Risk aversion and storage in pre-industrial economies: from Babylonian times until the industrial revolution.

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Abstract

In pre-industrial economies, with frequently reoccurring famines, the ability to reduce volatility by means of storage is possibly a great asset. Yet, there is very little evidence on the existence of long-term storage, let alone on its underlying motives. In this paper we present a model of storage built up from the underlying consumer preferences. Using the model, we find that the existence of profit maximizing storage does not lead to stationarity of price series. Hence, it does not affect the nature of autocorrelation in price series as has been argued in the literature. However, non-profit maximizing storage aimed at reducing the chance of famine (i.e. the convenience yield) causes the relative change of prices to be predictable based on previous period price (stationarity), which also means it rather reduces the first-order autocorrelation coefficient. Applying this to the data, we find that in countries like the Netherlands and England and Japan commodity prices become increasingly stationary (autocorrelation decreases) over time, suggesting a more important role for the convenience yield while we find the opposite trend for countries like France and Italy. Finally, we found that in countries with a dual crop structure like Babylon and China, the convenience yield is lower since the famine frequency is lower. This implies that Babylon, both being an early economy and a dual crop structure, had one of the lowest convenience yields.

1. Introduction

In pre-industrial economies, inter-annual price volatility was much higher due to the uncertainties of next year's production (e.g. McCloskey and Nash 1984; Poynder 1999). Therefore, an important strategy to reduce risks of famines was storage. Yet, even though much evidence exists of all kinds of storage (government or other) the underlying motives for storage remain unclear. For example, Erdkamp (2005), Will et al (1991) and Claridge and Langdon (2011) stress the role of the government (either because reducing the chances of unrest, or to feed the army (a similar claim being made by Aperghis (2009) for Babylon). Yet, the estimates of government storage are generally small and not profitable. For example Persson (1996, 709) argues that these public granaries were unable to stay solvent for long periods due to the unpredictability of bad harvests. Therefore, McCloskey and Nash (1984), Poynder (1999) and Van Leeuwen et al (2011 forthcoming) focus on profit maximizing storage of private individuals. They compare the costs of storage (mainly consisting of foregone earnings from alternative investments) and benefits (being equated to the seasonal price increase) and find that the former outweigh the latter. Consequently, they find little evidence of significant levels of storage in such diverse regions as early modern England and France, as well as ancient Babylon.

Poynder (1999), however, argues that when costs outweigh the benefits, a motivation for storage still exists. Based on Kaldor (1939-40) he argues there might be a convenience yield, i.e. people will store more than is economically profitable in year *t* since they want to reduce the risk of famine in year *t+1*. Following Nielsen (1997), Poynder argues that the first-order autocorrelation of prices (i.e. correlation between the levels of prices in two consecutive periods) conveys information on storage. However, Nielsen only argued for profit maximizing storage as a lower than average price in year *t* means high levels of storage and a low price in year *t+1* while a higher than average price in year *t* results in low levels of storage and, hence, a high price in year *t+1*. Poynder, on the other hand, argued that both profit maximizing –and convenience yield storage existed with low prices, while only convenience yield exists in years with high prices.

This interpretation of the convenience yield suffers from a problem though: almost all series contain autocorrelation of the price levels, even those that cannot be stored such as butter (Persson 1999). Indeed, if the supply – and demand shocks are autocorrelated (for example a bad harvest is followed by another bad harvest because of lack of seed) this will also cause autocorrelation in the prices. Hence, autocorrelation between the levels of prices may have other causes than just storage.

In this paper we therefore take a closer look at storage as a risk reducing factor for the individual. We try to model storage in such a way as to incorporate both profit maximizing storage and a convenience yield. The formal model is presented in the next Section where we first describe the model in words and then provide the mathematical proof. This model results in some simple to test hypotheses which is done in Section 3. Section 4 describes the results. We end with a brief conclusion.

2. A dynamic model of storage

2.1 A brief description

In this subsection we briefly describe the model in words followed by the formal derivation in the next subsections.

Using an economic model based on individual utility, we try to establish when people will store and how this affects prices (which is basically what we have in the form of data). In case of profit maximizing agents, with the ability to store grain, we would expect that our best guess for current prices is the previous period price.[1] Of course, next year's price may be higher, or lower than the price in the current year, but nobody influences the prices in such a way that a price in- or decrease becomes predictable. This implies that price changes are not autocorrelated (the change in price from year 1 to year 2 is not correlated with a price change from year 2 to 3) and not predictable by past prices. In statistical terms: prices follow a random walk.

