error is unaffected) provided sufficiently many lagged price differences are included in the VAR to remove serial correlation in residuals. Second, Nielsen (forthcoming) introduces a technique to measure the speed of adjustment when there is measurement error.

disequilibrium); e.g. Uxbridge adjusts to London; second, “symmetric loadings”: both prices adjust the same amount to remove disequilibrium; so Alnwick and Berwick adjust towards each other. We analyze four possibilities for measurement error magnitude (whose standard deviation is compared to standard deviation of disturbances to the underlying price). Earlier, we compared measurement error standard deviation to that of observed prices, S_h/S_p: we report this relationship in table 11 when the half life is two. This is lower than the ratio $\sigma_\eta / \sigma_\varepsilon$ because the measurement error induces a negative moving average error in equation (7). Our results above suggest relevant simulations are when $\sigma_\eta / \sigma_\varepsilon$ is between a quarter and a half.

Table 11 here.

Figures 6-8 summarize measurement error effects on estimation by plotting median impulse response functions when half life is two time periods and sample size is 200. Top-left curves, calculated with no measurement error, differ only slightly from the true impulse response functions because a sample size of 200 removes nearly all of the small-sample bias. Figures 6-7 show measurement error effects with asymmetric loadings. Shocks to A should be permanent, but some of the effect appears temporary with measurement error; conversely some of the shock to B appears permanent despite being temporary. Estimated response functions to the exogenous price are more biased. Figure 8 shows the effect for symmetric loadings (the impulse response functions are idential for both prices), with little bias in the temporary versus permanent effects. Unsurprisingly more measurement error leads to more bias in the estimated long-run effect, but there is more distortion to the estimates when one market is dominant (asymmetric adjustment).

Figure 6 here.

Figure 7 here.

Figure 8 here.

Regardless of asymmetry, convergence speeds are over-estimated when there is measurement error. In figures 6-8, compare top-left graphs (no measurement error) and bottom-left (measurement error observed in English data). The estimated shock half life falls erroneously from two weeks to one. Table 12 shows that the bias depends on the true half life: small-sample bias means that half lives are always biased down slightly, but measurement error magnifies this hugely, especially when the true half life is high: when $\sigma_\eta / \sigma_\varepsilon = 1$, less than half the disequilibrium remains after one period, regardless of true half life. Since many analyses suggest half lives of several months, even half a year (Persson, 2000) our Monte Carlo simulations suggest that these biases may be important in practice.

Table 12 here.

Is classical measurement error an appropriate assumption? Measurement error is hard to observe and depends on the data set. The data presented in Figure 1 suggests that average prices in a market could vary considerably due to sampling error, which is likely to be close to classical measurement error. From Rothamsted bushel weight data (1844-83) we calculate autocorrelation in our two plots was -0.021 and 0.036, consistent with classical measurement error in annual data (details in appendix A6). Other economies (e.g. those with inter-year storage) could still have autocorrelated errors; each case must be checked. Private English grain trade letters also describe random price shocks arising from quality variation (e.g. Oxfordshire History Centre, SLC101), again consistent with classical measurement error in our case.

6. Year-on-year quality variation

Inter-year grain quality variation may be important. We show yield/acre (quantity) and quality are positively correlated. So true quantity (tonnes of grain) was greater than the bushel measure in good years, lower in bad years. How does this bias the estimated elasticity of demand?

Rothamsted furnishes two useful data sets. Cultivar trials, 1871-81, provide yields and bushel weights (appendix A6); so do continuous wheat experiments started in 1844 (appendix A5) (Lawes and Gilbert, 1864; 1884). The latter are extremely detailed, reporting dressed corn average bushel weight, total dressed corn weight and total offal weight. We analyze two time series, 1844-83: the plot manured with yard dung, and the plot remaining unmanured. These plots best reflect conditions on working farms, where – to 1860, at least – most land received yard dung or nothing. Table 13 reports results for the manured plot and pooled regressions for both plots (the unmanured plot is presented separately in appendix A5). Since neither slope coefficients nor intercepts differ significantly between manured and unmanured plots, the pooled regression is our best estimate. We estimate all regressions for the whole period and for a sub-sample omitting 1853, 1879 and 1880 (years with particular problems and low yields).

Panel A reveals a positive, statistically significant time series yield-bushel weight correlation; omitting bad outlier years gives estimated elasticities of about 4% in typical years. Panel B reports results for different cultivars. Walton (1999) posited a negative yield-bushel weight correlation across cultivars. We find a large – but statistically insignificant – negative elasticity (-0.11) using the largest possible balanced panel (1873-78); the overall relationship is positive. But one cultivar need not dominate others: some may be better adapted to alternative soil types or produce more straw. The within-group estimator reveals similar results to the time series: a positive elasticity of 5%, rising to 11% if bad outlier years are included.

Table 13 here.

Suppose elasticity of density to yield were 10%. What does this imply about bushel weight fluctuations? National agricultural returns report average English wheat yields of 30.7 bushels, 1885-1914, with a standard deviation of 2.6 (8.5%). A harvest two standard deviations above average would see yields 17% above average, implying a bushel weight increase of 1.7% (=0.17×0.10), or 1lb if bushels averaged 60lbs. This is below 18th century estimates (tables 4 and 6), when observers suggested bushels weighed 2lbs above (below) average in good (bad) harvests. Of course, 18th century yield volatility may have been higher. Clay pipe drainage installation may have reduced volatility by removing excess water more effectively and reducing crop losses in wet years, lowering yield volatility after the 1830s (Phillips, 1989). Our 10% estimated elasticity of density (quality) to yield (quantity) is more likely too low than too high.

