Unravelling the influence of environmental and socio-economic factors on historical grain price variations in Medieval and Early-Modern Italy

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Abstract:

Grain Price (GP) volatility is central to pre-industrial economies – in the past, governments have fallen because of their inability to manage food crises, many of which arose from grain shortages. In this thesis, I present an in-depth analysis of factors that have caused GP variation across the Northern-Italian city-states of Milan, Venice and Tuscany, from the 14th to the early 19th centuries. Following Adam Smith's logic of supply and demand controlling prices, changes to weather should play a decisive role on GP variation by affecting the harvest success/failure. Starting from this assumption, I first explore temperature as the key determinant of grain price volatility across Northern Italy, both looking at wider European temperature through the Luterbatcher temperature reconstruction, and a more local Alpine tree-ring record. After using de-trending methods to remove the effects of long-term inflation on the economy, I conclude that direct correlations between GP and temperature, across Italy, are low ($r<0.1$). Never-the-less, a similar analysis on Stockholm, Sweden, shows a stronger relationship ($r=0.2\pm0.1$, de-trending method dependent). Granger-causality only produced positive results for Sweden, and I argue that failure in correlation in Italy is because of Europe-wide trade, and Italy's uniquely advanced provisional mechanisms. In addition, by applying Empirical Mode Decomposition I find periods of sustained high (≈5 years) GP to correspond with periods of intense war, social unrest and plague, also displaying a cyclic behaviour. I show that economic cycles either do no play a role in GP, compared to social unrest and war cycles, or that economic cycles have a subtly different mechanism than today. Ultimately, I conclude that GP variation is influenced, first and foremost, by population and global silver supply, then subsequently by: market integration, plague (feeding back into population), war, social unrest, and then weather. However, I further conclude that a linear regression model based on population and temperature can explain significantly GP volatility during times of peace ($r=0.63$), as reflected in the situation of 18th century Milan.

KEYWORDS: Italy, Historical Grain Price, Economic and Social Cycles, Climatic influence, Regression Analysis

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1.0 Introduction

In recent years, an increased number of studies have accentuated the importance of climate fluctuations on societal success. For instance, a study by Zhang et al. (2005)[1] established a link between paleoclimatic records and the historical occurrence of wars, social unrest and dynastic transactions in China. Another example comes from Buntgen (2011)[2], who argued that Rome's success was due to the above average precipitation and little temperature variation, that lasted until around 250 A.D., when there were wild shifts in temperature and precipitation. Faced with these changes, Rome did not fare well: it split in two, in 285 A.D., and was sacked by the Gauls, the Visigoths and the Vandals. Thus, the link between climate and society is often presented as a black-or-white story of societal success or failure. But defining society success, demise or even collapse, is often an incredibly hard thing to do - does it need to be instantaneous, or does a slow waxing and waning of change count? Did the Byzantium Empire collapse because of the Justinian plague, or did it survive? As a result, a much broader spectrum of parameters needs to be considered to achieve a greater understanding of what societal success/failure really means. One metric that has the potential to holistically capture such parameters, and to also offer ease in measurement due to its quantitative nature, is that of economics – times of prosperity and stability lead to a strong economy, and vice-versa. Looking at the link between a country's or region's climate and its economy can offer insights into a society's wellbeing. But climate cannot be considered in isolation, and the interaction between the various other societal dynamics and its impact on the economy should also be considered. Economic measures offer the possibility to assess such factors in more depth.

Although less impactful today, from a medieval and early-modern perspective, the most important economy was the grain economy. People relied on grain, in the form of bread, ale or porridge[3], to obtain their daily calories. Overall, grain in this period formed: 80% of a harvest worker's daily calories, 78% of a soldier's, and 65%-70% of a noble's[4], thus, being the main source of energy in most people's diet. As such, the price of grain was of great significance for the people living in those time. From a researcher's perspective, the price of grain becomes, therefore, an indication of market performance and failure during those times. It also allows for an evaluation of market liberalization and links to political authority[5]. The question remains as to what factors cause the grain price (GP) to change. Instinctively climate should be one of these factors since climate effects crop production, reducing the *supply*, which then causes a response in the price, based on the logic of Adam Smith's third law[6].

Of course, climate is not the only external factor that affects GP and the economy as a whole. Esper et al. (2017)[7] showed that European GPs volatility were tightly coupled with temperature changes, with the apparent exception of the Thirty Year War. Thus, war clearly has the potential to be another factor. They also raised another crucial point, the long-term inflation caused by changing demographics and labour factors, as well as the influx of gold and silver into Europe from Spain (after the 16th century) causing underlying trends. In this thesis, I define trends as being a long-term tendency, where across a timescale of multiple-generations the average price will be significantly higher or lower than other periods in time. At the opposite timescale, there also exists the interannually volatility.

In-so-far possible factors influencing GP are: silver influx, climate, demographic changes and war. On a similar theme to war, are the disturbances in society due to internal political strife, and the devastation caused by epidemics. To this list, I can add the effects of plague and social-unrest. Here, I investigate these effects, and the relative contribution these may have to the trends and variation. As will be seen later, there also seemed to be a third timeframe, short-term variations, that has not been explored that of 5-20 years, where there are sustained periods of mini-inflation and deflation, which I describe as a cyclic behavior since it is the presence of a short peak at regular intervals superimposed onto the much longer overall trend. To use an analogy to explain the superimposition of timeframes, there is an increase in temperature on a yearly basis due to global warming (trend), yet this changes across seasons (cyclic behaviour of inflation and deflation), and within a season there are *random* extreme hot and cold days (interannual variation). As such my overall research question becomes: '**What factors causes the price of grain to change?**'. I should challenge prior literature by starting with the question: Is climate one of the factors that influence GP? If so, is the climatic influence notable, or is its effect outweighed by other contributions to GP variation? Lastly, I should turn to the question: On what timescales do factors that affect GP occur, and is there any cyclicity amongst those timescales?

To date, no study on Italy* has focused on quantifying how strongly climate influences grain price variations, but climate has been used, in a similar way to Zhang et al. (2011)[8], in order to describe the changing economy or demographics[9,10]. Alfani (2010) sums up the literature linking climate and economy, in Italy, nicely: 'climate is only used as a means to explain famines'[11]. He then subsequently proceeds to claim that whilst climate does play a role in the occurrence of famines, bad weather, alone, is not sufficient to explain the occurrence of famines. In this context, he rather emphasizes the role the Italian *annone,* and other institutions responsible for (urban) provisioning, and over time, population dynamics and agrarian innovation. Although famines are not necessarily coinciding with high grain price, and vice-versa, any research investigation into if climate is a factor in GP should be holistic in nature and should stress the importance of institutions and address how other factors may play a role.

Italy has the unique situation of being relatively advanced in Europe during the late medieval period, fueling the Renaissance and as such, it is perhaps less prone to climatic changes, especially since the enlightenment brought with it agricultural improvements. Italy was not only at the heart of the Mediterranean geographically, but also economically, as all trade passed through one city-state or another, making the region much less isolated than other areas of the world. As such, when I investigate the relative weight that our GP factors have, the story is going to be different in each location. To confirm if climate is indeed a factor in GP variation, I have obtained a record from the Swedish city of Stockholm. If a relationship is only established in Sweden then that would imply: a) climate has different strengths across temperate zones or b) other factors have greater influence at disrupting a grain price signal, or c) a mixture of both.

Butzer (2012)[12] summarises the problem I face '…at issue is not where climate change is relevant for social-historical change, but how we can deal more objectively with coupled systems that include a great tapestry of variables…' across different timescales. Butzer then continues to describe that a system requires certain conditions, that can then be further exasperated by other factors leading to stabilization and instability, before leading to social breakdown or a partial recovery. His conceptual model is shown below, which I believe is recorded in the price of grain:

* I define Italy as being the geographical region of the Italian peninsula, and not the politically unified state that came about in 1861. Until that time, Italy was political, a series of independent city-states.

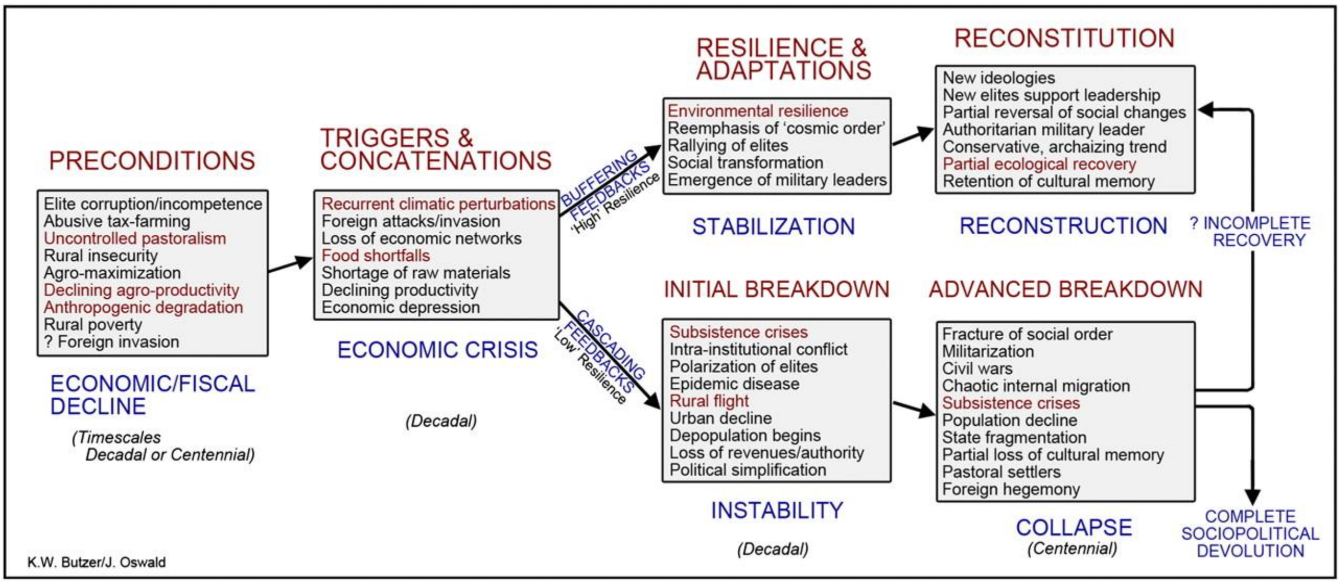


Figure 1: 'A conceptual model for historical collapse, situating the variables and processes of stress and interaction discussed in the text. Timescales range from multidecadal to centennial. Alternate pathways point to important qualities of resilience. Red superscripts identify stages that are elaborated by blue subscripts. Environmental components (red within boxes) are secondary to sociopolitical factors.' Taken from Figure 1 of Butzer (2012)

To summarise, I wish to match timescales of GP variation to social factors. I intend to show that population and silver describe the long-term trends, whilst testing if climate alone can explain volatility or if those times of highest grain price require other factors to explain them, like Butzer details, to push a system over the edge, at which point a climatic signal would be significantly weaker. This has yet to explain what causes the short-term variation.

Discovered in indicators, such as prices, interest rates, foreign trade, coal and pig iron production there are hypothesised cycle-like phenomena that occur consisting of an expansion, boom, recession and then depression. Varying from 3-5 years to a much larger 45-60 year oscillation these have only been discovered in the modern economy, with no-one looking back further than the turn of the 19th century. These waves, as detailed in section 2.4.1 are due to push-and-pull mechanisms, for example, immigration waves, but could they exist in earlier economies?

Besides economic cycles, there are also many theories describing the cyclic behaviour of society in theories such as 'Generational Dynamics' theory of John J. Xenakis, which essentially argues that generations immediately after a major crisis (e.g. civil war and world war) will be much more risk-averse[13], and Peter Turchin's science dubbed 'Cliodynamics' describing the war-peace-war life-cycle of imperial nations[14] and Ibn Khaldun[15] Assabiya (Further elaboration can be found in 2.4.2). These cycles would present themselves in the clustering of war and internal strife or periods of peace. I intend to show that these cycles produce those short-term grain price variations.

2.0 Literature review

Studies focusing on price volatility tend to focus either on explaining the 'stepwise' inflation periods of price revolutions[16] or try to explain price volatility from a single perspective. In practice, the price of grain is affected by many factors, and it is important to realise that I have listed but a few. There are some, which are simply much harder to quantify, or are singe instantaneous acts, such as the ever-changing costs of transport, and political reforms. However, I hope to have captured those factors that constantly change, and yet are systematic. This section reviews the existing studies on the relationship between grain price and the factor, as well as the possible mechanisms behind each action.

2.1 Silver

When precious metals entered Spain, they drove up the Spanish price level and caused a balance of payments deficit. This deficit arose from Spanish demand for foreign goods far outweighing its own exports. The deficit was financed by these precious metals entering these foreign trading country markets, in turn increasing their overall monetary supply and driving their price levels up[17]. Prices further increased upon the discovery of Mercury (necessary for silver processing) deposits in the Andes (See Figure 1 of Garner (1988) for the change in silver exports over time)[18]. Known as the *Spanish price inflation* the cost of goods rose just after the successful Spanish conquests of Mexico (1519-21), and gradually increased further with the slow Spanish colonization of Peru (1532-72), and other parts of South America. There are alternate theories as to what caused this price revolution, such as China's (Ming dynasty) switch from silver currency to paper money, which potentially drove up the value of silver[19]. Flynn and Giráldez (1996) continue to explain that the collapse of the Ming dynasty (in favour of the Qing dynasty), and reduced profits per unit of metal, led to a slow decline in the 17th century.

2.2 Population

The then Prime Minister William Pitt said 'A man could enrich his country by producing a number of children, even if the whole family were paupers.'[20]. Population is in some way linked to the economy, however, the relationship is, of course, complicated and divides opinion.

Thomas Malthus is the leader of thought for one party, arguing that the generally stationary, and relatively low world per capita income, prior to his time (at the end of the 18th century), was related to the very slight rates of population growth[21]. According to his theory, the causation went in both directions. High incomes increased population levels by stimulating higher birth rates, simply by the mechanism of being able to afford children, and cutting down mortality by reducing the levels of malnutrition. Furthermore, greater income means greater civil projects, including improved sanitation, which helps reduce the effects of pestilence. On the other hand, higher population decreases the income per person via reductions of marginal productivity. This double-edged sword between population and the production of resources is at the heart of the Malthusian model, suggesting long-run equilibrium. Emphasised by the idea that population grows exponentially, whereas the fixed supply of land grows arithmetically when demand outweighs supply, the population naturally reduces itself by war, starvation, plague and 'moral restraint'[21]. However, much of what has happened, especially since the agricultural revolution, adds inconsistency, as population has continued to grow, but so too has per-capita income.

Malthusian effects would be weaker under a more modern urban economy, due to smaller agricultural and natural resources sectors. Under urban circumstances, the increased density promotes: increased specialization, greater investment in human capital, and also the increased concentration of intellectuals promotes technological advancement. Even today, an abnormal number of patents are granted disproportionately to urban centres[22]. A side effect, as it is the case today, is the migration of rural population to cities. Naturally, this has a negative impact on the supply of agricultural production, due to the labour force being substantially reduced. However, this is offset by the improved agricultural efficiency developed by the same urban centres and is the story of the Boserupian model[23], where the invention arrives just to increase the carrying capacity, just as population reaches its apex. This development was seriously underappreciated by Malthus and meant that his theory struggled to explain the population expansion after his time.

Without the development of technology, and with an increase of population, the product per unit capital increases as well, but the labour productivity declines because of the increased division of fixed capital, mostly land, between a higher population. A point is then reached where production cannot support population, leading to a population decline. However, with the introduction of technology, it is then possible that the product per unit of capital, and product per unit worker increases. Once the output of a worker increases, then so does the economy. As such, with technology, it is possible for the population to continue to grow and not long-term stabilize.