In the model we come to the result that the size of storage depends on past prices. In other words, the choice to store from year *t* to *t+1* depends, among others, on the prices in year *t*. This is the same as is suggested by, for example, Poynder (1999). Here, however, we deviate from the previous literature: instead of explicitly assuming a connection between prices and storage we treat the problem as a dynamic optimization problem. We assume that people derive utility from either selling the grain or storing it. We examine two cases: in the first case agents will gain utility from selling grain on the market, while in the second case they also gain utility from having a storage. This latter case represents the existence of a convenience yield.

In the first case, we find that a higher price will reduce storage (equation 21 below). This is the same as argued by Poynder (1999). After all, a higher price makes it unlikely that next year's price will be even higher, hence making storage unprofitable. Since we arrive at the result that the growth rate of storage depends on the growth rate of prices, when these are substituted to the formula for price we find that the growth of current prices does not depend on the growth of past prices. Consequently, as long as the motive for storage is income maximization (including consumption as well), the price remains non-stationary, and price changes are unpredictable.

[1] We would arrive at the same result if no storage was possible, but supply and demand were not autocorrelated.

Now, what happens if we add the convenience yield (i.e. reducing the risk of famine next year)? Basically, now the price in year t+1 depends differently on that of t+1 and t. If there is a convenience yield, more will be stored if the price in year t is high than without the convenience yield. Hence, the price in year t+1 will be lower. This means there is a negative autocorrelation between the price differences from year t to year t+1.

In sum, we argue, together with Persson (1999) that autocorrelation in the level of prices may be due to a variety of factors unrelated to storage. As long as agents are motivated by revenue maximization, we find that prices do not deviate from a random-walk or random-walk with drift process. This means that price changes are not predictable based on previous period prices. Only when convenience yield as an additional motive enters the individuals optimization problem do we find that past price may help to predict price changes. In order to find out if empirics confirms the results from the theoretical model we need to turn to a formal testing. This can be done using a unit root test, which is done in Section 3.

2.2 The model

In this section we offer a simple formalized framework that can later be used to derive the behavior of agents. As first step, we define a demand function as follows:

$$Q_t^d = \alpha_0 P_t^{\alpha_1} e^{u_t} \quad (1)$$

Where P_t is the price and u_t denotes the random shocks, which is assumed to be random with zero mean. We assume here a demand function with constant price elasticity (α_1<0) and no cross-price elasticities since we assume that a single staple food is produced by the economy, hence there is no substitution. There are other factors that could be introduced in the demand equation, like population and income per capita, but in order to keep the model simple we choose to omit them. This does not undermine the results from the model since we apply it strictly to preindustrial economies where change in per capita income and even population are so small that they can be safely included in the demand shocks denoted by u_t.

The supply depends on two factors: the amount of staple produced (Q_t) of which only a portion λ_t is brought to the market, and the price (P_t).

Therefore the supplied amount is:

$$Q_t^s = \lambda_t Q_t \quad (2)$$

The equilibrium price can be obtained by combining (1) and (2):

$$P_t = \left(\frac{\lambda_t Q_t}{\alpha_0 e^{u_t}} \right)^{\frac{1}{\alpha_1}} \quad (3)$$

In order to see how prices in different periods are related, we can express the log difference of prices as follows:

$$\Delta \ln P_t = \ln P_t - \ln P_{t-1} = \frac{1}{\alpha_1} \left[\Delta \ln \lambda_t + \Delta \ln Q_t - \Delta u_t \right] (4)$$

so:

$$\ln P_t = \frac{1}{\alpha_1} \left[\Delta \ln \lambda_t + \Delta \ln Q_t - \Delta u_t \right] + \ln P_{t-1} (5)$$

This means that unless any factors in the bracket depend on past prices, we can expect that current prices contain a unit-root.[2] In other words, prices should be non-stationary as long as there is no level effect on the growth rate. The task at hand is to find out which factor might depend on past prices.

In a pre-industrial society it is very unlikely (with the exception of dramatic demand shocks like Black Death in Medieval Europe) that production would depend on prices. It is possible to have substitution among goods, of course, but in this model we have only a single crop (or alternatively some caloric equivalent of all goods produced). Hence we can eliminate

[2] We are aware that this result comes from the functional form of the demand function. Still, assuming constant price elasticity is not illogical. Price elasticity should not change much once tastes and per capita income are not likely to change either; hence we believe that this functional form is applicable to a pre-industrial economy.

Q_t from the candidates. What may depend on prices, however, is the portion of goods supplied to the market (λ_t), which determines the magnitude of storage as well ($1-\lambda_t$).

2.3 Storage with optimizing agents

The key to solve the problem is to understand what factors affect the decision regarding lambda.