Estimating wheat demand elasticities *adjusting for year-on-year quality variation* generates estimates 10-15% higher than those based on unadjusted quality. Barquín's (2005) exhaustive study of European wheat demand elasticities from the late mediaeval period to 1914 incorporates all previous estimates, such as Fogel's and Persson's; he suggests a late 19th century English elasticity around 0.43, and 0.68-0.78 for other countries (pp. 260-1). Year-on-year quality variation adjustment would push estimates to 0.5 for England, and 0.8-0.9 for other countries. Barquín makes similar-sized adjustments for carryover and seed. But those effects are offsetting, whereas quality variation pushes estimated elasticities decisively downwards.

7. Intra-year quality variation

Several studies analyze intra-year grain price patterns (McCloskey and Nash, 1987; Clark, 1999; Brunt and Cannon, 1999). Grain price paths are theoretically saw-toothed – starting from a post-harvest low, rising gradually through the year, dropping abruptly at the next harvest. Why? Grain holders must be compensated, receiving gains to offset storage cost (granary rental), losses (to vermin) and opportunity cost (return from investing capital elsewhere). This conceptualization rationalizes inference of rates of return on capital – steeper intra-year grain price rises imply higher local interest rates. Now incorporate quality variation into the analysis.

The best grain was never marketed but retained – or sold privately – for seed (Ellis, 1744, 339-40); Trowell, 1750, 9; Porter, Office of the Committee of Privy Council for Trade, BPP 1795, 186). Winter (1798, 131) states seed grain commanded a 10% premium. England never suffered a famine requiring farmers to sell seed corn for milling, so we never see it in markets. The worst grain (offal/tail corn) comprised smaller kernels, maybe broken and contaminated with non-wheat seeds (Ellis, 1745, 129) and was consumed on-farm. But if the harvest turned out lower (or demand higher) than expected then offal coming to market late in the year could put downward pressure on (rising) prices, since those units would be lower quality. Then we systematically underestimate price increases in high-priced years.

With offal at 6.5% of the harvest, and 10% retained on-farm in 1801 to feed farm families, no offal was marketed Brunt and Cannon (2013, 324). 1851 on-farm consumption was maybe 5.3% of the total, given changes in agricultural population recorded in the Census (BPP, 1852-3). By 1845 – the eve of free trade, with grain imports at maybe 10% of consumption – 5.3% of consumption constituted 5.8% of domestic output. So on-farm consumption likely still absorbed all offal, especially since some was used for fattening livestock (Walton, 1999).

How does offal affect market prices? In Barclay's (1845, 192-3) price data for dressed grain and offal, for five different cultivars, offal sold for a mean 14.7% discount. Marketing only offal in the final pre-harvest month (an extreme assumption) would reduce prices by 14.7% – about equal to the average intra-year price increase (Brunt and Cannon, 2013). So grain holding return might appear zero, although truly 15%. Unproblematic in English data (significant offal likely never came to market), bias could arise in other countries and circumstances (e.g. famines). Brunt and Cannon avoid price data from late in the harvest year, when contamination is most likely.

Intra-year quality variation impacts barley. Brewers bought best quality malting barley post-harvest, when markets were most active (Brunt and Cannon, 2013). Trade then fell sharply and involved lower quality (non-malting) barley; price impact was large. Price courants report malting barley (several cultivars) and other barley. For example, Tuesday editions of the *Courier and Evening Gazette* list prices of many grain and seed types, including barley, fine barley, malting barley and fine malting barley; in 1799 they traded around 38, 41, 45.5 and 49 d/bu respectively. The *Morning Chronicle's* "Corn Exchange Report" in 1841 has grinding and malting barley at around 22.5 and 29 sh/qu respectively. With malting barley commanding a 20% premium, trading all malting barley in the autumn – and all grinding barley in spring – generates a 20% price fall, offsetting intra-year price appreciation that acted as a holding return. Without good data on malting mark-up and the monthly share of malting barley in total trade, we cannot separate these two effects. Thus barley prices are useless for inferring holding returns.

Oats may mirror barley. Horses consumed oats; so did humans (notably in northern England and Scotland) as porridge and oat bread. High quality oats went for human consumption (Palmer, BPP 1834, 258); so, counterintuitively, high quality oats traded systematically in low-income areas. There was likely systematic oat quality variation through the year – human supplies secured first (at high prices) and horse oats later (at lower prices). It seems wise to treat intra-year oat price movements with some caution.

8. Conclusion.

We examined international and English wheat quality variation, spatially and over time (intra-year, inter-year and long run). Variation arises primarily from bushel weights – useful because it is quantifiable. Contemporaries assessed quality by inspection, so market prices reflected it.

Inter-year quality variation was small. Quality and yields being *positively* correlated annually, variation in quality-adjusted wheat output was around 15% higher than unadjusted variation. Time series analyses – e.g. estimating demand elasticity – can control for this, given available quality data. Estimated demand elasticities would rise by 15%, compared to previous estimates.