2.2.1 Urban specialisation

David Richardo's law of comparative advantage[24], where an agent will specialise and produce more of the good in which they have a higher productivity, trading this good for other goods produced in seemingly specialised areas, seems to hold true in Medieval Italy. Each of the city-states became specialised within a certain sector, and became the *brand-name* of Europe: Sicily, and Southern Italy to a lesser extent, was the breadbasket of Europe, focussing on agricultural production, meanwhile Tuscany focused on cloth making[25], Milan was renown for its metal goods and armour, Genoa was a trade centre of ivory and gold from Africa, and Venice dominated the control of silks, spices and perfume from the East. This specialization not only made Italy a hub of internal trade but combined with the use of trade guilds, they became the world experts in it. As such, there was an immense flow of money fuelling the Italian economy, which also coincided with greater urbanisation. Becoming specialised in an industrial sector came at the cost of neglecting their agricultural production. In Tuscany, this led to grain becoming a precious commodity, as Florence depended on imported wheat to survive, only producing enough for five months of the year[26], the remaining amount being extracted from its *contado* (the region surrounding the city). In the early 14th century, it was so bad that it was forbidden to export grain from its *contado,* and a communal grain magistrate was operating, from 1274 onwards, to handle the grain supply[27]. The example of Florentine bankers exchanging Florentine cloth for Southern Italian grain, as well as elsewhere, illustrates how specialisation developed. This led to increased purchasing power to buy grain from elsewhere, so peasants who previously toiled the fields could now become craftsmen, adding to this vicious cycle. As the rural population decreased, the urban relied more and more on imported grain, which comes with ever increasing transport costs. Thus, the cost of food went up.

In short, whilst it is debated if population sponsors economic growth, or if economic growth sponsors population growth, it does seem to be fair to say that population does reflect the current state of the economy, and most crucially the cost of food. I have explored two types of population, urban and rural, both of which continued to grow over time. An urban population increase will have a positive impact on the grain price, as there is an increased demand, despite the increased supply. The costs also rise in an urban setting, as areas become more specialised, but on the other hand, technological efficiency also increases. There is also the rural population, an increase in which would lower the price, as there would be more production.

2.3 Climate

2.3.1 Mechanisms behind climates effects on crop yield

Crop yield is dependent on the environment and should the environment in some way damage the crops, the output (or supply) would be less and thus with an unchanging demand (population), it leads to higher equilibrium prices. The mechanism behind how environment destroys crops is somewhat more complicated. For example, a few days of exceptionally cold temperatures are enough to cause ice crystals to form inside of the plant, and these can slice open the cell walls and ruin the plant tissue. At the other end, at extremely hot temperatures, enzymes start to denature, hindering plant growth. Extreme drought can destroy crops because plants close their stomata to retain precious water, but this reduces a plant's ability to recapture CO_2 which is essential for photosynthesis. Moreover, water is also necessary for structural support. On the other hand, heavy rainfall could hinder the completion of specific agrarian tasks; washing away the seeds; flooding fields; and covering them with sand or detritus; and also by fostering the growth of certain crop diseases[28]. The consequences of either too much, or too little, rain or temperature can be catastrophic for the crops.

2.3.2 Modern evidence of economic crises from drought

Even with modern agriculture, we experience climate influencing the price of grain - take for example the current drought occurring in one of Argentina's most fertile agricultural regions. The drought has raised large concern for farmers in the region, and for Argentina as a whole since the Argentinian economy is at its heart an agrarian economy. Thus, high or low prices for soy and other commodities can either sustain or bust long-term governmental investment plans. The drought has caused a decrease in both quantity, and quality of the crops, with grain exports being cut by $3.4 billion[29], and has subsequently had a ripple effect around the world, with countries like those of Latin America now turning to the US for their access to soyabeans[30].

2.3.3 Previous climate and grain price literature

Early work by Beveridge (1921, 1922) showed historical wheat price from Central Europe to consist of a cyclic behaviour corresponding to recurring weather conditions[31,32] and was expanded upon by Granger and Hughes (1971)[33]. In addition, in 1978, Pfister confirmed the correlation between grain harvest, and price data and pointed to the effects snow cover and rainfall would have had with crop yield and agrarian productivity[34]. Zhang et al. (2011)[8] established a set of causal linkages between climate change and social crises. By using temperature and what they determined to be social-economic variables, including GP data, they found that, of all the variables, temperature was the only variable that simulated the 'golden' and 'dark' ages of Europe's past millennium. Meanwhile, the aforementioned Esper et al. (2017)[7] established a strong link between temperature and climate. Zhang et al. (2011)[8] and Esper et al. (2017)[7] acknowledge that the price is affected by multiple factors, such as transport costs, market integration, long-term inflation, and changing demographic factors. They then used a Butterworth and High-Pass filter, respectively (a description of detrending methods can be found in box 1) to remove inflation on their grain price data.

Both studies use a wide collection of European cities, from Madrid to Gdansk, and from Sienna to Exeter, part of the reason being the lack of many continuous records across time, and so obtain as long a timeseries as possible, they then explore the average grain price variations and compare it to an average European-wide temperature. The main caveat with this is that any crisis that occurs in one city, will find its price heavily diluted by the absence of crises among all of the other cities. The conditions that would cause a sharp increase (or decrease) amongst enough datasets would have to be a *European catastrophe* to disrupt grain markets so much. The main factors that could affect Europe-wide would be a war that affected the whole of Europe politically (like the highlighted point of the Thirty Years' War), or a change in Northern hemispheric climate. Studies have looked at individual cities and used GP, but their focus has not been to link variations with climate, but more demographic change.

This study wishes to focus on the what causes GP variation, meanwhile, Esper et al. (2017)[7] ask the question, and rightly so, 'does climate affect GP'. In Figure 5 of Esper et al. (2017)[7], they performed superposed epoch analysis, not looking at when the price is high, but instead what the price does during a famine. Thus, they are exploring times of high GP coinciding with a food supply shortage, and then correlate this to temperature. Naturally, the majority of famines do stem from crop failures, although some do come from logistic failures, and the majority of crop-failures come about due to weather extremes. In a recent study focusing on today's America, 39% of crop failures can be explained by climate and soil[35]. Climate and soil can be expected to have played an even bigger role in the past, which has been attenuated in recent centuries thanks to the improvements in agricultural technology or methodology, examples being four-field crop rotation, enclosure laws, larger variety of crops, improved transport, improved large-scale irrigation works, and the list goes on. Even crop failure due to crop-viruses find themselves augmented hugely by the current weather[36]. The correlation between grain price and temperature is less surprising, given the focus on times of famine. They did, however, also perform superposed epoch analysis on the driest and wettest years using the PDSI (Palmer Drought Index) reconstruction. Here, during the driest and wettest summers, there was a response, in GP. Furthermore, there has been no attempt to explain the regular periodic prices increased-visible in Figure 4 of Esper et al. (2017). To summarise literature that uses the changing environment to explain GP variation, there is the instinct to focus on averages rather than a detailed holistic study to explain, instead of trying to establish if climate plays a significant role.

2.4 Social factors (War, Plague and Social Unrest)

War, defined as large-scale violent conflict, and social upheaval, defined as internal political-strife, can influence the price of goods in multiple ways. A large contribution to the price of crops is transport. In unrest and war, transport breaks down, not just because of naval blockades, but also because roads become unsafe to travel. Physical infrastructure becomes prone to damage, and in times of uncertainty, foreign and local investment becomes incredibly unfavourable. With a focus on grain, it has not been unheard of for Italian armies to carry sickles, to reap and obtain the enemies' harvest[37]. Vegitus, the military authority revered during the Middle Ages, sums it up: 'The main and principal point in war is to secure plenty of provisions for oneself and to destroy the enemy by famine. Famine is more terrible than the sword'[38]. In fact, wars were timed to coincide with the collection of harvest, in the hope of obtaining a quick surrender.

As an example to the extent in which war reduces (or, in case of a siege, stops) the import of food and leads to the downright destruction of crops is provided in a letter to the Pope, written by city representatives of Parma, dated the 13th February 1527: *"All around in the countryside, up to six miles from the city, there is no bread, no wine, no hay, no straw, especially where our soldiers were and are billeted, no food reserves, no barrels [of wine or other], but everything has been burned. Each day houses and granaries continue to be burned, great quantities of hay and straw have been lost, many beasts great and small are eaten by the soldiers, who are openly robbing us, they sack houses in many places as if they were Spanish or Landsknechts [...]. Streets are unsafe, merchants are kidnapped and all goods and every kind of food being transferred by road are stolen. In much of the territory of Parma work has stopped, they are not sowing fave [broad beans], veze and other legumes that make for much of the crop, vines are not pruned, woods are not cut*."- Translated by Alfani 2010[11].

This description is even more impressive given that Parma was complaining about the behaviour of **Allied,** rather than hostile troops. Not just decreasing market efficiency, war has the effect of draining the coffers that might else-wise have been invested in domestic improvements and diverts political attention from managing crises. Often, to fund wars, taxes are raised, which is never a popular outcome, leading to riots. These events might-appear as short-term upheavals with equilibrium soon to follow, but there are also long-lasting consequences. Take for example the end of the Italian Wars (1494-1538) which saw Spanish political and financial supremacy over Italy, as well as the decline of the Holy Roman Empire. The consequences for Italy are considered in the long-run disastrous, as they experienced a period of economic decline and general loss of political liberty under the repressive Spanish domain. More specifically, during the siege of Florence (1529-1530), the city experienced the large-scale destruction of its suburbs, which ruined its export business. Italy's urban population fell by half, and a combination of ransoms and emergency taxes drained finances. Meanwhile, in Lombardy, the industry collapsed as looms were wrecked by invaders. In addition to the damage of invading armies, the defensive method of scorched earth, ironically hardly delaying the invaders, caused recovery to last much longer and be more painful[39].

Lastly, the movements of troops help spread diseases to an already malnourished society and can cause an epidemic, as it is seen in Northern and Central Italy, in 1629-1631, when the French and German troops spread the bubonic plague. Like war, plague has the effect of breaking trade, as ships would, in theory, not call into infected cities, or trading ships would be subject to periods of quarantine. Its other effects are more reflected in the change of population, and long-term societal change. The mid-14th-century plague had different outcomes across Europe. In Western Europe, the long-term effects of the plague outbreak created a time of increased social mobility, as depopulation further eroded the peasants' already weakened obligations to their traditional hold steads. Manorialism, an essential part of the feudal society, never recovered. The land was plentiful, wages rose and so did opportunities for welfare progress[40]. In contrast, in

Eastern Europe, the remaining peasant population was held tighter to the land than ever before through serfdom, thanks to renewed laws.

In the specific case of Florence, which was the most urbanized, and most densely populated states in Europe (the average urbanization rate for Europe is 10% in 1300, whilst in Tuscany, it was 27%[41]) upon the arrival of the plague, the population of Florence went from 90,000 to 50,000 people[42]. The extent to which subsequent economic decline was because of the population crash is still being debated, however, the loss of faith in governmental institutions is apparent -The existing oligarchy in Florence became unstable, as many died or fled to safer parts of the world. During this turbulent period, a class of mainly immigrants, with no aristocratic background, who grew their wealth from trade, emerged, known as the *gente nouva*, or the new men[43]. Together with the minor guilds, they challenged the existing oligarchy and ultimately led to the Ciompi revolt, which is considered a key event allowing for Florence's future aristocratic rule[44].

2.4 Cycles

2.4.1 Economic fluctuations

As mentioned above there are hypothesised natural fluctuations in the economy between periods of expansion (growth) and contraction (recession). Describing various economic schools of thought is not the aim of this paper, instead, I am going to describe the four main business cycles discussed in the literature, although is important to note, that although they are referred to as cycles they do not necessarily consist of uniform or predictable periodicity:

- **Kitchin cycle (3-5 years)**
  - This cycle is believed to be due to the time lags in information. I.e a delayed reaction to a commercial situation produces increase output, and subsequently floods the market, decreasing the price[45].
- **Juglar cycle (7-11 years)**
  - Over the course of 7-11 years, one can observe the investment into fixed capital, such as the renovation of production machinery.
- **Kuznets swing (15-25 years)**
  - A medium range economic wave, due either to immigrant inflow and outflow[46], infrastructural investment[47], or cycles in land values[48]. However, it is important to note that the existence of this swing was called into question by Howrey (1968)[49], because of the choice of filter used to discover it. Nevertheless, more recent research has shown that it can still be found without the use of a filter[47].
- **Kondratiev wave (45-60 years)**
  - A considerable number of explanations for the observed wave have been proposed. Initially, Kondratiev wave (also known as K-waves) were connected to inflation shocks caused by major wars. Kondratiev himself accounted for the K-wave as the basis of capital investment

dynamics. Most recently, the K-wave has been connected to waves of technological innovations[47].

More general economic cycles, now being more commonly referred to as economic fluctuations[50] take the sequence, at least in the context of today, of boom where real national output rises faster than the trend rate of growth, which leads to rising real incomes and an increase in house and share prices. There is an increased demand for capital goods, as businesses invest to meet the increased demand and exploit greater profits. In turn, this creates more jobs with higher wages. Other factors that increase are government tax revenues as people spend more, and companies make greater profits. There is also a higher demand for imports should the economy not be able to match demand, leading to a large trade deficit. Meanwhile, a recession is a fall in the level of real national output, in other words, growth is negative. Defined by rising unemployment, a fall in purchases and a general decline in business and consumer confidence. This declines the value of exports and imports, along with a drop-in government tax revenue. Furthermore, in an attempt to sell excess stocks, there are large price discounts, but this has the side effect of producing much lower outputs. In between, there is the recovery and slowdown which act to complete the cycle. These cycles have not been explored in relation to the price of grain, but it is easy to transpose how such effects in a medieval economy would cause periods of high and low prices in the form of mini-inflation peaks.

2.4.2 Social cycles

Sociological cycle theory argues that events and stages of society and history have a trend to repeat themselves, this is not to say that social progress cannot exist, or that there is an exact periodicity determining periods of war and peace. The presence of political-demographic cycles has been known for quite some time, for example, Postan (1950)[51]. A dedicated thesis could be raised to discussing sociological cycles, my aim is to not establish the existence of one particular cycle over another but to raise awareness that such cyclic behaviour affects GP. As such, I will introduce the reader to some of the more popular theories, after explaining the basic logic of the models:

Population reaches a carrying capacity of the land, and growth rates decline. With reserves depleted the system experiences demographic collapse, which increases the severity of famines and epidemics, increasing internal warfare and other disasters. All the time, living standard decline and the system undergoes significant stress adding to the severity and numerously of the above. After collapse, resources become available allowing for per capita production and consumption to considerably increase, which allows for population growth and the start of a new sociodemographic cycle. Below are brief summaries detailing the mechanism behind the more popular theories.

- **Generational Dynamics:**
    - Xenxakis (2004)[13] generational dynamics follows a relatively simple premise. Societies and nations make mistakes and then learn from them. But as generations grow older, retire, and die, they are replaced by a generation too young to remember, and did not live through, those mistakes and lessons, and as such lessons are repeated. His analysis focused on the fact that the risk-aversive leaders, who lived through WW2 are now gone, replaced by leaders of the baby boom generation who are more likely to be risk-seeking, arrogant, hubristic, self-assured and narcissistic. In general, he argues that upon the changing of the guard, crises are better managed (by the risk-averse generation) or terribly managed (those who grew up in peace).