The representative agent derives utility from two possible actions: it can sell some of its production at price P_t or it can preserve and store them. Storage is subject to a cost (portion τ of the goods is lost in each period as a result) but we also allow for lending which yields an interest rate r.[3] The consumption of goods is expected to yield utility as well, but we assume that in a traditional society per capita consumption is fixed at some level. Our choice of ignoring the choice of consumption reflects our preference for the simplest possible model, but also our belief that in a pre-industrial society, with a very narrow range of consumer goods available, increasing consumption much above the sustenance level would be pointless anyway.[4] Next we formalize the idea:

The utility of the representative agent (the population is set at unit) is a function of the revenue from trading, and the existence of storage (T). We can model the situation without convenience yield by simply omitting storage from the utility function.

[3] An important distinction must be made at this point in relation with the literature on storage and convenience yield. Most authors (see McCloskey and Nash 1984) define interest rate as one of the cost factors of storage. The idea is that by storing grain agents forfeit the possibility of making some revenue by lending their money. In their approach, interest rate is an important part of opportunity costs of storage, and should be understood as the interest rate on credits in money. In our model, interest rate is introduced as a possible gain from storage. We assume that agents may simply loan some or all of their stored grain, and receive grain in return in the next period. The r is going to be therefore a real interest rate on grain loans divided by the share of storage loaned. If one seeks to observe the effect of a change in the monetary interest rate instead, it should be seen as an increase in τ.

[4] Including consumption in the utility function would not change our results in any significant way. We would receive a second equation as first order condition of maximization, and that would finally lead to the result that there should be some constant ratio between consumption and marketed goods. But the amount of goods sold on the market can also be seen as consumption. We simply assume then that everyone sells a portion of its production, and also everyone acts as a buyer as well, i.e., there is no direct consumption, all transactions happen in the market.

$$U_t = f(P_t \lambda_t Q_t, T_t)\ (6)$$

Where we assume that

$$\frac{\partial U_t}{\partial \lambda_t} > 0\ (7) \text{ and } \frac{\partial U_t}{\partial T_t} \geq 0\ \ (8).$$

The storage accumulated according the following formula:

$$T_t = (1-\tau)(1+r)T_{t-1} + (1-\lambda_t)Q_t\ \ (9)$$

The problem for the agent is to choose lambda in a way that it maximizes his utility along its lifespan. This can be solved by applying the Bellman principle.

The problem can be written with value function V as follows:

$$V_t = \max_{\lambda}\left[U(\lambda_t, T_t) + \beta V_{t+1}(T_t)\right]\ (10)$$

The first order condition with respect to the choice variable requires that:

$$\frac{\partial V_t}{\partial \lambda_t} = \frac{\partial U_t}{\partial \lambda_t} - \beta \frac{\partial V_{t+1}}{\partial T_t} Q_t\ = 0\ (11)$$

or

$$\frac{\partial U_t}{\partial \lambda_t} = \beta \frac{\partial V_{t+1}}{\partial T_t} Q_t\ \ (12)$$

Next we differentiate the value function with respect to T_{t-1}:

$$\frac{\partial V_t}{\partial T_{t-1}} = \left(\frac{\partial U_t}{\partial T_t} + \beta \frac{\partial V_{t+1}}{\partial T_t}\right)(1-\tau)(1+r)\ (13)$$

From the equation 12 we can express both $\frac{\partial V_t}{\partial T_{t-1}}$ and $\frac{\partial V_{t+1}}{\partial T_t}$:

$$\frac{\partial V_t}{\partial T_{t-1}} = \frac{\partial U_{t-1}}{\partial \lambda_{t-1}} \frac{1}{\beta Q_{t-1}}\ (14)$$

and

$$\frac{\partial V_{t+1}}{\partial T_t} = \frac{\partial U_t}{\partial \lambda_t} \frac{1}{\beta Q_t}\ (15)$$

which, after substitution into (13) yield:

$$\frac{\partial U_{t-1}}{\partial \lambda_{t-1}} = \left(\frac{\partial U_t}{\partial T_t} + \frac{\partial U_t}{\partial \lambda_t} \frac{1}{Q_t} \right)(1-\tau)(1+r)\beta Q_{t-1} \quad (16)$$

Let the utility function specify as follows:

$$U_t = \frac{\left(P_t \lambda_t Q_t\right)^{1-\theta}}{1-\theta} + bT_t \quad (17)$$

Which is a combination of linear and Constant Rate of Risk Aversion (CRRA) utilities, with θ≥0. The closer θ gets to zero, the more households are willing to smooth their revenues from selling crop on the market. If θ=1, the above function would simplify into:

$$U_t = \ln(P_t \lambda_t Q_t) + bT_t \quad (18)$$

In this case derivation with respect to λ would cause prices and production to drop, and lambda would not be dependent on price at all. Hence we take the more general case as in (17).