Marked cross sectional quality variation was *inversely* correlated with local yields (places generating high volumes produced low quality). Long run stability in England – the same counties grew the same cultivars for centuries – suggests it was an equilibrium. Localities optimally chose high quality (near London, for cakes) or high volume (Lincolnshire, for ship's biscuit). Cross sectional quality variation means Law of One Price never holds strictly – prices never fully converge, even with zero transport costs. Price variation coefficients are problematic for measuring market integration; the wider the net is drawn (local-national-international), the more quality variation we see and the further we are pushed from the Law of One Price (irrespective of transport costs). Effect size changed over time (international quality differentials in 1825 and 1855 vanished by 1914), generating spurious evidence of market integration.

Transient random intra-year quality shocks bias market integration measurement using ECMs because price responses to quality shocks are confounded with responses to price shocks. Wheat quality volatility was sufficiently high that the literature likely overestimates half lives by 100%.

Systematic intra-year quality variation was likely not problematic for English wheat, but was for barley and oats. So English the former offer a safe basis for inferring rates of return on grain, but the latter do not. In other countries or time periods, systematic variation in intra-year wheat quality cannot be discounted *a priori* and must be considered when analyzing price variation.

Further research on grain quality variation (using official or courant prices, agricultural census) could increase precision and reliability of estimated demand elasticities and market integration.

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Figures and Tables

Figure 1. Bristol weekly wheat prices, 1790.

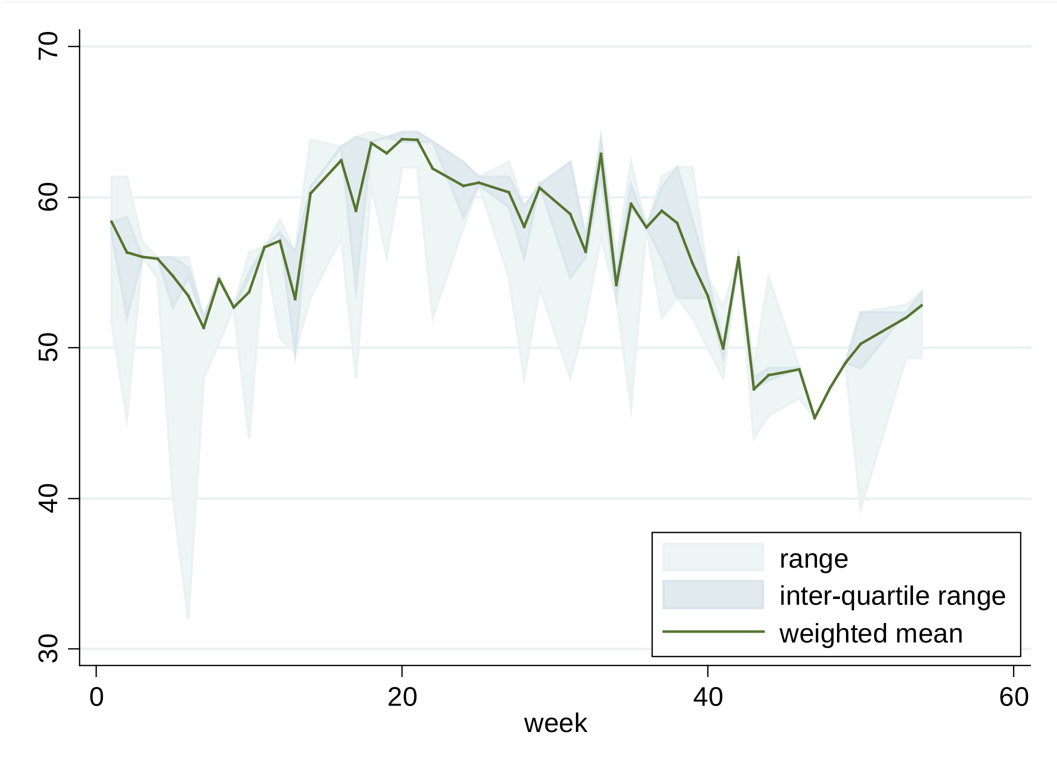

Table 1: Summary of information from Corn Inspectors in 1834

	Average, usual or mid-range bushel weight	Range (maximum - minimum) of bushel weights	Range of bushel weights relative to average
No of observations	46	18	18
Average	62.10	3.95	0.06
Minimum	58.63	0.50	0.01
Maximum	67.50	8.00	0.13

Authors' calculations from BPP (1834), 105; details in appendix A2.

Table 2: Relationship between price and bushel weight.

Dependent variable: ln(average price per bushel)	(1)	(2)	(3)
ln(bushel weight)	0.6108*	0.6528+	0.5527
	(0.2564)	(0.3515)	(0.3504)
Region FEs		✓	
County FEs			✓
N	40	40	40
Adjusted r²	0.1287	0.1129	0.4775

Regressions include a constant. SEs in parentheses, clustered at county level in specifications (1) and (2). Dependent variable is average log price, 1828-42, where markets are dropped if more than 5% of prices are missing (details in appendix). $^{+}$ $p < 0.10$, * $p < 0.05$.