- **Asabiya:**
  - Ibn Khaldun[15] believed that there was a measure of 'social cohesion' or 'group solidarity' referred to *asabiya* and that each dynasty has the seeds to its own downfall, based on his observation and experience of the Arab world. He explains that on the peripheries of great empires, peoples had greater asabiya, and tribes, because of their greater social cohesion, would unite and become the future ruling house. As the new rulers they would establish themselves at the centre of their new empire, and afterwards would become increasingly lax, and more concerned with maintaining their, now prosperous, lives. Thus, a new dynasty had the potential to arise amongst the peripheries. Further Khaldun (1377)[15] discusses a second cycle that of the 'Laffer Curve', in which tax rates would rise initially increasing tax revenues, but eventually an increase of tax rates causes a decrease in the tax revenues, which discouraged people in the economy to produce.

- **Demographic cycles:**
  - Koroteov (2006)[52] argues, like Malthus[21], that population will grow until it reaches the carrying capacity, at which point there will be a population decline, subsequently followed by a population increase once stability has been achieved, initiating a new cycle. However, upon each cycle due to the advantages in technology has a longer duration and has a higher maximum pre-collapse population. They also argue the existence of an 'intercycle' due to lingering effects of internal warfare.

- **War-Peace-War:**
  - Turchin (2003)[14] argues that the need for societies collective action forms empires. In which, high levels of cooperation are needed to band together, and fight a common enemy. But as empires grow, the wage gap increases – the rich get richer, and the poor get poorer. Consequently, conflict replaces cooperation and dissolution of the empire inevitably follows.

The above examples illustrate how a mechanism can be responsible for stability fluctuations which could easily influence the price of grain by introducing concentrated periods of war, plague or social unrest, whose individual effects where detailed out earlier

2.5 Summary

What is apparent is that weather, war, social unrest and plague all act as shocks to the economic system, with the latter three, along with the effects of population and silver influx having long-lasting effects that lead to entire societal changes. Climate acts along these long-term timescales, which is the scale that Zhang et al. (2011)[1] focused on, whereas, Esper et al. (2017)[7] establishes the relationship between inter-annual environmental change and grain price. However, neither paper focuses on a single city, which is prone to the full-force effect of war, plague and social unrest that have such a disturbance on the price of grain. This difference in focus arises from the different phrasing of the question from 'Does Climate cause GP', a general trend analysis, to the more holistic analysis 'What causes GP and does the role of climate get felt when it comes to an individual city'. Further raised is the existence of economic and social cycles, which have not been discussed before in the context of historical grain price timeseries. Economic cycles describing high price in boom, followed by a cycle of recession, depression and recovery have not been explored in a pre-19th-century setting. Neither have social cycles been mentioned in the context of grain price. Finding short-term cycles in the GP would be strong support that social or economic cycles are recorded in the price of grain.

3.0 Methodology

In the upcoming section, I describe the methods that are taken, starting with how we will acknowledge the influence of silver and population. Followed by explaining how I observe cycles of grain price. Finally, I outline the statistical tools that will be able to determine if temperature plays a significant part in defining GP. A separate section (4.0) is dedicated to describing the origins of data used in this analysis.

3.1 Long-term descriptive analysis

Due to the sparse reconstructions of silver-influx, and none in digitalized form, the establishment for how silver has affected the price of grain will be limited to a descriptive analysis -focusing on the relative timing of the trends. Sadly estimates of population are limited too, with the first official census occurring in 1871, before that estimates have mostly been reconstructed from parish registers[53]. Despite some uncertainty about the trend and level of population the general picture has been constructed, because of this uncertainty such analysis is to be restricted to descriptive methods. By comparing England and Italy which have had different population rates but the same global silver supply, I hope to theorise which of these two factors has the greatest weights.

3.2 Determining cyclic patterns

A similar story exists with the social data, we can see from the literature review the effects that war, plague and social rest have had. However, it is much harder to quantify, although there are timeseries detailing the timing of events, complete records on their relative strengths is impossible. Although for some wars, there are estimates of mortality rates, the style of warfare has changed over the centuries, changing from mercury armies partaking in economic warfare- the Condottieri, to much larger standing armies. Further, it would be hard to disentangle the indirect effects war has had, for example, the case in the Seven-Years-War (1756-1763) when Italy was heavily taxed by Spain to fund its war. Furthermore, plague and social unrest have been on a general decline (except for the side-effects of the French Revolution), as such to give a weighting would be an arbitrary task. To test if it has a link with GP I have had to make events binary. Thus, our timeseries are the number of events that occur in a given year. Given the coloniality of the events, and the fact that knowledge of bad harvests is known in advance means that rival city-states can start a war leads to a question of cause-and-effect. However, we can still test the relative timing of these events and test my concept that there are cyclic behaviours in GP that are linked to social and economic cycles. Due to the timeseries of events being non-linear and non-stationary it becomes redundant to perform Fourier analysis or Wavelet transform. Instead, I turn to Hilbert-Huang Transformations (HHT) to determine any cyclic patterns. The HHT is the result of empirical mode decomposition (EMD) and Hilbert Spectral analysis (HAS), it used EMD to decompose a signal into so-called intrinsic mode functions (IMF), along with a trend. An IMF represents a single oscillatory mode, equivalent to a simple harmonic function, but it is more general: instead of having a constant amplitude and frequency like a harmonic component, an IMF can have varying amplitude and frequency along the time axis. For a full explanation as to the technique, see Huang et al. (2014)[54]. HHT will be performed on the longest Italian record- Tuscany, showing the decomposed waves that reflect the different scales of trends and cycles. Then, HHT will be performed on timeseries of plague, war and social unrest. For all timeseries, the first IMF's that describe the highest orders (those with the longest wavelength) are summed, so that it reconstructs the GP and social factors with the lowest frequency oscillations removed. Then a comparison of the timing can be performed to see if the peaks of GP correspond to peaks in social factors if so then this would imply that the sustained cyclicity of GP stems from social factors.

In this analysis, the HHT stoppage criterion was defined as 0.3, when the standard deviation becomes smaller than this value the sifting step to produce an IMF stops and no more IMF's are constructed. 0.3 is the typical value in EMD analysis[55].

3.3 Establishing the presence of a climatic signal

Thanks to paleoclimatic reconstructions it is now possible to reconstruct past climates on an annual level. As described above climatic effects on agrarian production levels would stem from precipitation and temperature levels. Unfortunately, since precipitation is very inhomogeneous and especially in light of the fact that Italy given it is 40% covered in hills[10] using a reconstruction of precipitation becomes less reliable than temperature. Thus, to establish a correlation, a temperature record is to be used. I choose to use a European-wide temperature reconstruction, as this would represent the Europe-wide temperature crises that would affect agrarian production across Italy's (Christian) trade networks. After all, the pre-knowledge of a bad harvest about to occur meant that pre-arranged purchases of grain could be brought from outside to resolve a harvest failure. Consequently, a Europe-wide record would capture some of these extreme crises that would remove the backup option in Italy of purchasing grain from elsewhere. To develop a picture of the temperature effects on a more-localised region, an alpine temperature reconstruction has also been selected. Accordingly, the Luterbatcher temperature reconstruction[56] and an Alpine temperature reconstruction[57] have been selected for analysis.

To answer the question if climate contributes to a timeseries of GP form a single city, several techniques are to be used. As detailed in the lit-review, previous studies focusing on GP have de-trended their data so as to remove the effects of inflation and deflation caused by changes in demographics society and economics: Manilia (2011)[58] used a Hodrick-Prescott filter to remove the cyclic behavior of GP, Esper et al. (2017) made use of a high pass filter of 300 years and Zhang et al. (2011)[8] smoothed their data with a 40-year Butterworth filter. Each filter works slightly differently but ultimately produces a timeseries with equal variance. To fully establish if climate played a role, and not an artefact of a specific filter, I have chosen to use all three. I have also decided to include the rate of change as a fourth de-trending method, hereafter described as the *differences* method – a brief explanation as to each filters method is given in box 1. Given the result of these filters should be performing the same result, if we have strong correlations across the board, then that would provide strong evidence that climate plays a role. The GP data was detrended with the above methods, using the computer language Python module's Statsmodels and SciPy to process the data. Like many functions, these de-trending methods require choosing a certain parameter. For consistency with the literature, I have chosen to use the 300 high-pass and 40-year Butterworth filter. Post-detrending the GP is then correlated with temperature to assess the influence of temperature variability on GP volatility. Although temperature also has periods of high and low temperature it has not been detrended, since the range of variation is similar to that of the trend, i.e the volatility is much stronger compared to the underlying trends. I have also included Siena, the only Italian city used by Esper et al. (2017)[7], because I wish to compare correlations of Siena individually and establish if their narrative would hold true without the averaging. As aforementioned, besides Italy, we are looking at Sweden to provide insight into if the climatic relationship varies over temperate zones.

I also realize that the role of temperature would be apparent on the preceding months of crop growth, rather than in the periods of sales. As such I should be looking at the correlation with temperature during the time of harvest, and not during the year of sales, from which we have the GP records. Therefore, there might be a delay in the temperature's effect on the system. Although it is worth mentioning that markets do often work on prediction, rather than reaction (i.e. traders would be aware that a bad harvest is likely to occur, and so would react), I add a series of lagged temperatures and repeat the correlation analysis, thus, hoping to capture any temperature signal that is lagged behind.

Besides testing for correlation, another key test is to establish a relationship between two items is granger-causality. Granger causality is a statistical concept that is based on prediction. If a signal, X1 (in our case, temperature), granger-causes a second signal, X2 (grain price), then past values of X1 should contain information that helps predict X2, above and beyond the information in X2 alone. By default, the null hypothesis is that X1 does not Granger-cause X2, and depending on the chosen threshold for statistical significance (two-tailed), the normal trio being 0.05,0.01 and 0.005, the hypothesis fails if the result is below this value. I perform granger-causality on each of our timeseries including the post-detrended versions. The limitations to granger-causality are that if both X1 and X2 are driven by a third process, with different lags, the alternative hypothesis might not be rejected. In a process where the true relationship involves three or more variables the result might be misleading, other sources arise from 1) nonlinear causal relationship, 2) nonlinearity and nonstationary timeseries (which mine are not).

The final test to be performed on determining if the price of grain is affected by temperature is a method known as superposed epoch analysis (SEA). SEA is a statistical tool that reveals a correlation in time between two timeseries. The essence of the method is to identify an event in one series and then extract data from the second sequence within a time range of the event in the first timeseries, then superimpose extracted timeseries synchronized to the timing of the event. I take the 10 highest recorded temperature years and decomposed the corresponding GP into shorter segments of 11 years centred around the year of highest temperature. This way showing how grain price reacts to high temperature, if temperature peaks cause harvest failure, thus higher prices then we would expect to see two peaks. The first the superimposition from temperature, the second the response in grain. For a greater historical context, the presence of a war occurring in Italy has been highlighted, in dashed lines, using the binary conversion detailed above. SEA was only explored for after 1400 A.D as that is when the timeseries of war starts and for the Tuscany timeseries as that was the longest record, but with the different detrended methods to remove the trend caused by inflation.

Box 1: Summary of detrending methods

- **Hodrick-Prescott filter:**
  - A Hodrick-Prescott filter is a mathematical tool, used often in macro-economics, to remove the cyclic opponent of a time series in raw data. It is used to obtain a smoothed-curve representation of the time-series, that is more reflective of long-term, rather than short-term, fluctuations[82]. The Hodrick-Prescott filter is a special case of the more generic band-pass filter.
- **Differences method:**
  - This is a simple method that explores the relative rate of change that two series have. It is simply the difference between a value and the previous entry:
  - X=x[t]-x[t-1]
- **High Pass filter:**
  - A high pass filter removes frequencies above a certain threshold (in this case chosen as 300 years) and retains high level frequencies.
- **Butterworth filter:**
  - Similar to the high pass filter, except it is designed to have a frequency response as flat as possible[83].

3.4 Linear regression model

The factors influencing GP occur on different timescales. In the long-term population and silver are dominant, meanwhile, temperature is playing at an inter-annual level, as are social factors (with lasting impacts). Because of this, our temperature signal on GP is going to be difficult to untangle from that caused by social effects, especially since filtration the data, removing, for example, years with war would reduce the timeseries too much. However, with a linear model, I can use different parameters to reconstruct GP representing the effects of different timescales. Using population to capture the long-term trends and temperature to explain the variation I aim to reconstruct GP, this would validate if these factors play a role, and further allow an investigation as to if the model breaks down, at which point I can explore what events are occurring at these times. Population should be divided into both rural and urban populations as they both play different roles when it comes to grain price as described above. The long-term trend attributed can be described by:

Equation 1:

$$Population\ Linear\ Model\ (PLM) = (\rho_{GP-Urb} \times Urb) + (\rho_{GP-Rur} \times Rur)$$

Where ρ is the correlation coefficient of urban and rural. The reliability of population estimates decline further back in time, given the difficulty to fully establish the effects of plagues. As such, the linear model is to be focused on the Milanese timeseries as this covers the entire span of the population estimates. According to my conceptual model, anything that a linear regression model of population does not explain can be explained by temperature. As such, the difference in GP and the linear population can be correlated to temperature. With a predicted GP being the predicted linear model plus a separate linear model based on temperature.

Equation 2:

$$Predicted\ GP = PLM + (\rho_{GP-PLM} \times Temperature)$$

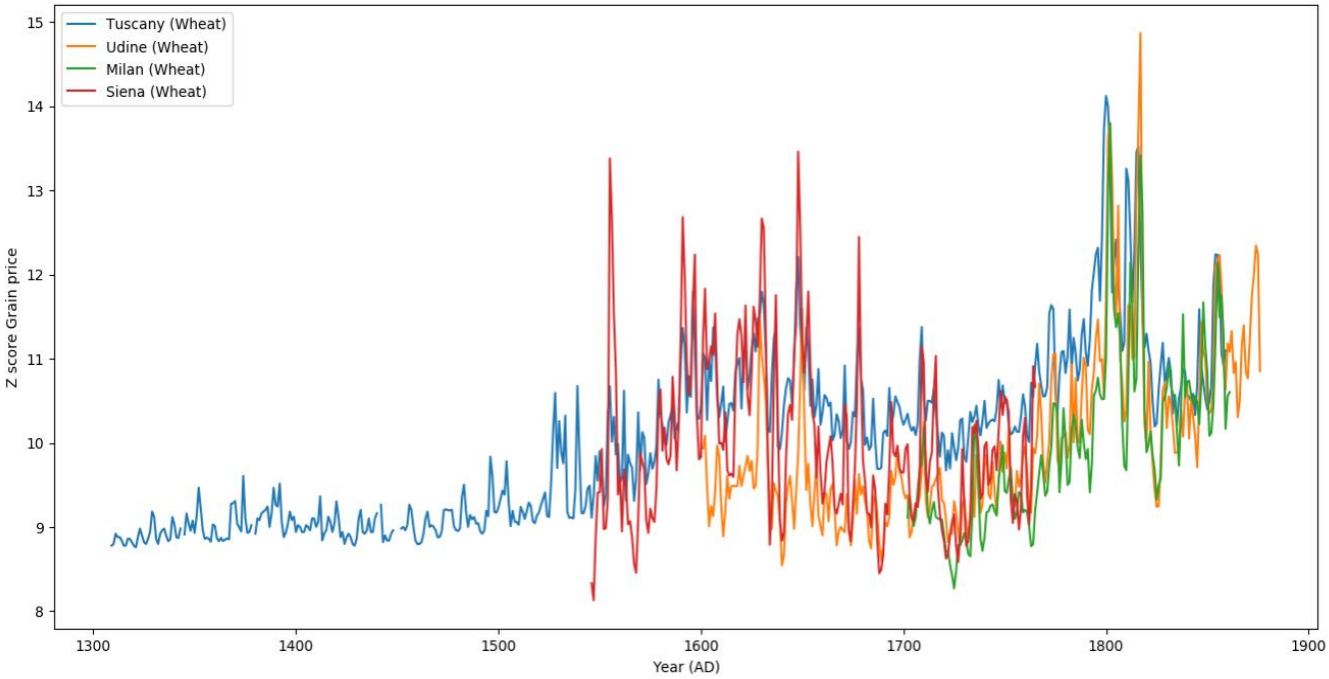
I can then compare the success of the predicted GP linear model with the real data by using correlation techniques, at which point the reliability can be established.