First we assume that there is no convenience yield (b=0). Then (16) simplifies into:

$$\frac{\partial U_{t-1}}{\partial \lambda_{t-1}} = \frac{\partial U_t}{\partial \lambda_t} \frac{Q_{t-1}}{Q_t}(1-\tau)(1+r)\beta \quad (19)$$

Using (17) we arrive at:

$$\frac{\lambda_t}{\lambda_{t-1}} = \frac{Q_{t-1}}{Q_t}\left(\frac{P_t}{P_{t-1}}\right)^{\frac{1-\theta}{\theta}} \left((1-\tau)(1+r)\beta\right)^{\frac{1}{\theta}} \quad (20)$$

Taking logarithm yields:

$$\ln\left(\frac{\lambda_t}{\lambda_{t-1}}\right) = \Delta \ln \lambda_t = -\Delta \ln Q_t + \frac{1-\theta}{\theta}\Delta \ln P_t + \frac{1}{\theta}\ln\left((1-\tau)(1+r)\beta\right) \quad (21)$$

Depending on the value of θ, prices can have both negative and positive effect on storage. If we assume θ>1 (see footnote 4 on possible values of theta), we find that an increase in prices will reduce the portion of goods sold at the market, and so increase storage.

Equation (21) can be substituted to equation (5):

$$\ln P_t = \frac{1}{(1+\alpha_1)\theta - 1}\ln\left((1-\tau)(1+r)\beta\right) - \frac{\theta}{(1+\alpha_1)\theta - 1}\Delta u_t + \ln P_{t-1} \quad (22)$$

We find in (22) that, if there is no convenience yield, lambda is cancelled out from the expression, and prices should follow a random walk or random walk with drift process, depending on the parameters in the first term of the right-hand side of the equation. Past prices enter equation (22) with a unit coefficient, which means that the growth rate of prices does not depend on the level of price in the previous period. The reason for this can be found in (21) where the growth rate of the portion of production brought to the market (λ) also does not depend on the level of previous period prices only on their rate of growth. As long as this is the case, we should not expect the prices behave significantly differently than in (22), and we should find log prices to be non-stationary.[5]

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[5] Since we assumed that the demand shocks denoted by u_t are random with zero mean, the (stochastic) trend in prices (if there is any) are finally determined by the discount factor β, the costs of storage τ, and the interest rate r. The reaction of prices to demand shocks, and changes in other parameters of the model depends on the θ. If $\theta>(1+\alpha_1)^{-1}$,(we can assume that the price elasticity of demand is between 0 and -1 since the demand for basic foodstuffs is usually inelastic. If, for example, $\alpha_1=-0.5$, then θ should be larger than 2 in order to have a positive effect of demand shocks on prices. It is usually found in empirical studies on agricultural sectors in developing countries that the constant rate of risk aversion is above 1. See e.g. Elamin and Rogers (1992)) higher interest rate or a positive demand shock *ceteris paribus* should reduce prices. If $\theta<(1+\alpha_1)^{-1}$, however, higher interest or a positive demand shock rate leads to higher prices. The prices should have no trend if:

$$\ln\left((1-\tau)(1+r)\beta\right) = 0 \text{ or } r = \frac{1}{\beta(1-\tau)} - 1$$

In words: interest rates should include the cost of storage plus the discount factor (which is the price of postponing revenue from grain trade by one period). Another important finding is that the quantity produced (Q_t) does not affect price changes at all: the portion of harvest marketed grows exactly by the same rate as production reduces, and so the two effects are offset. Interest rates, therefore, should not deviate much from this equilibrium ratio. If some institutional factors cause interest rates to rise above this value, we can expect a reduction in prices as a result. This may be offset however by limited access to credit, which would ultimately act as a reduction of the available interest rate of the representative agent. Also, we assumed in this model that money is not a good itself (i.e. has no internal value). In preindustrial societies, however, where money was usually made of precious metals, debasement would also lead to inflation, even if real interest rates (in this model r denotes real interest rate or interest rate expressed in grain) do not change.