Table 3. Relationship of price to bushel weight and other qualities.

	ln(price/bushel)	ln(price/bushel)
ln(bushel weight)	2.0806**	1.0974+
	(0.4205)	(0.4650)
ln(impurities)		-0.0079+
		(0.0037)
ln(gluten)		0.0042+
		(0.0019)
ln(flour)		0.0001
		(0.0040)
N	10	10
Adjusted r^2	0.7229	0.8763

Regressions also include a constant. Standard errors in parentheses $^{+}$ $p < 0.10$, ** $p < 0.01$

Table 4: Bushel weights of British grain (lbs/Imperial bushel).

	Corn Returns Act 1791	Dodd 1856	Corn Returns Bill 1881	Brunt and Cannon 1839-1915	Johnson 1902
Wheat	59	60	60	60.75	63
Barley	51	48	50	50	56
Oats	39	40	38	38.8	42

Notes. See appendix A4.C.

Table 5. Variations in the weight of an English bushel of wheat.

Evidence of Richard Page			
	High quality		Low quality
Good year	66		52
Bad year	60		48
Evidence of Patrick Stead			
	High quality	Second quality	Third quality
Good year	64	62	59
Bad year	60	57	55
Evidence of Colonel Charles Pasley			
Average	65		55

Notes. BPP (1834): Page, 354; Stead, 95-6; Pasley, 273-9. Colonel Pasley, Royal Engineers, conducted a series of experiments in grain crops measurement methods. He also gives bushel weight variation for other crops: rye (51-58lbs); barley (46-51); oats (36-44); peas (61-69); beans (61-68).

Table 6. Flour produced by wheat of various bushel weights.

Bushel weight	Flour content by category (%, by weight)							
lbs/bu	House-holds	Second quality	Third quality	Fine middlings	Coarse middlings	Flour total	Pollard, bran	Waste
Panel A. *c.* 1788								
58	54.5	16.3	6.8	4.0	0	81.6	17.1	1.3
Panel B. *c.* 1795								
62	64.5	6.7	0.0	4.4	3.0	78.6	19.4	2.0
60	65.4	6.5	0.0	4.4	2.9	79.2	18.8	2.1
58	61.6	6.0	0.0	4.7	3.9	76.2	21.1	2.6
56	0.0	61.8	4.5	4.2	4.0	74.5	22.8	2.7
54	0.0	54.5	6.0	6.5	6.5	73.5	23.7	2.8
Panel C. *c.* 1841								
64						82.1		
63						81.3		
62						79.9		
61						76.7		
Panel D. *c.* 1856								
63	77.78			2.0	1.6	81.4	16.5	2.2

Notes. Calculations in appendix A4.D. Panel A based on Albion Mill data (Bennett and Elton, 1898, vol.3, 290); Panel B from evidence of Robert Ardlie, Appendix 6 of British Government, “Fourth report”; Panel C on Miles, “Report… Cambridge”, 391-5 and Le Couteur, “On the pure and improved varieties”, 113-23; Panel D from Dodd 1856, 184-5.

Table 7. Relationship between wheat bushel weights (lbs) and wheat prices (d)

	First quality grain	Second quality grain	Third quality grain
Good harvest			
Bushel weight	64	62	59
Price (d/bu)	480	456	420
Price (d/lb)	7.50	7.35	7.12
Bad harvest			
Bushel weight	60	57	55
Price (d/bu)	960	888	840
Price (d/lb)	16.00	15.58	15.27

Source. Evidence of Patrick Stead, BPP 1834, 95-6.

Table 8. Yields of wheat cultivars in bu/acre (bushel weights in brackets).

Cultivar	*c.* 1841	*c.* 1871	*c.* 1914
Club Wheat [Square Head]		49.2 (61.1)	38.7 (61.7)
Red Rostock [Russian Red]		45.4 (59.9)	36.6 (59.5)
Red Chaff		39.0 (61.5)	37.4 (60.4)
White Chiddam	22.5 (62.7)	37.1 (62.0)	
Golden Drop	27.6 (61.3)	46.8 (62.5)	
Old Red Lammas	30.5 (63.2)	39.6 (62.6)	
White Chaff	44.9 (59.8)	48.9 (61.0)	
Bole's Prolific	49.8 (61.3)	44.0 (61.5)	
Bristol Red	45.6 (62.0)	42.1 (61.3)	
MEAN	36.8 (61.7)	43.1 (61.8)	

Notes. We matched all possible cultivars, based on sources cited in table 4; 1841 estimates based on very small N – Old Red Lammas has four observations, other cultivars only two!

Table 9. Imported wheat bushel weights (lbs), *c.* 1825 and *c.* 1900.

Panel A: c. 1825						
Britain	Ireland	Saarbrücke	Holstein	Danzig	Odessa	Taganrog
60.75	60	56	57.5	63	59	70
Panel B: c. 1900						
Britain	Australia	Argentina	India	Russia	USA	
63	63	62	62	62.5	63	

Notes. Panel A: BPP 1826-7, 683 (Odessa), 700 (Holstein, Danzig), 725 (Taganrog); Brunt and Cannon (2004, 35-6) (Britain); BPP 1821, 307 (Ireland), 371 (Saarbrücke). Panel B: Johnson (1902, 5,20,22).