4.0 Data

4.1 Grain price timeseries

Grain data was obtained from the International Institute of Social History (IISH)[60] and covers the 550 years of Tuscan history, as well as the cities of Udine and Milan, and any gaps in the record were linearly interpolated, with a maximum number of subsequent interpolations as two. The Tuscany record is comprised of a combination of records from Pisa and Florence, two neighbouring cities that became part of the same political region (Tuscany) in 1406. Due to the correlation of the two timeseries being close to 1[58], it was reasonable to perform an average for a continuous record, but is referred to as the Tuscany record for ease. These cities provide insight into the price of grain, in our case wheat, for the three powerful city-states of Milan, Venice and Tuscany. Wheat was chosen as this is the staple crop of Italians, with other major grains being considered secondary. I also included Siena, the only Italian city used by Esper et al. (2017)[7], because we wish to compare correlations of Siena individually, with Siena being treated as part of a greater average. Siena was historically an independent city-state; however, it lost its independence to Tuscany in the Italian War (1551-1559). Also included is the Swedish city of Stockholm, although this record is constructed from an average price of Barley and Rye (when both accounts are available), Barley and Rye are the staple goods of Sweden, with Wheat not being grown. The unit of GP differs, the Tuscany, and Swedish record are recorded in Grams of Silver, meanwhile, Udine and Milan are measured in the Italian Lire, and Lira Milanese. To resolve this issue of different units, the grain price data was standardized and provided a Z-score +10, the +10 is to avoid any problems in the analysis where the problem arose of approaching zero.

Figure 2: Locations of grain price timeseries within Italy.



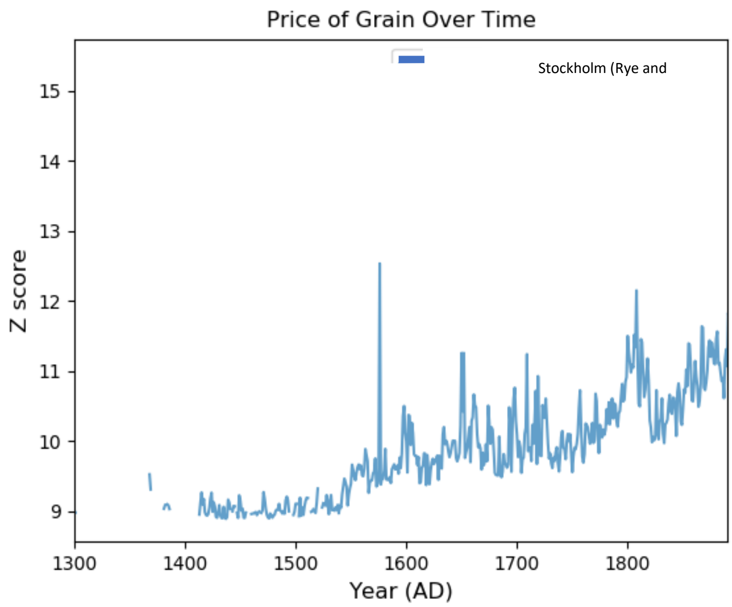


Figure 3: Time series of the cost of grain in the Italian cities of Tuscany (1300-1850), Udine (1600-1874), Milan (1701-1860) and Siena (1546-1765). [Top]

Timeseries of the price of rye and barley for Stockholm (1412-1913) [Left]

4.2 Climate reconstructions

As detailed above for climate data I must rely on temperature rather than precipitation, and I have chosen to focus on a Europe wide reconstruction, Luterbatcher, and a more localized reconstruction from the Alps.

The Luterbatcher reconstruction[56] is a 5 by 5-degree grid reconstruction of European Summer temperatures (June-August), going as far back as-138 C.E., based on the calibration and transfer of tree-ring, as well as existing documentary, evidence using Bayesian hierarchical modelling. From this, I calculated a mean European temperature. Given that Italy was unusual with its extensive trade networks, especially earlier on in our time-series, a Europe-wide average would give an indication as to what European-wide environmental calamities are occurring. For example, Italy might be heavily affected economically, when a climate crisis occurs in the Baltics. To build an array of climate reconstructions for every Italian agricultural trading partner would be a daunting task and would also require a historical analysis of the events occurring for each of them. For example, a naval blockade, which is not climatically induced, would seriously hamper global grain trade, as we saw happening with the resulting French and Spanish famine because of Britain's 1709 naval blockade.

Meanwhile, the summer temperature anomaly (June-August) based on Central European oak samples (Alpine temperature reconstruction[57]) will give a greater insight into the environment of Northern and Central Italy. A temperature reconstruction from a more local source adjacent to the agricultural regions of Tuscany (and the other cities) would offer even greater local representation, but sadly no records covered the time of interest. Overall, I feel that these two temperature records will provide an indication of the climatic situation of Europe and Northern-Italy.

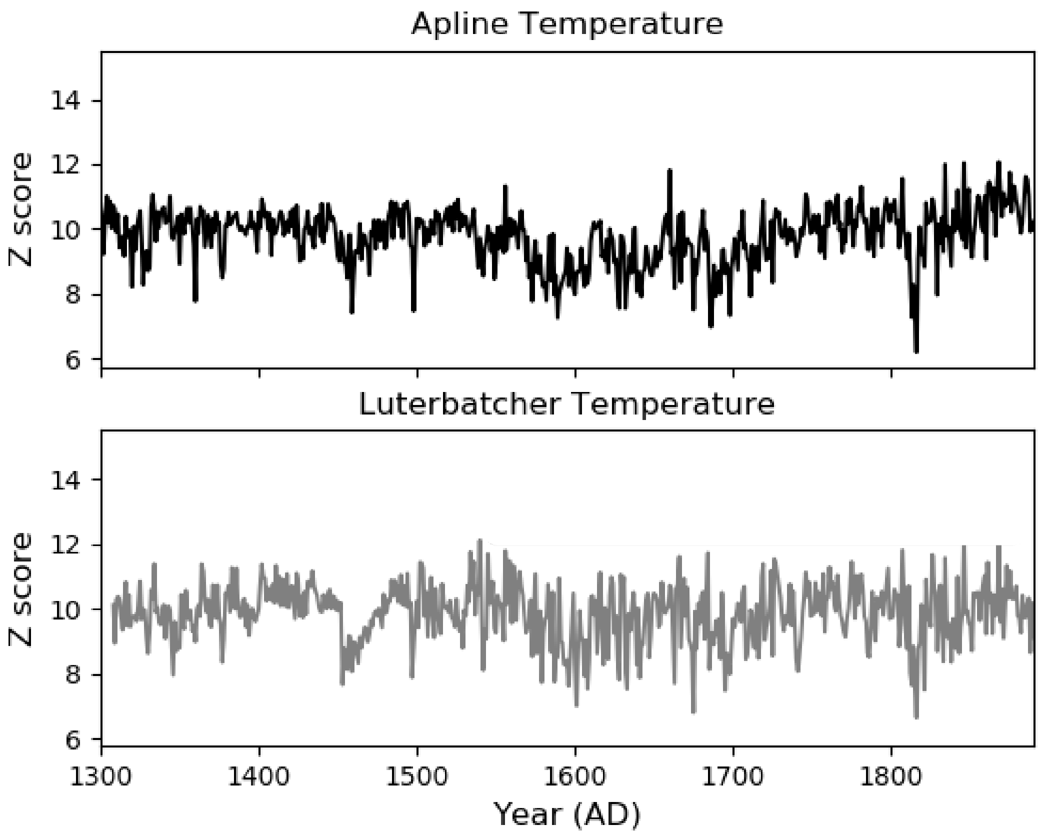


Figure 4: Alpine (Büntgen et al. (2011) and Luterbatcher (Luterbatcher et al. (2016) Temperature reconstruction, covering the years overlapping our Italian GP data.

4.3 Population estimates

Population estimates were taken from the Historical Database of the Global Environment (HYDE)[61]. HYDE presents gridded timeseries of population and land use for the last 12,000 years. Estimates are centennial from the start of our GP record centennial and decadal after 1700 A.D. Population data were logged, linearly interpolated, then anti-logged in order to interpolate to annual increments.

4.4 Timeseries of social factors

In constructing timeseries of social factors, I filtered the following databases to be recording of events that happen in the modern-day geographical region of Italy. I only explore the social factors for Italy, and although this does not fully capture the changing political influence of the individual city-state GP records, it captures the effects of local connections- for example, plague outbreaks in Milan affect Florence, while restraining the effects to what directly involves Italy. As such a war in the (for example) Holy Roman Empire is not recorded unless one of the city-states is involved, or the frontlines of conflict take place in Italy. Plague outbreaks are digitized by Büntgen (2012)[62] and provides a complete record of known plague outbreaks across Europe and China, beginning in 1346 and ending in 1900. A collection of all recorded wars are available from the Centre for Global Economic History and is compiled by Brecke (2012)[63]. Although not complete, it is the most extensive collection of wars made, with its first entry being 1400 A.D, detailing state actors, location, the start and end date, as well as in some cases fatalities. The timeseries of social unrest outbreaks was constructed from Sorokin's *Social and Cultural Dynamics Volumen III (1937)*[64], which includes a list of recorded internal disturbances across Europe. Social disturbances take a variety of forms, but are categorized as:

- Political disturbances, with the aim of establishing a new political regime.
- Socio-economic disturbances, directed toward the modification of existing social and economic order.
- National and separatist disturbances, in the hope of either national independence, autonomy or achievement of some other privileges.
- Religious disturbances.
- Others, such as the murder of the King of Naples (1345).

Overall, our Italian record, covers 130 revolutions, conspiracies, peasant uprisings and many more. As well as my separate timeseries which were normalized, a combined 'catastrophe' timeseries was constructed by summing the separate timeseries of war, plague and social unrest then normalizing in its own right. The units of these timeseries are thus the number of events in a given year.

5.0 Results

5.1 Correlation between grain timeseries

Table 1: Correlation between grain price timeseries across their common years

City	Tuscany (1308-1858)	Udine (1600-1874)	Milan (1701-1860)	Siena (1546-1765)	Stockholm (1412-1913)
Tuscany	1	0.75	0.69	0.79	0.79
Udine		1	0.88	0.64	0.66
Milan			1	0.56	0.65
Siena				1	0.03
Stockholm					1

The Italian timeseries of grain price sees a steady increase in price up until the mid-14th century, at which point the price stabilizes, that is up until the turn of the 16th century when there is another linear increase in price. In 1629 the price starts to undergo a linear decline in price, before reversing and increasing again in 1710. This is the trend across the cities, although there is a different base level with Tuscany having a higher price. The trend for Stockholm is similar, except there is no decline in the 17th century, instead, the price is stable until the late 18th century. Across Italy, the cities correlate highly amongst themselves (Table 1). Tuscany and Siena correlate the highest, but given they are part of the same city-state for the majority of the timeseries, that is not too surprising. Key- events are distinguishable across the timeseries such as the disruption caused by the Italian Wars. However, the effects are not equal, for example, Siena when it was under siege in 1553 the price increases disproportionally- it is such events that would be averaged out with a Europe-wide analysis.

These changes between inflation and deflation correspond with the timing of demographic change from the outbreaks of epidemics- The Black Death and the Italian Plagues of 1629-1631, but also the increases in global silver supply, with the Spanish settlement of the Americas. Especially notable is the timing of Italian GP increases and the conquest of Mexico. This applies too in Sweden, although with a slight lag.

5.2 Temperature data

The correlation between the Alpine and Luterbatcher temperature reconstructions is significant (r=0.70), both showing key periods, such as the cold phases of the Spörer (1460-1550) and Maunder minimum (1645-1615)[65], as well as the one-off events, for instance, the Year Without Summer (1816).

5.3 Climate and grain price

To establish a relationship with climate, I correlated the temperature to the GP as both raw and post-detrended data. The correlations with temperature are low in Italy no matter the de-trending method used, and despite using the Luterbatcher temperature reconstruction and with the 300-Year High-Pass filter, both used in the Esper et al. (2017) analysis, the correlations are much lower (Appendix 1). Even the Siena dataset, which is one of the cities used in the Europe-wide analysis, has a low correlation emphasizing how individual cities have a lower correlation than averages. On the other hand, the duplicated Siena dataset used by Esper et al. (2017) has a correlation of only r=0.03 with my high pass detrended data and their high pass detrended data. This is probably a case of de-trending through different computational tools, despite the same parameters, regardless it shows how important the de-trending methods are in affecting the strength of correlations. The best correlations for Italy occurred with the raw data, which requires heavy caution upon interpretation, as this could be capturing the periods of climatic 'good' and 'bad' times corresponding to periods of historic 'golden' and 'dark' ages, discussed in Zhang et al. (2011)[8]. Across Italy, there is a tendency for Milan and Udine to have a slightly higher correlation, but it is important to note that these records start later. Meanwhile, the Stockholm, record has a stronger correlation with temperature, even after detrending with the Hodrick-Prescott (r=0.34 Luterbatcher reconstruction) and Butterworth (*r*=0.25 with Luterbatcher) filter. It does, however, not establish any relationship with the High-Pass filter. The inclusion of a lag into the data did not improve the correlations.

A scatter density plot (Figure 5) of GP and temperature for the Tuscany record emphasizes the lack of correlation, although it becomes apparent that there are two centralized areas, the one before 1660 the other after, capturing the permanent offset caused by inflation in GP. Furthermore, as described before both low and high temperatures destroy crops, at both extremes, there is a supply shortage. Thus, one possibility for the absence of correlation would have been that the GP should be performing a U-shaped scatterplot of temperature and grain price, with the extreme temperatures causing high GP. Such an explanation can be ruled out, as no such pattern is visible.