Another, not surprising, finding is that storage reduces conditional price volatility. To see this, let us define Q as follows: $Q_t = Q_0 \cdot e^{v_t}$ where $v_t \sim N(0,\sigma_v^2)$. When lambda is fixed at 1, eq. (5) becomes: $\ln P_t = \alpha_1^{-1}\left[\Delta v_t - \Delta u_t\right] + \ln P_{t-1}$ and the residual variance is: $Var(\Delta \ln P_t) = 2\alpha_1^{-2}\left[\sigma_v^2 + \sigma_u^2\right]$. If there is storage, without convenience yield, equation (22) is valid and then the residual variance becomes:

$$Var(\ln \Delta P_t) = \left[\frac{2\theta}{(1+\alpha_1)\theta - 1}\right]^2 \sigma_u^2$$

. The variance without storage is larger than with storage a long as the

What if having a storage increases utility (in other words, convenience yield exists)? To find it out, we take the derivatives of (17) and substitute them into (16):

$$\frac{\lambda_t}{\lambda_{t-1}} = \frac{\left(b(1-\tau)(1+r)\beta\right)^{\frac{1}{\theta}} \lambda_t Q_{t-1}}{P_{t-1}^{1-\theta}} + \left(\frac{P_t}{P_{t-1}}\right)^{\frac{1-\theta}{\theta}} \frac{Q_{t-1}}{Q_t}\left((1-\tau)(1+r)\beta\right)^{\frac{1}{\theta}} \quad (23)$$

With b=0, this expression simplifies into (20). Unfortunately, this time the formula remains much less convenient:

$$\lambda_t = \left[\left(\frac{P_t}{P_{t-1}}\right)^{\frac{1-\theta}{\theta}} \frac{Q_{t-1}}{Q_t}\left((1-\tau)(1+r)\beta\right)^{\frac{1}{\theta}}\right]\left[\frac{1}{\lambda_{t-1}} - \frac{\left(b(1-\tau)(1+r)\beta\right)^{\frac{1}{\theta}} Q_{t-1}}{P_{t-1}^{1-\theta}}\right]^{-1} \quad (24)$$

We do not need to go further, however to see the major difference between (23) and (20). While in equation (20) the growth rate of λ depended on the growth rate of prices but not on their level, in (23) the price of the previous period enters the expression, with a negative effect (as it is in a denominator). For this reason, we can safely argue that convenience yield (that we modeled by including the stock in the utility function) moves the prices away from unit-root and may cause them to become stationary. We can observe that if price goes up in period t *ceteris paribus*, the portion of grain marketed in period t+1 is going to decrease faster than without convenience yield. That is, higher prices in t will *ceteris paribus* increase the portion of goods stored more than without convenience yield.

In Table 1 below we summarize some of the results of this model.

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inequality: $\frac{\theta^2}{(0.5\cdot\theta-1)^2} < 2\left(1+\frac{\sigma_v^2}{\sigma_u^2}\right)$ holds. With reasonable values of theta (somewhere between 1 and 2) this is the case as long as the magnitude of supply shocks is larger than that of the demand shocks.

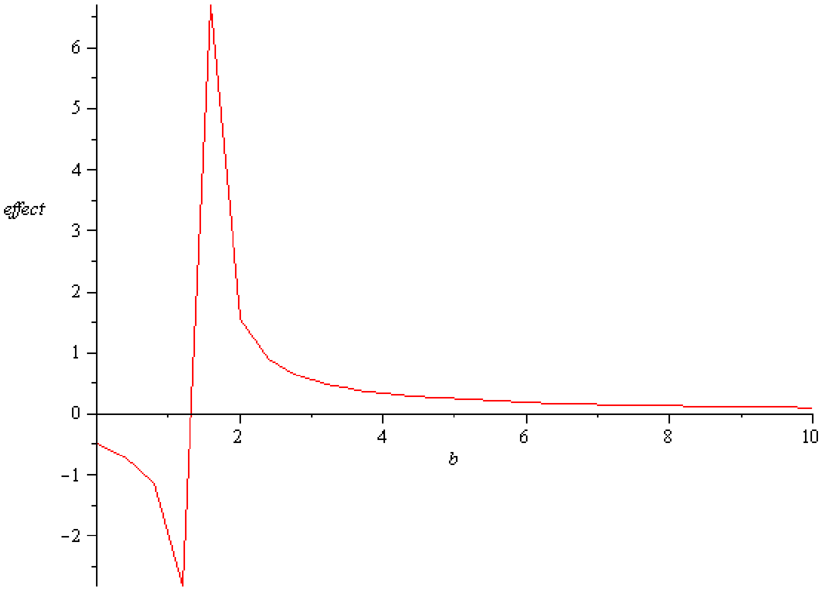
Table 1: Some outcomes of the model

event	storage	prices
cost of storage (τ): i.e. direct losses of grain, rent, opportunity cost of storage increase	increase	increase
direct gains from storage (interest rate on grain) increase	Decrease	decrease
positive demand shock (effect can only be temporary)	no direct effect	increase
positive supply shock (only temporary effect)	increase when b=0 (otherwise depends on θ and b)	no effect
price in previous period was high	Decrease	increase

Note: The effect of convenience yield depends on the value of b (the marginal utility of having storage). At high values of b the reduction in storage is slower than with low or zero b. In case of supply shocks, the effect of b is not straightforward. At low levels storage will increase, at high levels it will decrease, at very high levels it will converge to zero (Figure 1.a). With extreme high risk aversion, the effect is positive on storage (Figure 1.b).