Table 10. Averages prices of wheat traded in England, 1855-74 (d/bu).

	Mean price, 1855-63	Import share, 1855-63	Mean price, 1864-74	Import share, 1864-74
English	85.14		81.77	
American	85.33	23.01	81.44	23.76
Canadian	83.12	4.44	79.66	4.51
Chilean			84.35	2.26
Australian			96.33**	1.01
Prussian	88.98**	14.06	86.66**	9.54
Mecklenburgian	87.65	1.98		
Danish	79.98**	3.93	77.64*	1.05
Belgian	84.22	0.55		
Dutch	83.81	0.56		
French	80.52	5.46	76.12*	2.62
Austrian Italy	85.28	1.13		
Russian	73.37**	14.08	74.48**	24.66
Romanian	70.55**	1.28	70.91**	0.97
Turkish	72.19**	1.51	71.16**	1.86
Egyptian	57.79**	7.06	70.93**	2.36
Total		79.02		74.60

Notes. British Government, "Annual trade and navigation accounts of the United Kingdom", various years. Data begin only in 1855 and format changes from 1864 onwards. We include all countries exporting to England every year (or nearly so) since volatility is high and including occasional exporters could generate erratic results. German prices for Prussia from 1870 onwards. Import share is share of *total quantity imported from all sources*, 1855-63 and 1864-74. * and ** means prices significantly different from English at 5% and 1% levels (matched pairs two-tailed t-test).

Figure 2. European/English wheat price relatives (all traded in London).

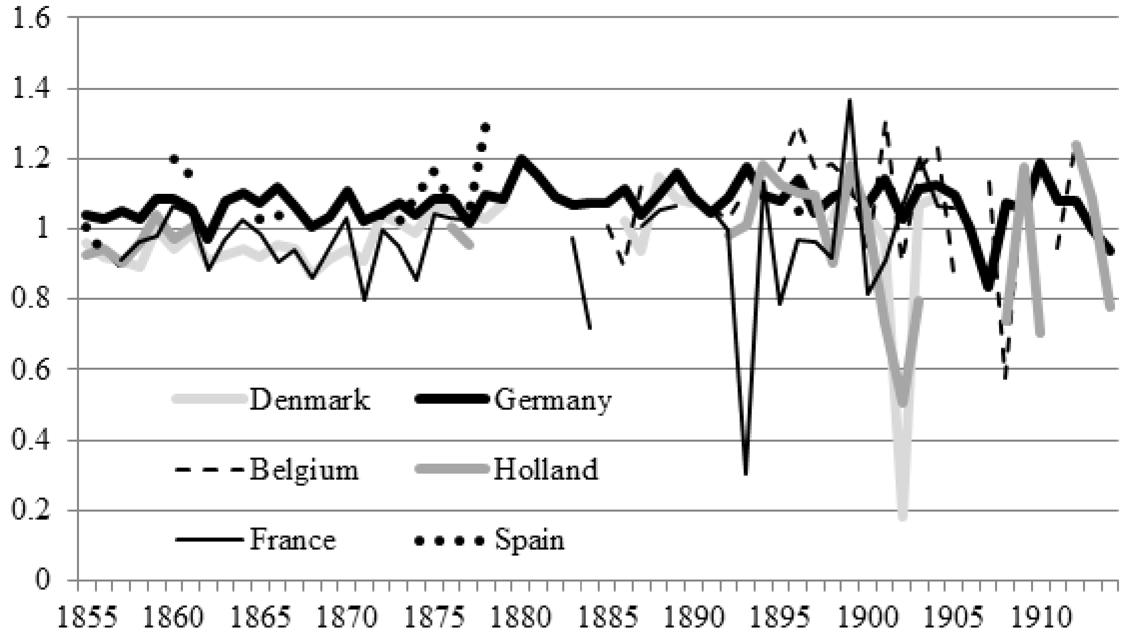

Figure 3. New World/English wheat price relatives (all traded in London).