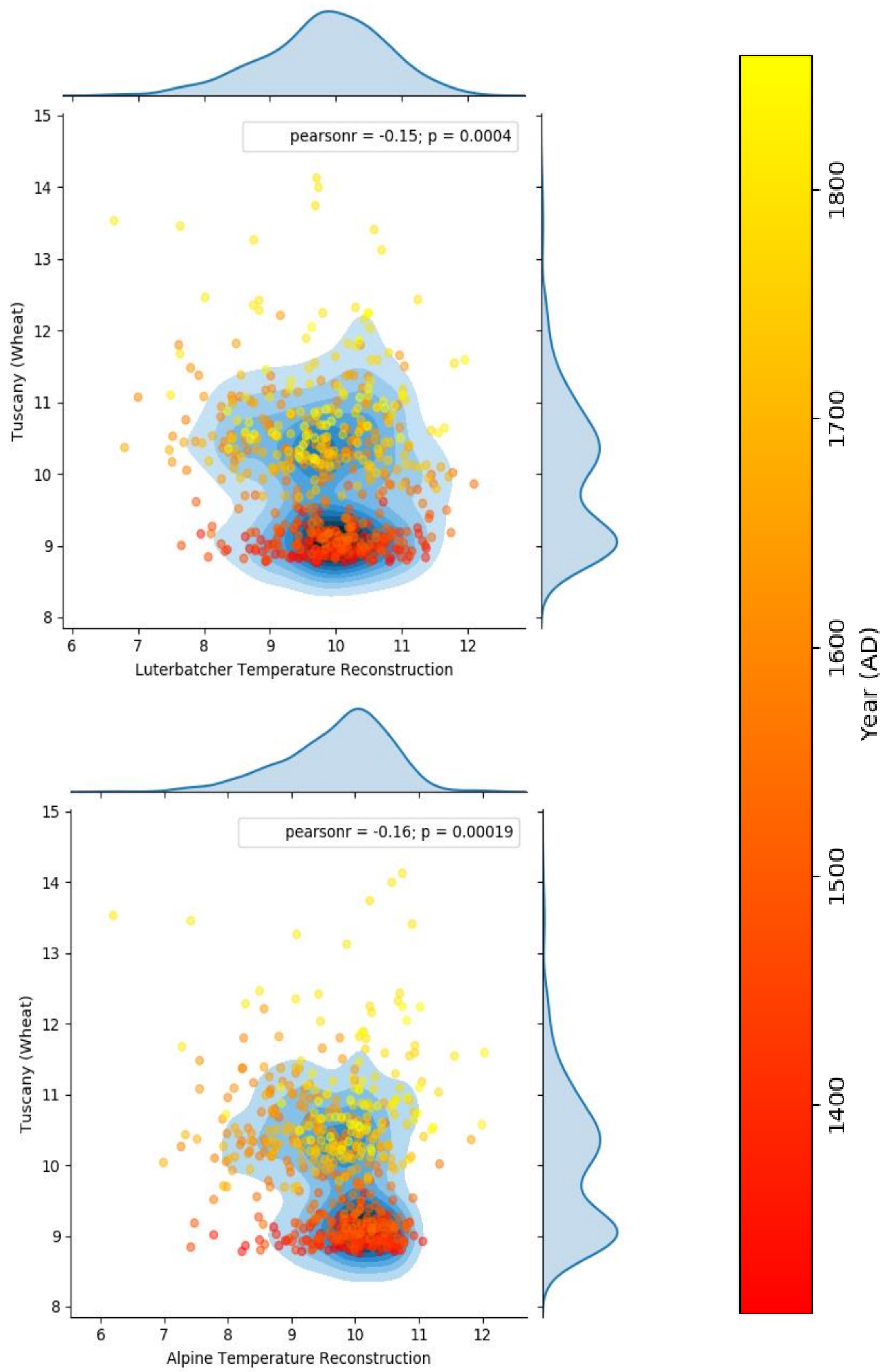


Figure 5: Density plot of grain price (For Tuscany, as this is the longest complete record) and Luterbatcher temperature (top) and Alpine temperature (bottom). Overlain is a scatterplot of grain price vs temperature, with color corresponding to the year of Sales.

The Granger-causality test is a method that establishes if X1 helps predict X2, in this case if temperature helps improve the predictive ability of GP. The results are in support of the null hypothesis (temperature does not Granger-cause GP) for the majority of cases. The only exceptions are first that of Alpine reconstruction, which Granger-caused the price of barley and rye in Stockholm with two of the detrending methods. Secondly, the Luterbatcher reconstruction Granger-caused Tuscany GP variation for the raw (processed but not detrended) data. Although it granger-causes with the raw GP, it should be recalled that this is non-linear, which is one of the key limitations for the statistical tool. In addition, the fact that there is no consistency across the de-trending method with the Alpine reconstruction means that it would be hard to support the concept that temperature does Granger-cause GP.

The final method for establishing a direct relationship between climate and the GP was that of SEA. The SEA analysis explored the response of GP (Green in Appendix 4) to the highest temperature peaks recorded (Red). If there was a sustained pattern of response to high temperatures, then due to the superimposition the response signal would reinforce itself. However, we see that, regardless of temperature reconstruction, and if detrended or not, that there is no apparent relationship. The window of 11 years is long enough such to allow recovery of prices and stabilization, after all, it is only when famines reached the urban settlements was the social and economic effects felt. Further, it would take (in the majority of cases) two bad harvests in a row or poor management for there to be a significant impact and not daily life. Admittedly, we see that war occurs at some point within the time window (expressed by the dashed lines) in most cases of the SEA. This should not necessarily be interpreted as high temperatures causing war, which would then affect the price of grain, but a caveat of the flagging system- Flagging whenever there is a war occurring at some point on the Italian peninsula gives the appearance that Florence, or any other city, was at near constant war. This is not true, although it should be realized that any city-state has a rich history in conflict. Unfortunately, changing the flag system to be only express a time of warfare around Florence has its own problems. By filtering the dataset this much, it fails to capture many events that indirectly have huge impacts on the Florentine economy, that are heavily described in Italian history literature, but because Florence is not deemed a warring actor it would not appear on the database. Putting aside the abundance of war occurring, grain price is scattered and there is no consistent response to grain price, which we would have expected given that high temperatures should theoretically cause droughts which cause prices to rise.

5.4 Linear model for GP based on population and temperature

The linear model used population to reflect the long-term inflation and deflation changes, with temperature being responsible for all other factors in GP variation.

Population and the overall trend of price follow each other fairly well, up until 1820 when population increased, whilst prices remained relatively stagnant, which has been attributed to European improvements in agriculture (Figure 6). The population linear model is built around the correlation between the urban and rural population with the GP, and quantitatively we can see that the relationship is strong with urban population, r=0.76, and for rural population, r=0.66. Temperature can explain the difference between the linear population model and the real GP, with the alpine reconstruction (r=-0.26), and to a lesser extent with the Luterbatcher reconstruction (r=-0.15).

The addition of both temperature models manages to replicate the changing price of grain with r=0.63, however, there are clear periods of model underestimation. The relationship between population and GP is much stronger before 1820 than it is after, this is attributed to improvements in agriculture. I identify six periods which stand out as being underestimated by the model, these six correspond to periods of war (Figure 7):

1) The beginning of the 18th century, coinciding with the War of the Spanish Succession (1701-1714).

2) Between 1733-35/6, which is right in the middle of the War of the Polish Succession, when the Bourbon powers of Spain and France attempted to check the power of the Austrian Habsburgs, although a preliminary peace was reached in 1735, with the war formally ending in 1738.

3) A period which coincides with the War of Austrian Succession, that in 1740 and ended in 1748. However, it was not until 1745 that the Spanish forces started to strike out at the regions of Lombardy and Genoa.

4) A sustained overestimate of price from the Seven Years War (1756-1763), in which although Italy was neutral, it was overly taxed by Spain.

5) The long period from 1793-1806, when grain price is much higher, matching the Wars of the First, Second and Third coalition (The war of the Fourth coalition, 1806-1807, did not focus on Italy but the Rhineland).

6) From 1810-1818, which captures a mixture of the Wars of the Fifth, Sixth and Seventh coalition, and also the extreme famine caused by the Year Without Summer.

This shows that war plays a strong part in disrupting grain price into what it elsewise might have been. This linear model also enforces the relationship between population and inflation periods. Unfortunately, to extend this record further back in time, would require far better population estimates than are currently available.

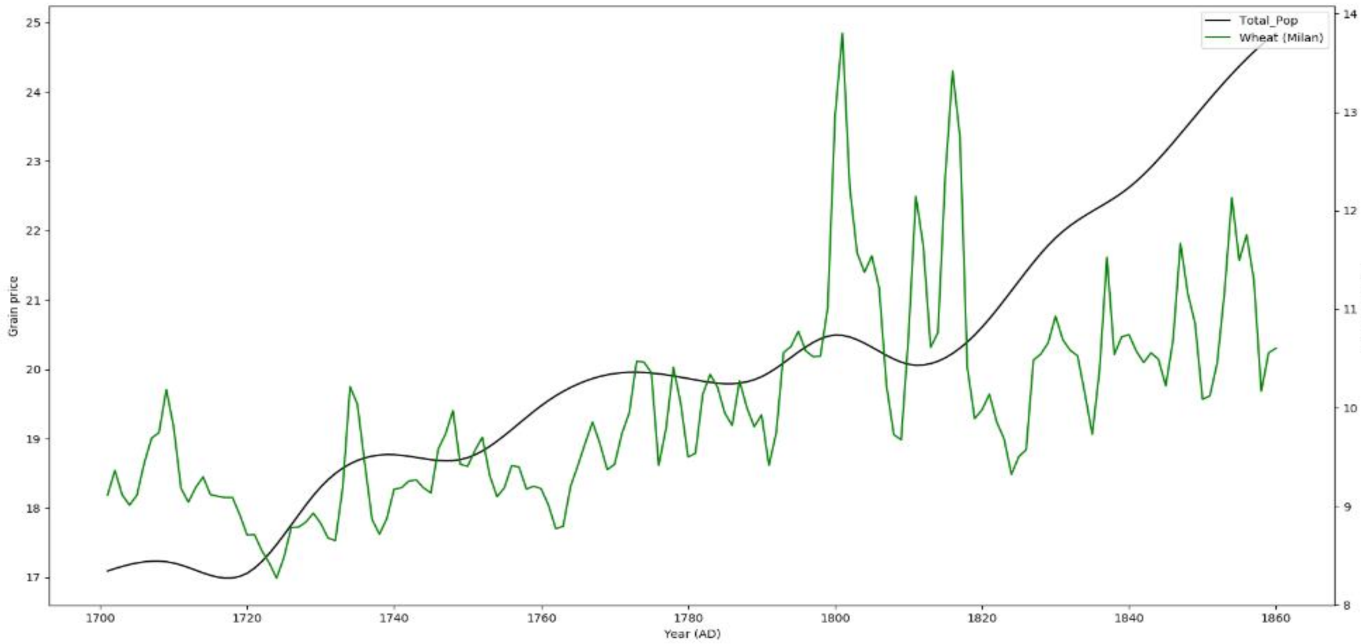


Figure 6: Sum of Rural and Urban population (black) and the price of grain in Milan. Note how waves of population match clustering's of GP

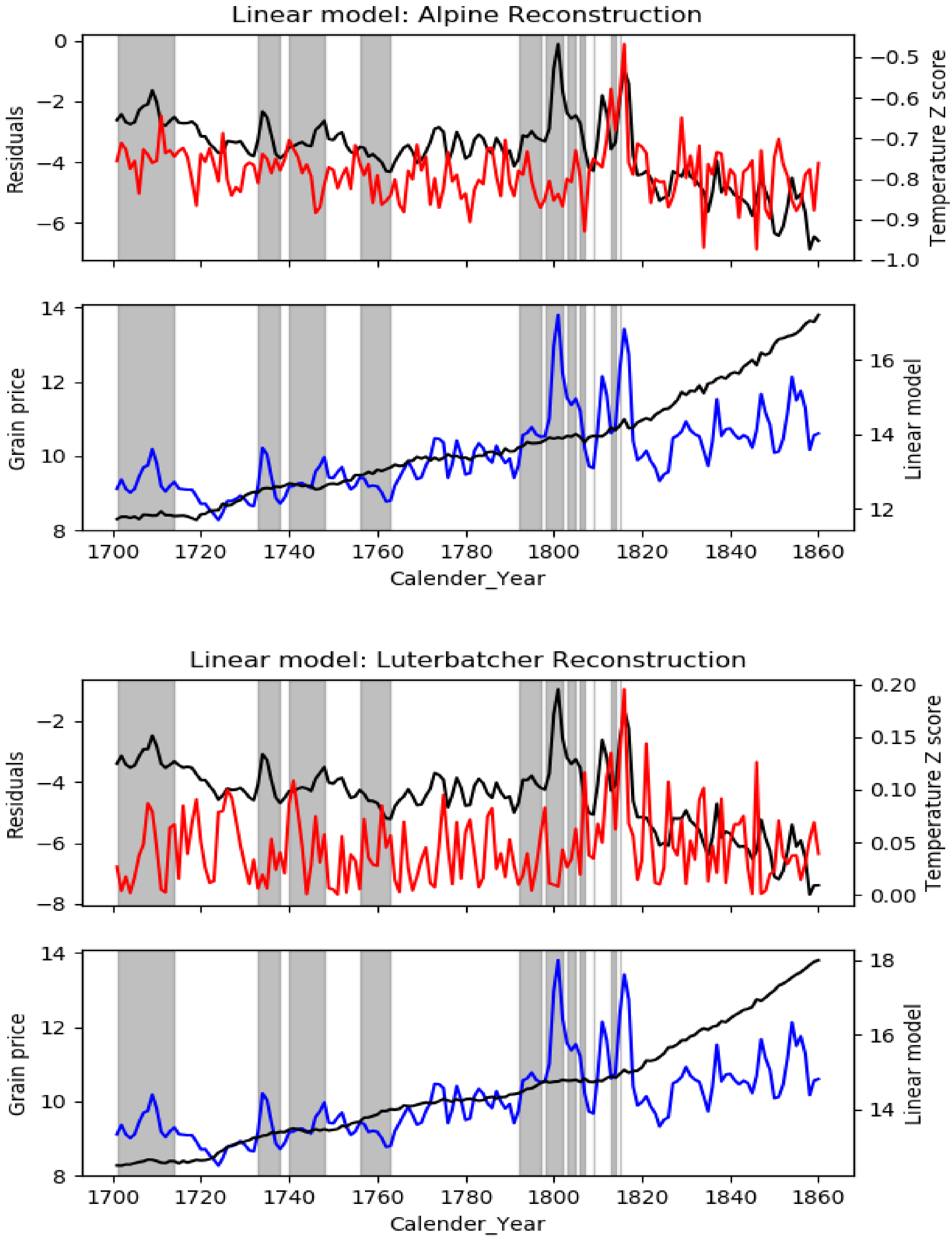


Figure 7: (Top) Temperature (red) and the residuals (black) between the linear model described by rural and urban population, and the historical GP timeseries. (Bottom) Grain price (blue) and the complete linear model (black). Note the periods where the GP is much higher than the model (Shaded grey).

5.5 Hilbert-huang transform

The principle behind the use of Hilbert-huang transform is to decompose a timeseries into a series of oscillators, but this might cause us to see self-produced signals, however, the social and economic theories give support that the cyclic system exists. We can see from the HHT decomposition of the Tuscany GP that the first IMF 1 and IMF 2 ably describe the inflation and deflation (Figure 8). Given how we divided the various GP factors into various scales. What I propose is that the highest IMF's relate to the variability of GP, which I attribute to temperature and the instantaneous effects of catastrophes, the middle IMF's are caused by social or economic cycles, and the lowest IMG's reflect the long-term population and silver changes.

We find that temperature is not detected as causing the signal in the higher IMF's (Figure 9), having a correlation of r=0.00. But this timescale has the instantaneous effects of war, plague and social unrest causing en-mass destruction. The relationship between catastrophes fairs better (Figure 10, r=0.10). Meanwhile, the correlation between population (a sum of the rural and urban population count estimates) and grain price, for IMFs 1-3 is much high (r=-0.28). Naturally, my division of IMF's are somewhat arbitrary but this helps illustrate the issue of factors occurring on different timescales.