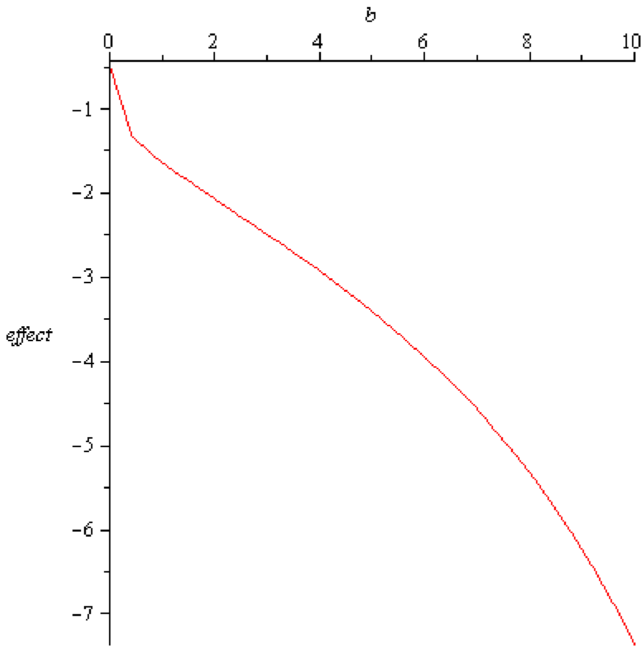
As in Table 1 above, the effects of a positive supply shock on the amount stored are not straightforward since it depends on the degree of risk aversion as well as the additional utility derived from storage. We can, however, model the effect of a supply shock on the amount of marketed products (the inverse of storage) given the rate of risk aversion (convenience yield). The results are reported in Figures 1a and 1b below where b=0 means no utility derived from storage and b>0 means increasing utility. If we assume a moderate rate of risk aversion, Figure 1a shows that a positive supply might decrease the marketed share (i.e. increase the convenience yield) if people derive little utility from storage. If people derive

Figure 1.a.: The effect of positive supply shock on the portion of marketed products, with moderate risk-aversion



Note: θ=1.1, $(1-\tau)(1+r)\beta$ =1, prices and quantities are set to one

Figure 1.b.: The effect of positive supply shock on the portion of marketed products, with very high risk aversion



Note: θ=8, $(1-\tau)(1+r)\beta$ =1, prices and quantities are set to one

more utility from storage, the marketed share becomes bigger (i.e. the convenience yield becomes smaller). If people derive even more utility from storage, there will be no effect on the share of produce marketed and, hence, the convenience yield will remain the same.

This picture changes if we assume that people are highly risk averse (see Figure 1B). In that case, an increasing utility derived from storage simply means a lesser and lesser share being marketed. This implies that a positive supply shock can lead either to more or to less storage, depending on the rate of risk aversion of the population.

3. Empirical test

As we could see in the previous section, if there is purely profit maximizing storage, the growth of the share of goods marketed grows in line with the growth of prices (equation 20). Hence, there is no relation between storage and last year's prices. However, if there is a convenience yield, the growth of the share marketed depends negatively on the level of past year's prices (equation 23).

We carry out some empirical tests to find out if historical price data reflect the working of a convenience yield as suggested in our model. We test if the growth rate of grain prices (log difference of prices) indeed were negatively dependent on past prices. If they were, we find indication that convenience yield was working, and agents engaged in inter-annual (or inter-harvest) storage. The test regressions are basically the same as in the (augmented) Dickey-Fuller unit-root test:

$$\Delta \ln p_t = \beta_0 + \beta_1 \ln p_{t-1} + \beta_2 trend_t + e_t \quad (25)$$

The results are reported in Table 2 and 3 below.