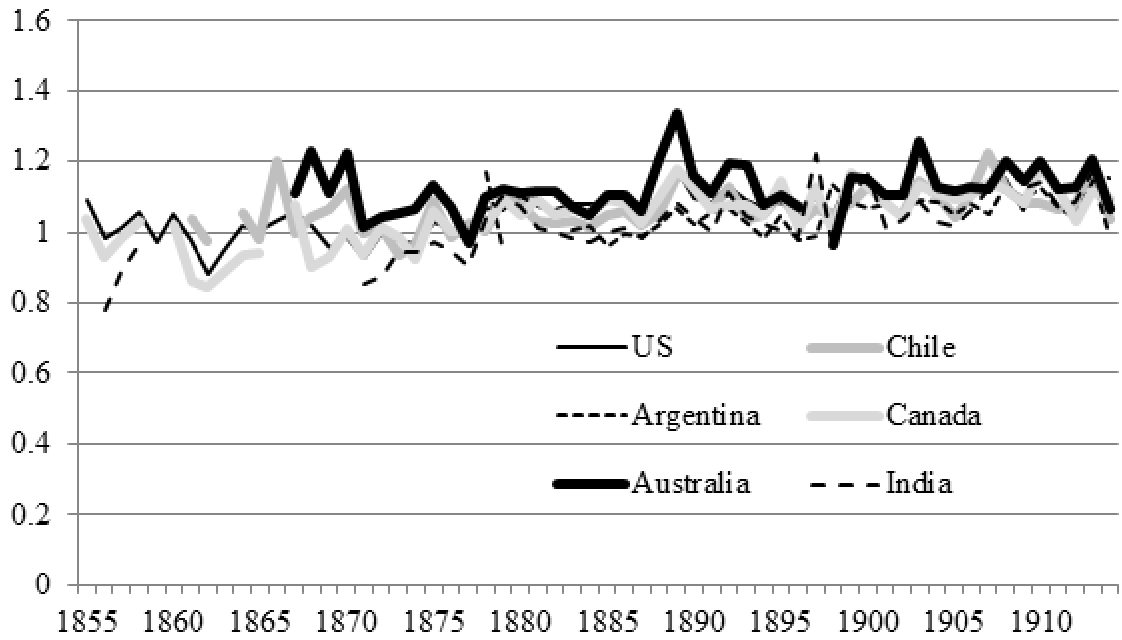

Figure 4. Eastern Mediterranean/English wheat price relatives (traded in London).

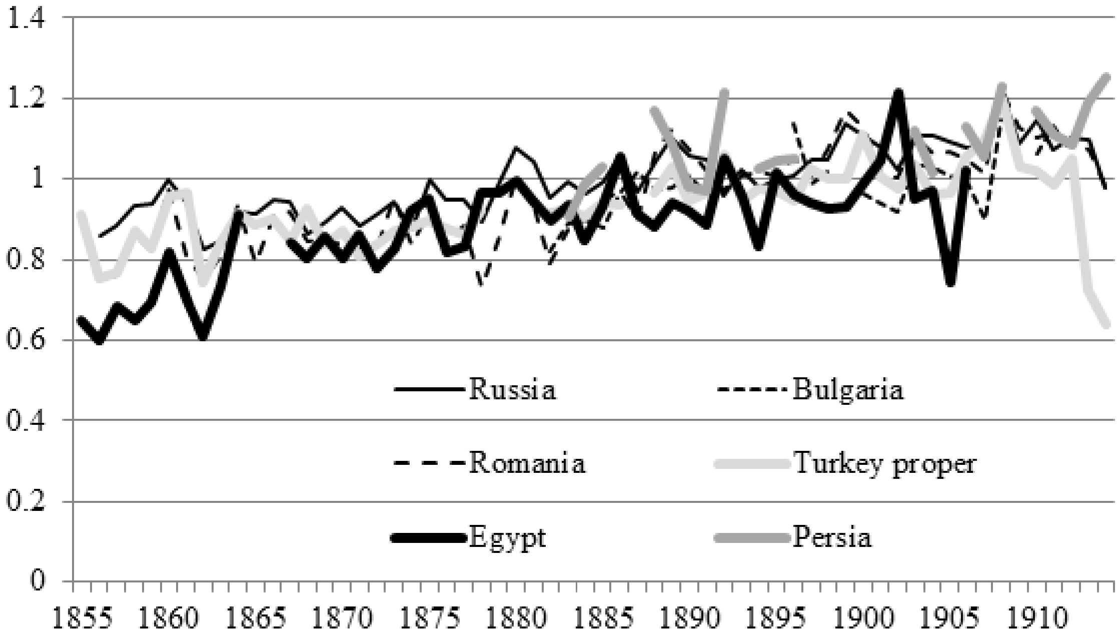

Figure 5. Prices of English wheat, wheat consumed in England and differentials.