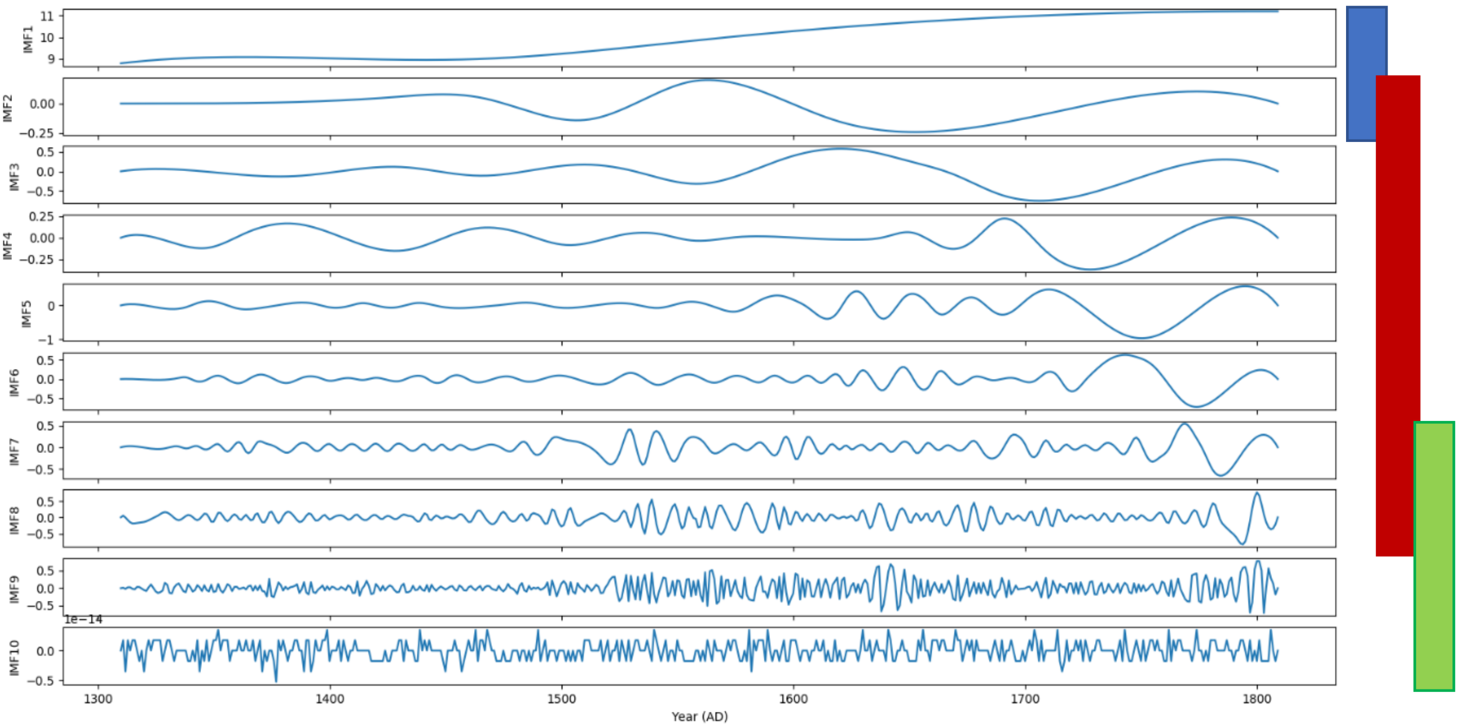


Figure 8: Breakdown of the largest 10 Intrinsic Mode Functions (IMF) for the Tuscany GP record. Note how the top two reflect population and silver influx changes (Blue Bar). I believe that the IMF's 2-8 describe catastrophes (Red) and that the higher orders, are a mixture of noise and weather (Green Bar).

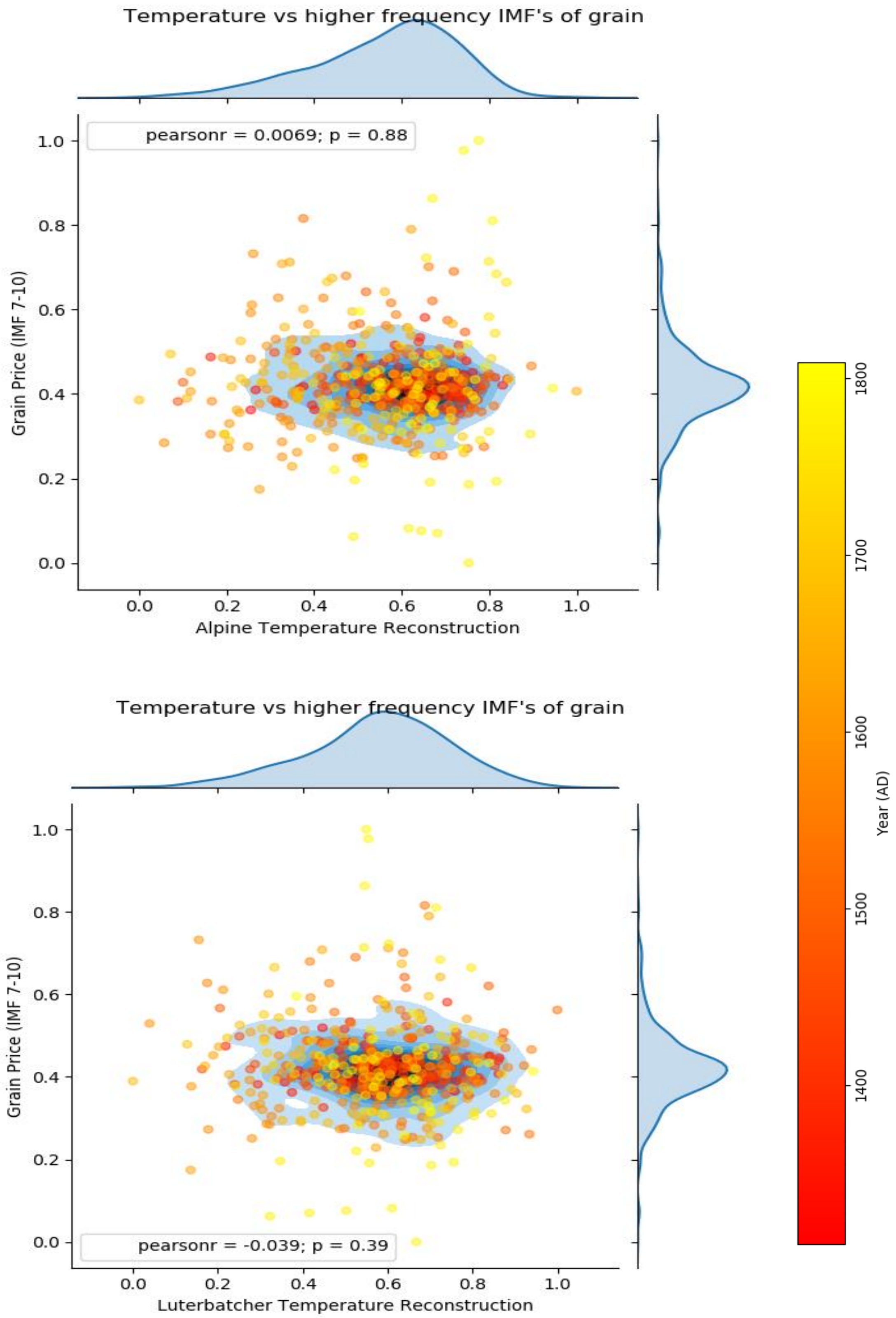


Figure 9: Density plot of temperature (Alps-top, Luterbatcher-bottom) reconstructions and the sum of grain IMF 7-10. Overlain is a scatterplot, coloured by the year of sales

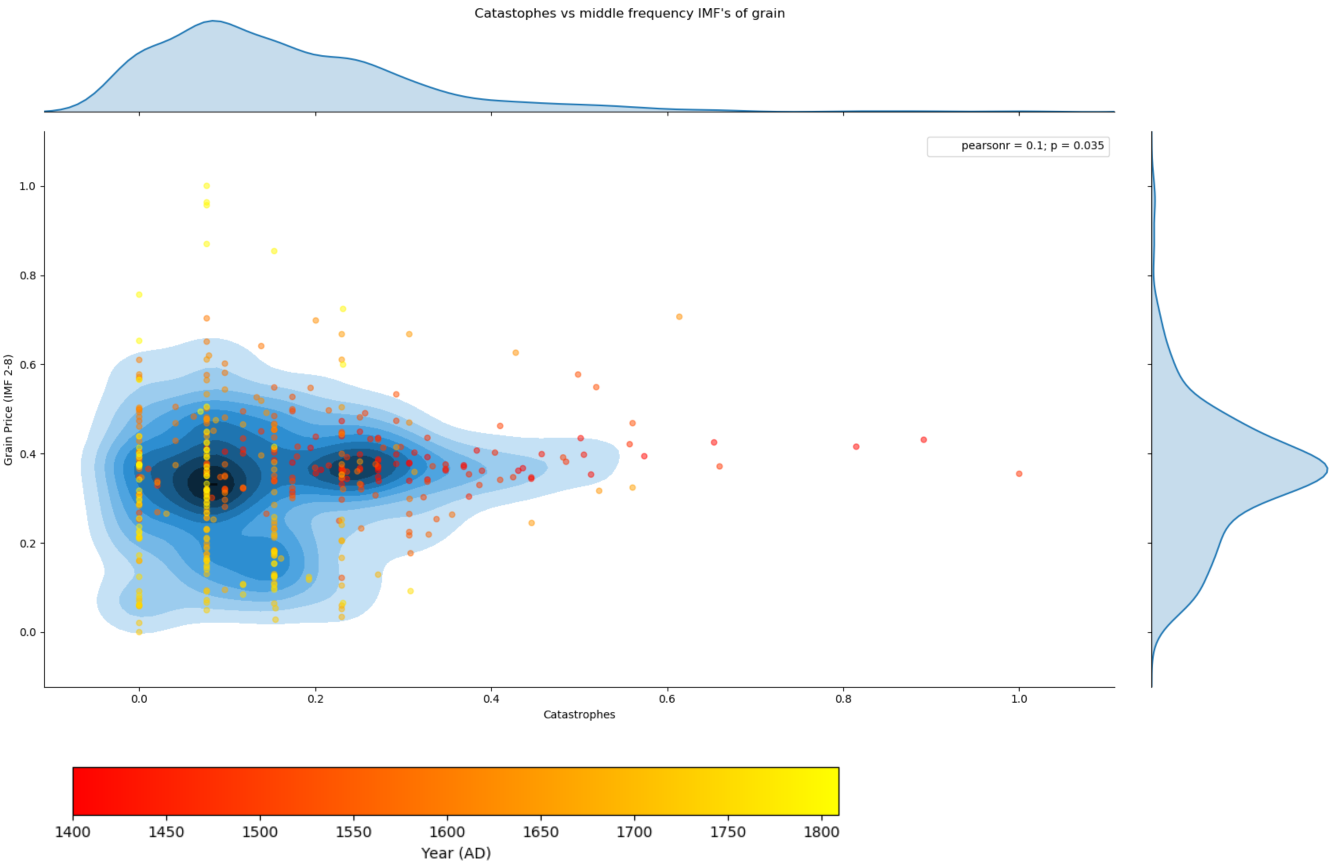


Figure 10: Density plot of 'catastrophes' against the sum of grain IMF's 2-8. Overlain is a scatterplot, with colour corresponding to the year.

Thanks to HHT, I can remove the highest order frequencies, that could be considered perturbations to a cyclic system, and then sum up the first IMF's so that we obtain the 'noise-free' signal Figures 11-13 show the timeseries of war, plague and social unrest in blue, in red is the sum of the first X IMF's which highlights the repetition of high and low-density number of catastrophes. The IMF breakdown of plague shows that epidemics strike every 10-15 years. Given than epidemics burn themselves out, it takes some time before the plague can strike again. We also see a gradual decline over time, but it is known that sanitation improvements have increased over the centuries. Due to the nature of the HHT and a cut-off number of IMF's, there is an artificial spike in plagues in the 19th century. Meanwhile, number of separate wars, shows a regular pattern of clustering- spaced out every 8-12, 20-25, 60-70 and 120 years, yet a gradual decline.

Social unrest has also seen a gradual decline, upturned by the onset of the French Revolutions. Throughout, social unrest undergoes an increase that occurs every 20 years. The IMF analysis was stopped at 1809, as that is when our population diverges from GP and therefore the contribution of what causes GP could be different.

Aligning what are effectively smoothed curves of war, social unrest with the sum of the first 8 IMF's reveals an interesting picture (Figure 14). Every peak of GP corresponds to a peak in war, plague or social unrest. Given the regular timing of such events, it seems possible that these cycles exist but more crucially the timing of sustained GP increases corresponds to grouping catastrophes

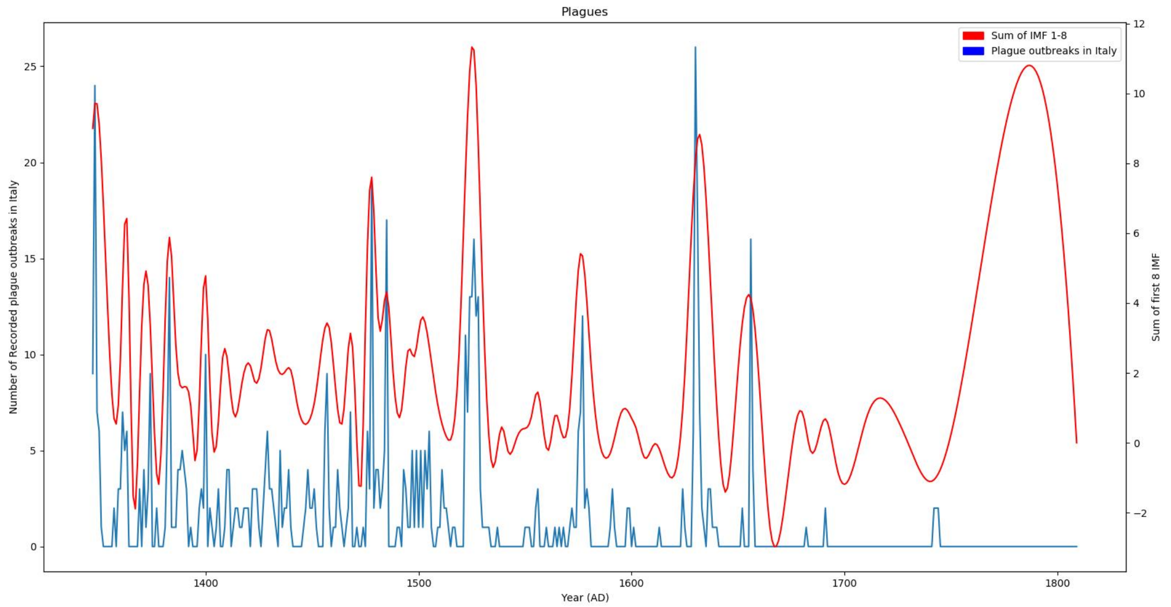


Figure 12: Sum of IMFs 1-8 (red) and timeseries of Plague outbreaks in Italy (blue). Note the artificial spike in the 19th century, this is because of the nature of where the IMF cut of was, if we included more IMF's then the oscillation would cancel this peak, but at the cost of describing individual variations