Table 2: unit root test Near east and Rome, ca. 300 BC-1700 AD

	β1	t-stat	p-value D-F test	R^2
Babylon 384-200 BC barley	-0.358	-2.37	0.388	0.14
Babylon 200-60 BC barley	-0.402	-3.96	0.015	0.20
Florence 1336-1377	-0.492	-3.54	0.049	0.25
Florence 1521-1615	-0.651	-5.07	0.001	0.32
Istanbul 1470-1676	-0.470	-5.70	0.000	0.28
Tuscany 1264-1350	-0.567	-4.17	0.010	0.30
Tuscany 1350-1500	-0.423	-6.15	0.000	0.21
Tuscany 1500-1700	-0.294	-5.82	0.000	0.15

Table 3: unit root test, ca. AD1500 -1700

	β1	t-stat	p-value D-F test	Country
Amsterdam 1482-1550 wheat	-0.448	-4.69	0.001	Netherlands
Amsterdam 1669-1758 wheat	-0.628	-4.71	0.001	„
Amsterdam 1828-1867 wheat	-0.779	-4.51	0.001	„
England, 1260-1340	-0.503	-5.17	0.000	England
England 1360-1550	-0.322	-3.09	0.109	„
England 1650-1800	-0.243	-3.87	0.013	„
England 1800-1900	-0.531	-6.85	0.000	„
Hiroshima 1650-1800	-0.309	-5.22	0.000	Japan
Hiroshima 1800-1858	-0.859	-3.51	0.039	
Douai 1360-1518 wheat	-0.419	-5.01	0.000	France
Douai 1650-1789 wheat	-0.331	-4.05	0.007	„
Beijing 1738-1800 rice	-0.411	-3.01	0.130	China
Beijing 1800-1900 rice	-0.196	-2.93	0.158	„
Shandong, Caozhou prefecture, rice 1744-1800	-0.200	-3.47	0.043	„
Shandong, Caozhou prefecture, rice 1819-1900	-0.127	-1.98	0.613	„
Guangxi, Guilin prefecture, rice, 1740-1800	-0.450	-4.70	0.001	
Guangxi, Guilin prefecture, rice, 1828-1900	-0.079	-1.39	0.867	„
Krakow, 1706-1728	-0.125	-0.402	0.9875	Poland
Krakow, 1800-1900	-0.411	-2.59	0.283	„
Semarang 1824-1868 rice	-0.615	-4.29	0.008	Indonesia
Louvain, 1423-1494	-0.066	-1.40	0.853	Belgium
Antwerp, 1750-1800	-0.099	-0.31	0.990	„
Barcelona, 1501-1550	-0.409	-2.87	0.173	Spain
Madrid, 1650-1744	-0.718	-7.07	0.000	„
Pamplona, 1814-1883	-0.327	-3.72	0.028	„

In almost all cases we find that the price changes were negatively affected by the previous year, i.e. higher prices in period *t* led to a reduction in the growth rate of prices from period *t* to *t+1*. For Babylon and China we found the coefficients to be insignificant though. Furthermore, whereas all coefficients were around -0.5 until ca. 1500, afterwards a divergence took place: countries like Italy, France, and China experienced a downward trending coefficient β_1, while countries like England, the Netherlands, Poland and Japan experienced a clear upward trend. The reason for this pattern will be discussed in the next section.

4. Discussion

It is difficult to distinguish a pattern in the data on first sight. But there are some patterns at closer inspection. First, Babylon and China are clear double crop economies contrary to, for example Indonesia which was an explicitly single crop economy. Given the time and region specific factors, it looks like dual crop economies have a lower coefficient; hence the convenience yield is lower. Although not explicitly modeled, this can come into the model by means of potential profit: the dual crop structure removed the need to smooth long-run income. Second, we find that after ca. 1600 there is a divergence: countries like England and the Netherlands found an upward trend while Italy a downward trend. How can this pattern be explained?

As we saw in equation (25), we test whether past prices negatively affect a price change. In other words, if past prices are higher, the growth of prices will be smaller and, vice versa, if past prices are low, the growth rate will be higher. This suggest that prices become stationary (they do not have a unit root) because there will not be a permanent increase or decrease in prices. But what does this say about the autocorrelation? A basic formula showing autocorrelation is the following:

$$lnp_t = \beta_0 + c_1 lnp_{t-1} + u_t \quad (26)$$

, where $c_1 <> 0$. This suggests that past prices are positively or negatively related to current prices. If we rewrite equation (25) in terms of equation (26) we get:

$$lnp_t = \beta_0 + (1 + \beta_1) lnp_{t-1} + u_t \quad (27)$$

This suggests that the more negative β_1 is, the closer $1 + \beta_1$ (which is equal to c_1 in equation (26)) gets to 0, i.e. the further from a random walk. In other words, countries like Indonesia and Holland that experience a high (or increasing) β_1 coefficient, actually find declining first order autocorrelation and move further away from a random walk.