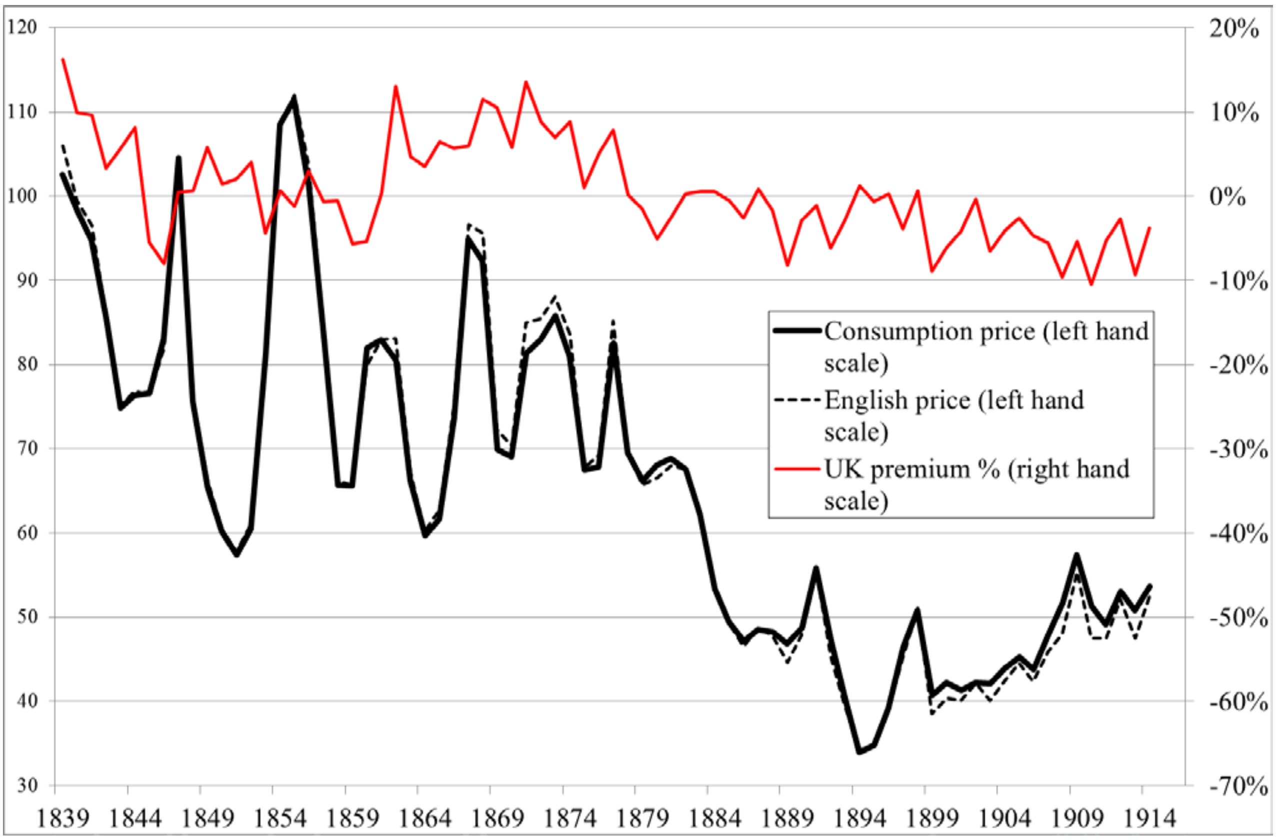

Table 11. Ratio of quality variation to price variation.