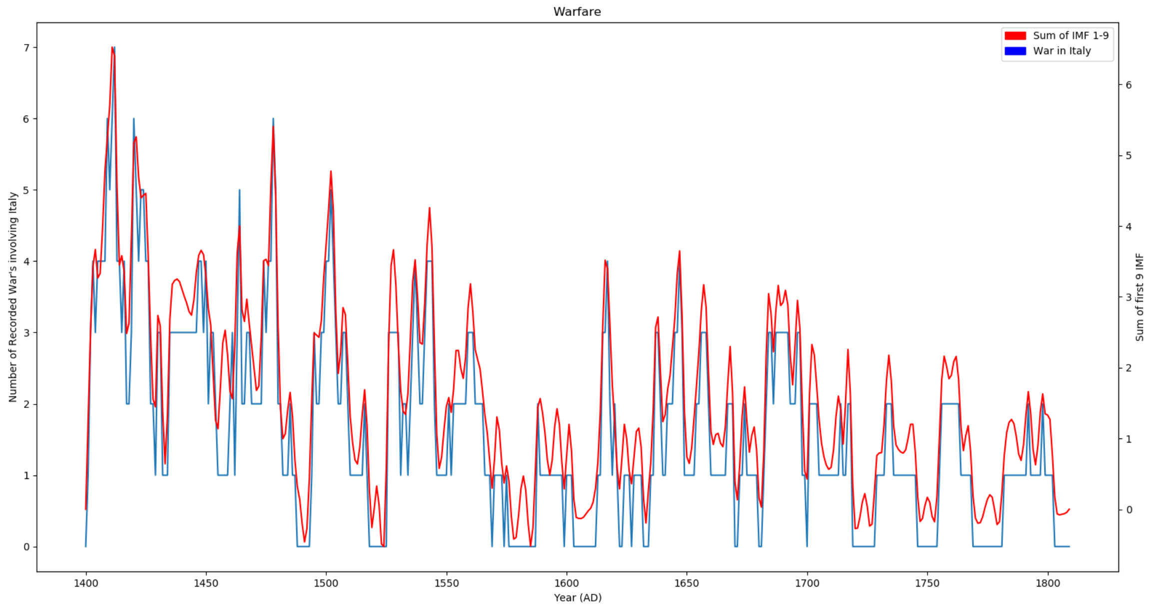


Figure 11: Sum of IMFs 1-9 (red) and the corresponding timeseries of the number of violent conflicts (blue)

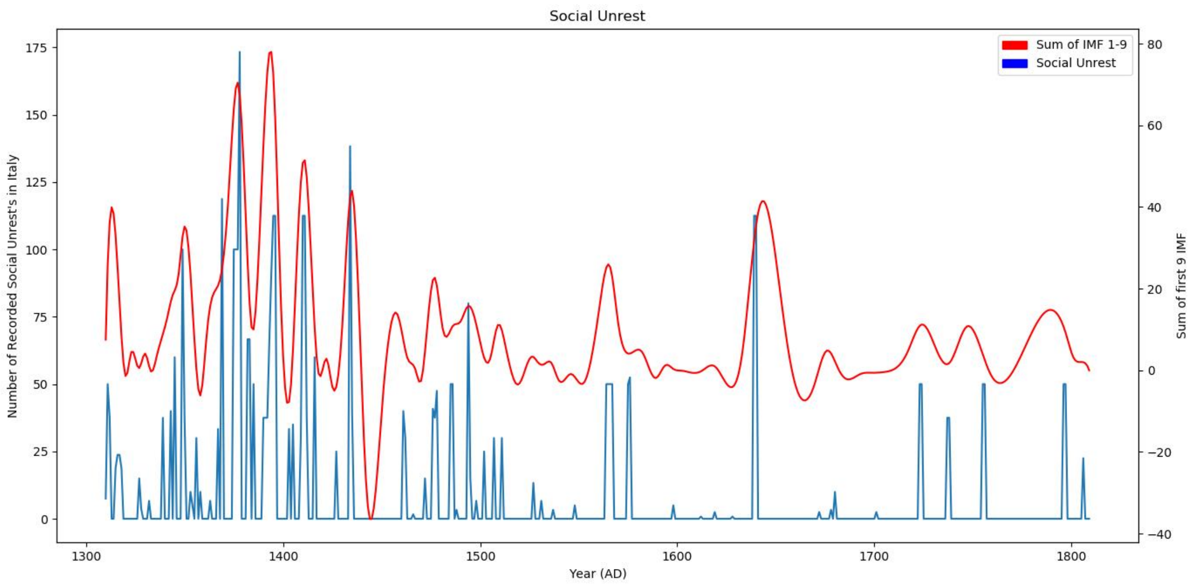


Figure 13: Sum of IMFs 1-9 (red) and corresponding timeseries of social unrest (blue)

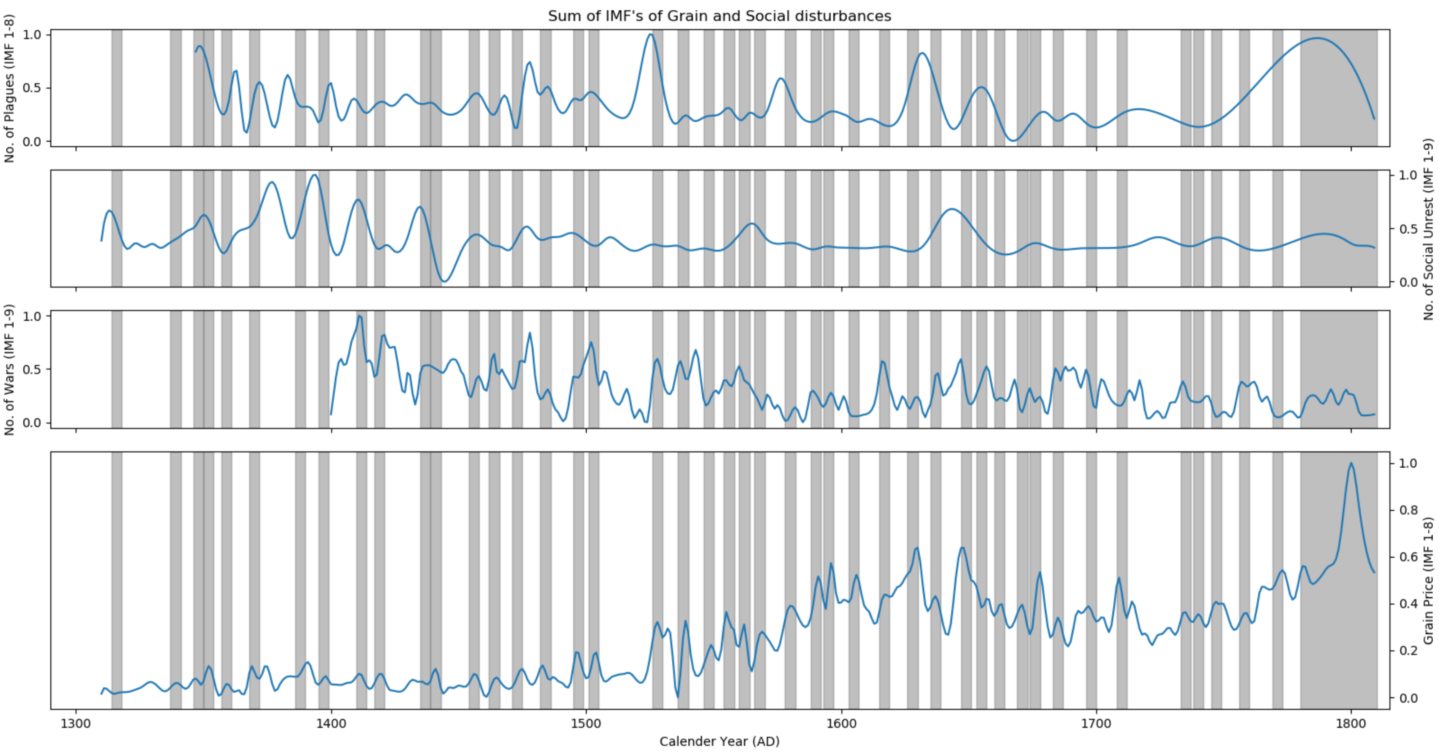


Figure 14: Periods of sustained GP increase correspond nicely with a peak in the cycles of war, plague or social unrest. Implying that these are not periods of economic prosperity but either price hikes from depression causing increased catastrophes or catastrophe cycles themselves. In blue is the sum of the relative number of IMF's and in grey shows years of high GP. Note this analysis was done for the Tuscany timeseries of Wheat.

6.0 Discussion

6.1 Silver and Population

Silver and Population play the largest roles in determining the overall GP by either adding to the market or increasing the cost of goods. The lag in the inflation experienced by Sweden compared to Italy, this is due to Italy being under Spanish influence, and Spain spending its newfound wealth on purchasing spices from the Italian city-states. The question remains as to which plays a larger role, this is difficult to answer. However, whilst silver declined in the 17th century with inflation decreased in Italy, but not in England (Figure 4, Malanima (2013))[66]. The countries did respond differently to plague, England's population recuperated quickly, whilst because Italia's rural population was harder hit than those in England, the ability for urban centres to recover, and therefore population, was stiffened somewhat.

This would tend to imply that population plays a stronger role, but by itself this would be a bold claim. Regardless, timing in the population and silver influx happen to strongly align with the inflation and deflation seen in the GP records.

6.2 The role of climate

Across the Italian grain prices, the fact that all grain prices respond to unique events, the common trend dominates. After all, these Italian city-states are connected by a complex trade networking, relying on intermediary towns, such as Rovereto which was between Milan and Venice, to trade one resource for another[67]. What is clear, however, is that individual cities are subject to unique situations such as the Florence or Siena sieges which would cause their price to go up. The correlation between cities is clearly dependent on the overlapping timescales between datasets. Stockholm correlates highly with Tuscany but this also includes the timeseries experiences gradual increases thanks to the Spanish price revolution, and common growth in the late 18th and 19th centuries. This also explains why Stockholm differ so strongly from Siena the times which overlap between the two datasets is when Siena differs from Stockholm, Siena sees prices gradually decline across the 17th and 18th century, whilst Stockholm sees stabilization. Yet, because the other Italian cities see declines they correlate highly.

By using de-trending methods to remove inflation, I expected to see a stronger temperature signal. In practice, what we see is the unprocessed raw data has the highest correlation, which implies that inflation periods correspond to periods of high and low temperatures, such as the little ice age and medieval climate optimum. Meanwhile, the de-trended GP timeseries had next to no correlations, this indicates that any influence on GP from temperature-induced harvest failure is either negatable or drowned out by other factors. On the other hand, the linear model aptly described GP variation with using temperature to explain volatility, however, this only investigates after 1700 A.D. Furthermore, Udine and Milan whose timeseries start later than Tuscany tend to have higher correlations. As such, it is possible that over time the influence that temperature has on GP has changed- with later in time being more climatic sensitive, hence the greater correlations and success of the linear model. We have seen that war, plague and social unrest affect the price of grain, both from historical examples and from the results of IMF analysis. The number of wars, plagues and social unrests have declined over time, meaning that there are fewer effects which could influence the GP in the later centuries. This might explain why locations differ in correlation, as they also differ across the time periods studied, and thus experience more-or-less catastrophes. Furthermore, the Po-valley was subject to massive irrigation improvements[34] during the second-half of our timeseries as there was an increased governmental policy to rely more on local agriculture, and this would increase the role local climate has to play.

It is worth noticing that the fewer wars towards the end of the GP timeseries they were more global, more violent, and it became much more about the restoring a status quo of European-wide power, and less about one city-state performing economic warfare on another. This increased globalisation trend is not limited to warfare but also increased global trade networks which might explain the increased volatility seen in the timeseries of GP as single events have much wider consequences. The fact that Stockholm has a higher correlation with climate than any of the Italian cities, the correlation coefficients being similar in strength to the findings of Esper et al. (2017), would tend to raise the concern that Italy is an exception to the rule.

6.3 The uniqueness of Italy

The high urbanization rates of the Italian city-state gave the manufacturing capacity to purchase grain. Florence famously traded cloth for Sicilian grain (70% of its total exports going to Tuscany[68]) and the sheer size of the urban market would have led to greater diversification of non-staple foods, which would have put less stress on the price of grain and in all probability, the wealthier urban residents would have been able to have a more varied diet, and as such reduced reliance on the staple cereal, grain[69]. However, this last point is probably offset by the congregation of the poor and destitute, who would rely even more so on cheap grain and charity.

In addition, Italy the greatest provisional institutions in early Europe[11]. Supplying the city 'legitimized the governing class in the eyes of the poor', who were measuring the changing stocks and quality of bread each day[70]. As it is the case today, these mechanisms were a fine line of preventing incoming grain from outcompeting the local production, whilst maintaining sufficient competition. In times of extreme famine, prices were modulated by the government, who on occasion where capable of successfully resolving what could else-wise have been crises. For example, in 1590, Medici officials already knew that the harvest was going to be bad, and so Ferdinando commissioned Neri Giraldi and Riccardo Riccardi to buy grain from the Baltics to 'fight the specter of famine'[71]. Their mission was a success, with huge quantities of grain arriving in the port of Livorno. These exceptional institutions mean that a temperature influence which might have caused a crisis in another city was resolved without an increase in GP. Of course, governments were not always were successful, but as long as the government was seen to act to protect their subjects, then the price might rise, from lack of supply, but revolts would not arise. However, if there was a sense of government indifference, then that was a much different story, showing how high prices can lead to social unrest, in addition to social unrest causing high prices. Such consequences did not stop governmental officials and traders stockpiling grain and selling it for a tidy profit, often by keeping grain just outside governmental jurisdiction. To reduce speculation, the city officials would often dump their remaining grain reserves to flood the market at opportune moments, which would then suddenly dorp the price.

The Italians had another major advantage at tackling famine compared to their counterparts in Northern Europe. Northern Europeans, such as those in Northern France, were often much more reliant on a single crop, whereas Italy had a much larger range of crops grown at the same time[70]. In the situation that one crop type was sensitive to failure, there were always others to consume, even if they were considered lesser-crops. Although, the introduction of maize, in the mid- 1500s, ended up being a reversion of this rule by the end of the 18th century, since maize produced a similar, if not superior, yield than wheat in most regions of Northern Italy. An extreme example of the faults of relying on a single crop is that of the Irish Great Famine when 2/5 of the population was reliant on potatoes. Admittedly, this example's severity is somewhat emphasized by the help (or lack thereof) from the British, with a 'culpable neglect of policies leading to mass-starvation'[72]. It is easy to see from this how in a one-crop world economic disaster is more likely to be devastating socially and economically, whilst Italy's multiple crops meant that there was a fallback option to stabilize the system. This example also emphasizes that although climate can help cause the failure of harvest, in this case, by providing a perfect environment for Phytophthora infestans (commonly referred to as potato blight) to foster, it also matters on the success or failure of political authority, which in the case of Italy is more capable than seen elsewhere.

The evolution of Italian agriculture was also subtly different from much of Europe, because the old towns decayed, but never truly vanished, thanks to the 'continuing moral, political and economic power of the local bishops'[73]. As a result, there were always markets, and towns as they recovered (it is unclear as to what crises is being recovered from in Hunt (1999)[73], but presumably it refers to the Black Death), approached the surrounding countryside for their sustenance, actively encouraging the cultivation of a wide range of produce, and not just cereal grains. Another difference arises from the fact that feudal practice of primogeniture never entirely took hold, and so land rights passed on to multiple heirs. Further, lordly landholdings were never too far away from a town, the place where nobles would mingle politically and socially, as well as undertake business. These factors resulted in a greater connection between countryside, town and city, absent from the rest of Europe, which might come into play in how temperature affects grain price.

Monasteries played a large role in grain purchasing than elsewhere in Europe, originally buying in small purchases, but in subsequent centuries, bulkier and bulkier purchases took place- which might further explain the volatility seen in later centuries in our GP records. During times of crises, monasteries were forced to re-enter the grain market and sold previously stored grain[70], thus flooding the market and dropping the price before a dire crisis.

In addition to differences caused by advanced provisional institutions, a wider range of crops and monasteries, Italy was unique in the form of its economy, allegedly having a proto-capitalist society by the 12th and 13th centuries, with people buying state bonds, paying taxes, and having private bank accounts. As such, the Italian economy, in general, was somewhat of an exception, straddling both medieval and modern society[74].

Italy's history is defined by its geography, this had the benefit of sponsoring trade. To put it into perspective, in the late half of the 14th century, it has been estimated that the Hanseatic League represented only 6.6% that of the Mediterranean[75]. This ability to trade allowed the ability to purchase grain and resolve crises. In Esper et al. (2017)[7] they note that their *peripheral* towns (Bruges, Exeter, Madrid, Barcelona, Sienna and Modena) have a lower correlation with the European-wide GP average, and say that this stems from trade through the Strait of Gibraltar and the English Chanel. Thus, it is logical that our Italian city-states who are home to substantially more trade will have even weaker correlations with GP. Trade has the unwanted consequence of bringing an increased number of plagues, whose arrival and devastation has been documented.