This is a peculiar finding: those countries with the highest convenience yields are also the ones with the lowest first order autocorrelation. This goes counter to what Wrigley (1987) and Nielsen (1997) have argued who claimed that more storage results in more autocorrelation. However, they argue about profit maximizing storage which, in our model, also means there is a low coefficient and, hence, reduces the first-order autocorrelaton less. On the other hand, countries like Babylon and China with very low or insignificant coefficients have relatively high autocorrelation. This leaves the question what is causing this reduction in autocorrelation in some countries while in countries like China and Babylon remain so high?

There seem to be two issues at stake. First, before the 17th century, most countries were to a large extent autarkic. Indeed, Van Leeuwen et al. (2011, this workshop) argue that trade in staples was largely local because of higher transaction costs. This changed after the 16th century. For example, trade in England only started in the 17th century, with the shift to the import of grain starting only in the 18th. Indeed, O'Rourke and Williamson (2002) have argued for the start of the trade in staple produce in the 17th century as the first wave of globalization. Increasing trade smoothed prices in those countries with strong imports such as Holland, Japan, and England. This can be explained by the convenience yield since firms can also hold stocks in order to anticipate future changes (Williams 1994, p. 39). Indeed, smoothing of prices by means of trade can only take place if there is not one country/region from which imports take place. Hence, potentially, the whole world now could supply grain to the richer/importing countries and thus functioned as an implicit convenience yield.

The same affect of smoothing prices and decreasing autocorrelation does not apply though, for those countries with much less imports, which also tend to be those countries with a larger agricultural sector such as France and Italy. They were much more dependent on local production and thus did not benefit from implicit convenience yield as did importer countries. Their economies not only stayed to a large extent agricultural, but also their labor productivity declined. Indeed, where Holland, England, and Japan continued to increase their output of agricultural products per agricultural laborer (see Allen 1988; Bassino et al 2011), in Italy and France this actually declined (Allen 2000). Hence, in Holland, Japan, and England average income rose while the share of people working in agriculture also declined. Even though this resulted in an increase of per capita income, an increasing share of foodstuffs had to be imported.

The autocorrelation (and the chance that we find a series to be random walk) was even higher for those countries which, by nature, had little need for a convenience yield such as China and Babylon. This has two reasons. First, it is well know that, as put by Reger (1994, 90-5), especially in regions where rain agriculture prevails in a climate with precipitation of hardly above 250 mm. p.a. and consequently harvests regularly fail, wise farmers are expected to store grain in case of emergency. Hence, the convenience yield is bigger in regions with rain agriculture because the fluctuations in the harvest are bigger there. The same has been argued econometrically for 20th century Kansas by Abdulkadri and Langemeier (1999). Second, China and Babylon are two well known examples of a dual crop structure, the one with rice and wheat and the other with barley and dates. As shown by Temin (2002), Babylon indeed exhibited strong autocorrelation (slightly more than medieval and early modern England), while Van Leeuwen et al (2011 forthcoming) showed that the dual crop structure smoothed consumption and reduced the risk of famine and, hence, the necessity for a convenience yield.

5. Conclusion

The role of storage as a risk reducing strategy has always fascinated scholars. From China, to the Inca Empire, to Rome, all societies have a certain level of storage. This was formalized by McCloskey and Nash (1984) on the basis of a cost-benefit analysis. This has led to a debate where Wrigley (1987) and Nielsen (1997) argue that autocorrelation is indicative of storage while Persson (1999) denies this on the basis that also series without storage (such as butter) exhibit autocorrelation.

We model that people derive utility from income smoothing and profit maximizing storage a well as from reduction in famine risks. We find that in the case of profit maximizing storage, the share of products marketed moves in line with price changes. Hence, profit maximizing storage is not affected by past prices but it will increase first order autocorrelation as assumed by Wrigley (1987) and Nielsen (1997).

This is not true,for convenience yield though. We find that over time the first order autocorrelation coefficient decreases in countries like Holland England, and Japan, while it increases in countries like Italy and France. We explain this by the increased trade in staples which O'Rourke and Williamson (2002) saw as a sign of the first wave of globalization. Since the world price smoothes fluctuations, we expect in the importing countries the implicit convenience yield increases and, hence, autocorrelation decreases.

In countries, however, that were highly dependent on agriculture such as France and Italy, we expect that price developments were less smoothed and demand and supply shocks became even bigger since they also had to cope with increased international demand (hence autocorrelation increased). Clearly, this was not true for countries that had, by nature, a safety valve in their agricultural production. For example China and Babylon both had a dual crop structure, which reduced the effect of past years prices and, hence, reduced the possible role of convenience yield among the motives to store grain.

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