$\sigma_\eta / \sigma_\varepsilon$	0	0.25	0.50	1.00
σ_η / σ_p	0	0.23	0.40	0.58

Figure 6. Asymmetric loadings: estimated effect of shock to price A

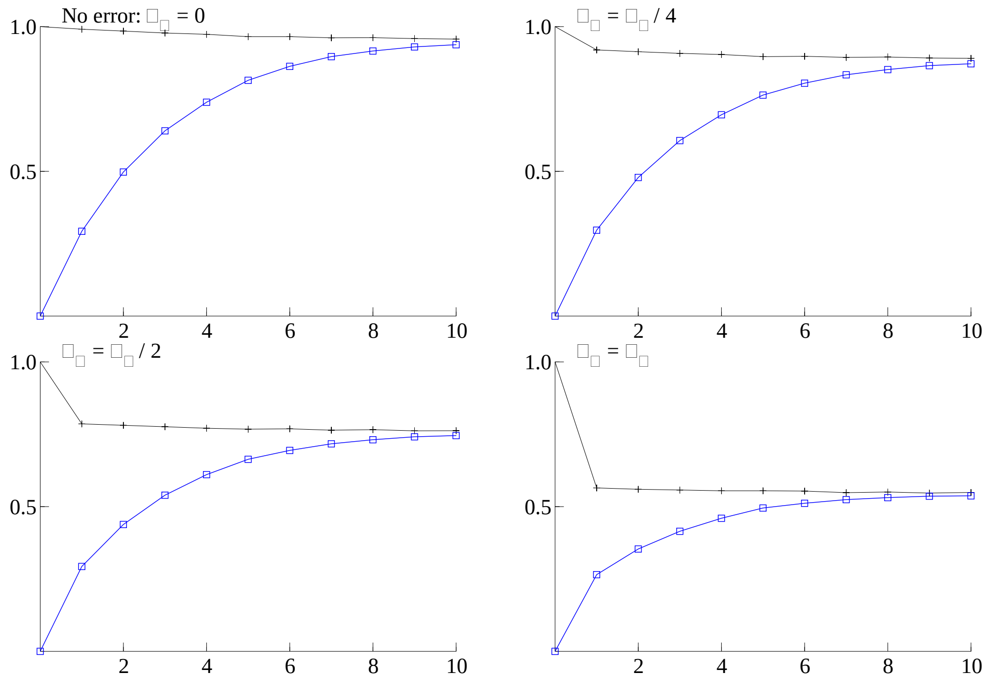

Figure 7. Asymmetric loadings: estimated effect of shock to price B

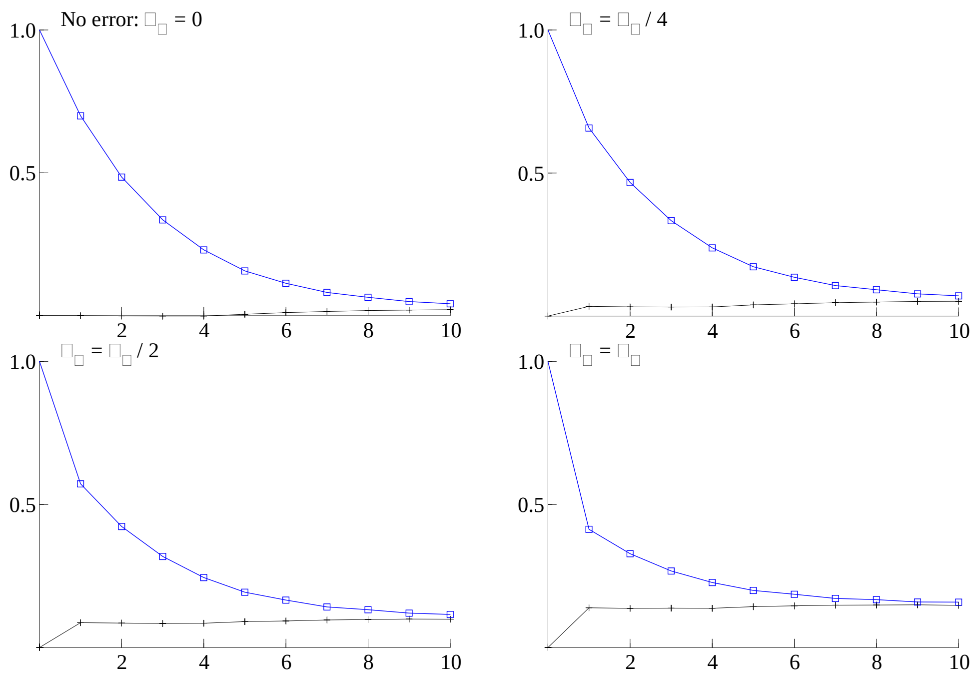

Figure 8. Symmetric loadings: estimated effect of shock to one price

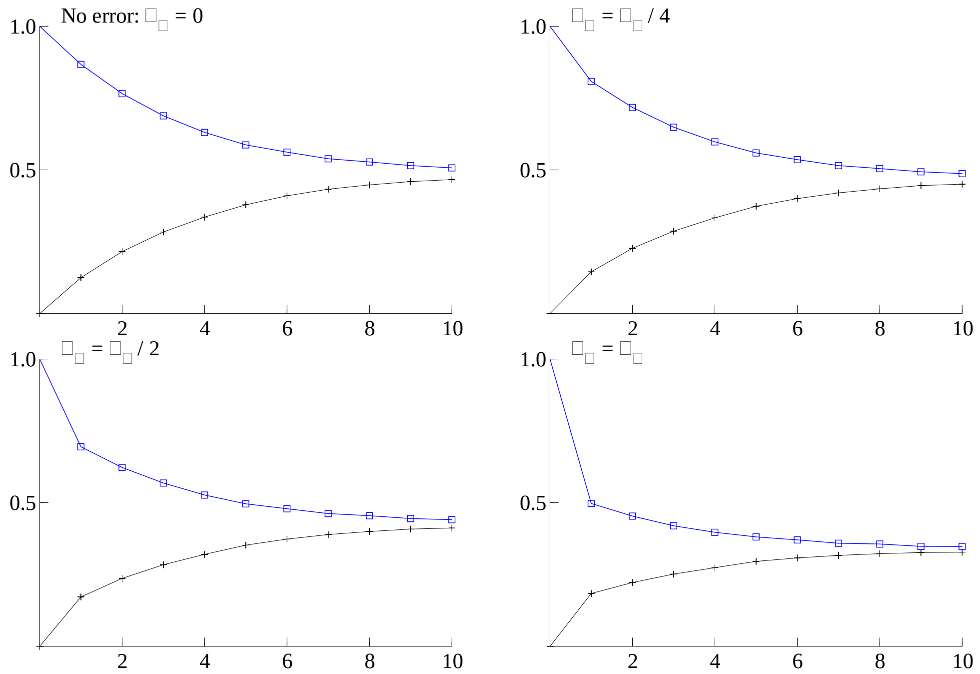

Table 12. Effect of measurement error on half life estimates.

True Half Life	Estimated half life as proportion of true half life			
	$\sigma_\eta = 0$	$\sigma_\eta / \sigma_\varepsilon = 1/4$	$\sigma_\eta / \sigma_\varepsilon = 1/2$	$\sigma_\eta / \sigma_\varepsilon = 1$
1	98%	89%	75%	61%
2	97%	83%	49%	36%
3	95%	80%	49%	25%
4	93%	78%	48%	20%
5	90%	77%	47%	16%
10	79%	67%	43%	9%

Table 13. Relationship between ln(bushelweight) and ln(yield).

Panel A. Time series data for two plots				
	(1) manured 1844-83	(2) manured sub-sample	(3) pooled 1844-83	(4) pooled sub-sample
ln(yield)	0.0838*	0.0365	0.0559***	0.0366***
	(0.0362)	(0.0354)	(0.0139)	(0.0062)
N	40	25	80	50
r^2	0.177	0.0330	0.261	0.182
Panel B. Panel data for different cultivars				
	(5) between-group estimator 1871-81	(6) between-group estimator 1871-78	(7) within-group estimator 1871-81	(8) within-group estimator 1871-78
ln(yield)	0.0985**	-0.0342	0.114***	0.0532***
	(0.0315)	(0.0279)	(0.0088)	(0.0084)
N	239	171	239	171
r2	0.289	0.0613	0.604	0.121

Notes. Regressions include unreported constants; robust standard errors in parentheses: regression (3) and (4) standard errors clustered by year. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$