Italy's geography is also its curse. Trapped between the varying superpowers of medieval Europe: The Holy Roman Empire, Austria, Span and France - Italy became battleground of Europe. As such, it was exposed to countless conflicts which affect the grain price, as apparent in the EMD analysis and the linear model. This is not to say that in contrast, Sweden was a *world of peace*, on the contrary it had its own historical episodes, such as the Kalmer Unification, the creation of the Swedish Empire, the wars against the Holy Roman Empire, Poland, Denmark, Norway, Lithuania, Russia and many more, as well as its own Enlightenment and colonisation periods. However, no part of Western Europe was more continuously ravaged by warfare than Italy, especially in the 14th century, and no region was more affected by the financial costs of war, principally 'in steeply rising regressive taxation'[76]. The increased number of wars and plague would cause short term perturbations to GP will mask further the existence of a temperature signal

Combined these unique situations provide explanations as to why the existence of any temperature signal might not be detected in Italy but would still exist in Sweden. With the arrival of invasions, epidemics and social disruption, the same provisional services and survival mechanisms which could cope in times of a tranquillity threshold much greater than the rest of Europe, cannot react at their best, producing a grain price hike. This is not to say that every grain price increase is a subsistence crisis. To push the coping mechanisms *over the edge* requires either the most extreme of climatic events (such as the 1817 Year Without Summer) and/or an external factor.

6.4 Limitations

However, the reason could be in our analysis. All trend filters are inherently ad-hoc, determining the trend rather than estimating some prespecified component for the trend. More vitally, they may produce distortions in the filtered data. Take the example of the Kuznets cycle (one of the economic cycles mentioned earlier) was shown even in filtered artificially generated white noise data by Howrey (1968)[49]. There is considerable evidence that the Hodrick-Prescott filter has, in the past, produced spurious dynamic relations among timeseries[77]. The Butterworth filter, in a review of Zhang et al. (2011)[8], was heavily critiqued by Harrison (2015)[78]. Meanwhile, exploring the rate of change has the major caveat that it assumes that markets respond to crises, and stabilize, in a sole year.

Equally the choice of temperature records might not be the most appropriate. Europe can be divided into two temperature zones: North of the Alps, and South of the Alps. Our local alpine temperature record is still on the North-East most section of the Alpine ridge, and as such might be a better proxy for Germany (and Northern Europe), than Italy (and Southern Europe). Meanwhile, the Luterbatcher record for Europe is perhaps overly extensive, given that its latitude range is from 75 to 35° North, ranging from Norway to Sicily. As such, although this is a Northern Hemisphere reconstruction, it is perhaps too much of a Northern reconstruction and not fully representing (especially after taking an average) the situation around the Mediterranean.

Of equal concern is that our temperature timeseries is an average of summer temperatures, which are not truly representative of the entire year. Fortunately, extreme events occurring during the summer period would have the most impact on a plant's productivity[79]. A review by Barlow et al. (2015)[80], exploring extremes of temperature on crops, revealed that excessive heat caused a reduction in grain number and reduced duration of the grain filling period, whilst frost caused sterility and abortion of formed grains. As such, I am only capturing some aspects of temperatures effects on the growth of grain, and more importantly, the temperature records explore averages, whereas in reality it only takes a few days of extreme weather to destroy crops. However, other grain-climate correlation studies used annual averages too.

6.5 Conceptional theory of short-term cycles

So far, I have established that population and silver link to the largest oscillating patterns of grain price, whilst temperature might explain the highest frequency patterns in GP but is not noticeable in Italy in part due to its unique social institutions and due to the greater than average number of catastrophes.

In an economic cycle, expansion is associated with higher prices, as such looking at our timeseries of GP, I would naturally argue that each sustained 'peak' in GP is a period of prosperity. But this is exactly when one finds periods of dense catastrophes. This means that the peaks of GP do not correspond to the boom of economic cycles, but to the increased number of catastrophes. Alternatively, if we accept the fact that wars, social unrest and plagues come about more during times of economic depression than they do in prosperity, then perhaps the times of sustained GP increases are not the times of boom from the economic cycles but the times of recession and depression. This second theory would suggest that economic cycles do exist but the complete reverse (in terms of net prices) than they do today. A conceptional model of these two explanations is given in figure 15.

During times of high grain price, we see periods of intense catastrophes. I propose that these are caused either by the depression occurring in economic cycles, causing periods of instability, or the peak of social instability cycles. As such, these cycles, whether driven by a social or economic logic, play a defining role in deterring GP on the short-term. To sum up, whilst population and silver influx appear to dominate the long-term oscillations, these cycles are superimposed as short-term variations. It has been argued that the interannual variability in GP is controlled by the changing climate, however I find that in the context of Italy such a signal is not apparent. This could be for a multitude of reasons, ranging from its institutions being to the increased number of catastrophes that Italy has been exposed to, and those same catastrophes group themselves in periods of high-and-low density which construct those cycles.

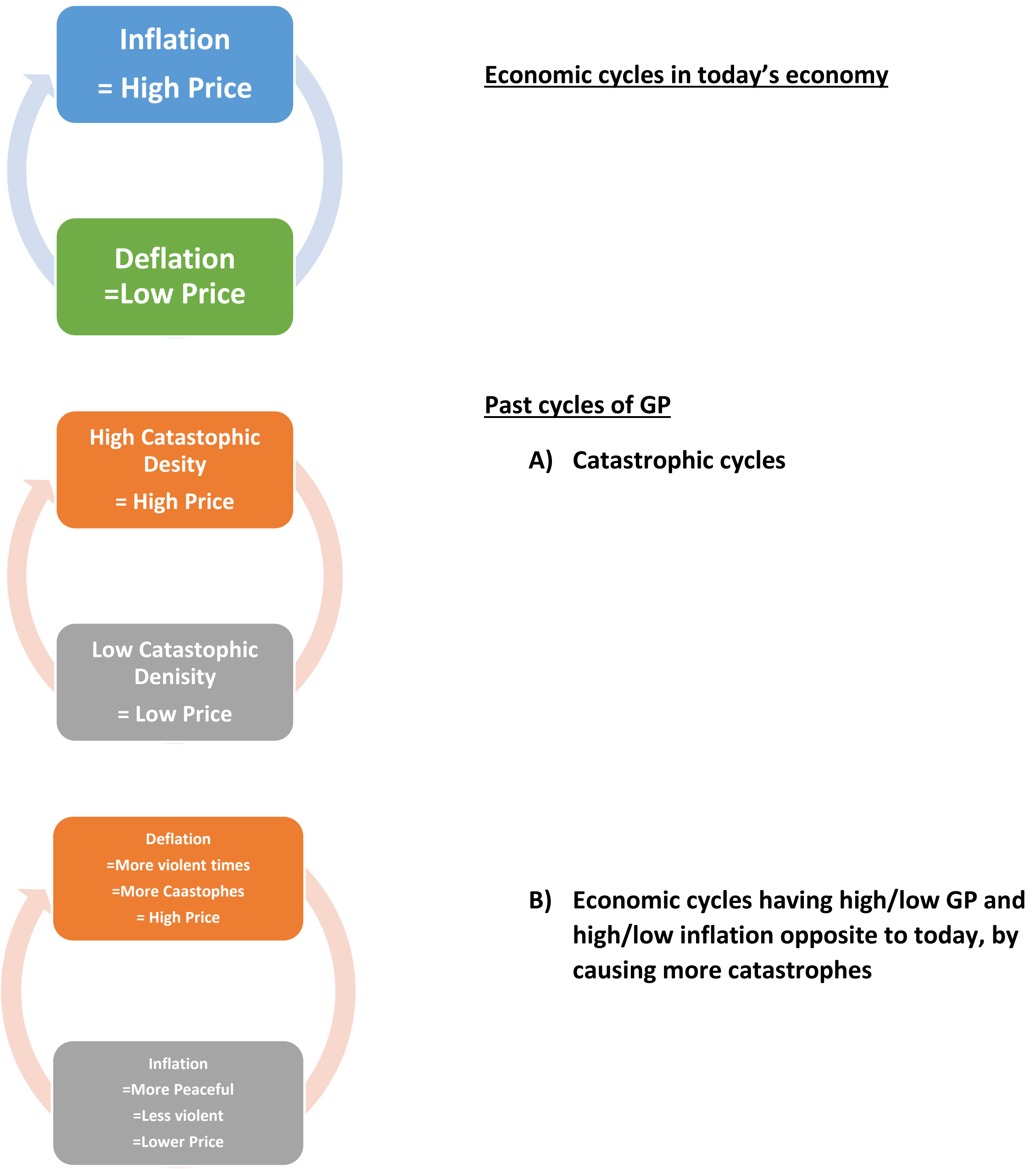


Figure 15: Conceptual model as to what causes the short-term variation that was uncovered in the HHT analysis. Top is the case today periods of High inflation correspond to high prices. Below are two possible explanations, the first using social theory to explain periods of intense catastrophic cycles which would increase the price (A) and the second model describing how economic cycles would cause periods of high and low numbered catastrophe events since periods of economic instability correspond with social stability (B).

7.0 Conclusion

In this thesis, I looked at the factors that affected grain price variation in Italy in the medieval and early-modern periods and have discovered that a multitude of socio-economic factors play a much greater role than interannual climate variability, thus contradicting findings of previous literature. To say as Jan de Vries (1980) once jokingly did that 'Short-term climatic crises stand in relation to economic history as bank robberies to the history of banking'[81] is definitely an extreme view. Even the most extreme of sceptic, would find it hard to argue that climate has never in the past provided a single sustenance crisis, without any societal consequences. However, it is one thing to argue that climate influences GP and another to say it is the dominant factor. Our findings show that grain price is influenced by much more than climate, and probably with the following weighting, at least for Italy:

- Demography:
  - Population levels, both urban and rural, have the strongest correlation with grain price. Population corresponds incredibly well with inflation.
- Silver influx:
  - Referring to the amount of silver entering the world supply via Spain. Unfortunately, without raw data, we can't statistically correlate silver and GP. The inflation and deflation effects are well-recorded and striking.
- Market integration and imperialism:
  - Being strongly integrated with global markets, and not isolationist, has the advantage that self-produced goods can be exchanged for those needed, in a crisis. However, it increases vulnerability to global catastrophes, that Italy itself is not directly involved in (for example, the 30-Years War and the consequential taxation).
- Epidemics:
  - Although in the short-term, the effects are apparent, with the decimation of a generation's agricultural and industrial populace, in the long-term, demographic effects truly reflect the effects of plagues.
- War:
  - War has both the short-term demographic consequences from mortality, but, more crucially, war is expensive, and results in either bankruptcy or heavy taxation, neither being good for the economy in the long run. War also causes the loss of infrastructure, as well as logistical disruption.
- Social unrest:
  - Social unrest follows the same pattern as war, except it often also involves political reform, which might change market policies (such as free-trade areas).
- Weather:
  - Weather can destroy crops and thus reduce the production. The lack of supply can cause a sustenance crisis.

Of course, weather is subtly different from climate. We saw the strong correlations between the raw GP and temperature records showing briefly the correlation between good and bad climates with 'golden' and 'dark' aspects of European history. For Italy, weather seems to play a weak role in determining grain price variations, but the relationship is apparent in Sweden. This is probably due to the increased global markets that Italy is subject to, better provisioning services, and a wider choice of crops to fall back on. This is also why we see a fractionally stronger correlation with the Luterbatcher reconstruction, as this captures the global market crises, as opposed to the more local alpine temperature reconstruction.

When starting this thesis, we were aware that economic cycles might be playing a role in causing periods of economic boom and crash. However, having reviewed the evidence that all peaks of grain price correspond to periods of catastrophe, we conclude that: either a) social cycles are instead dominant, or b) the role of economic cycles is reverse to that of modern periods, meaning that times of depression have higher prices, probably due to the increased periods of catastrophes. Lastly, we see a changing role in factors over time. The effects of plague weakened at the end of the 16th century, as they became less and less frequent. The frequency of social unrests has gradually decreased over the centuries and so, too, has war, although it should be remembered that the intensity and global effects have increased.

7.1 Need for Further Study:

There is definitely a need for further study, as there are only a few studies that look at past grain markets. Only a few of these look at climate, and fewer still look at the presence of economic or social cycles in the past. Lastly, a greater focus needs to be placed on interdisciplinary studies. There is a tendency to focus on just one mechanism behind the varying strength of an economy (nominally climate or population), and no focus has been put on the relative weighting of these factors, and how relative contributions have changed over time. Moreover, either things are focused on a short-length study (decadal) for a single region or average huge regions on a multi-centennial regime. I highlight instead the need for more holistic studies, capturing smaller regions over longer periods. I hope this thesis raises and partially addresses these concerns, sufficiently establishing the multi-factor influence in GP, and hope that future studies can be carried out, especially outside the niche of Western Europe.

To view all code and links to the raw data, please see the following link or scan the QR code:

https://drive.google.com/drive/folders/1vnqg-P5h41N8IvLjJEmHxsG7WuXrpaY-?usp=sharing

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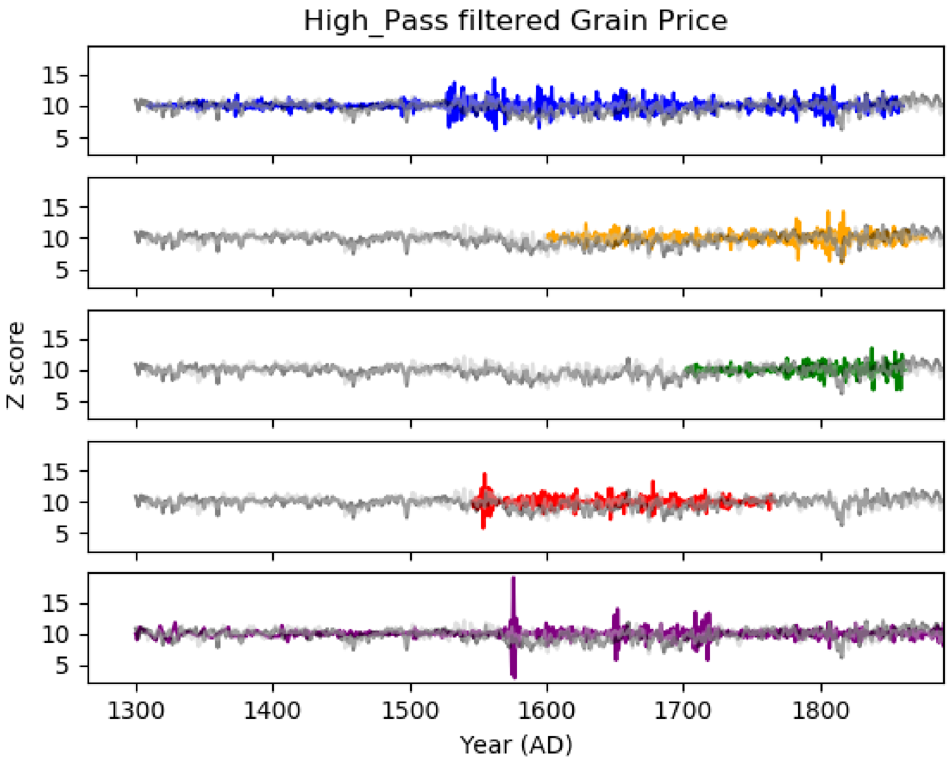
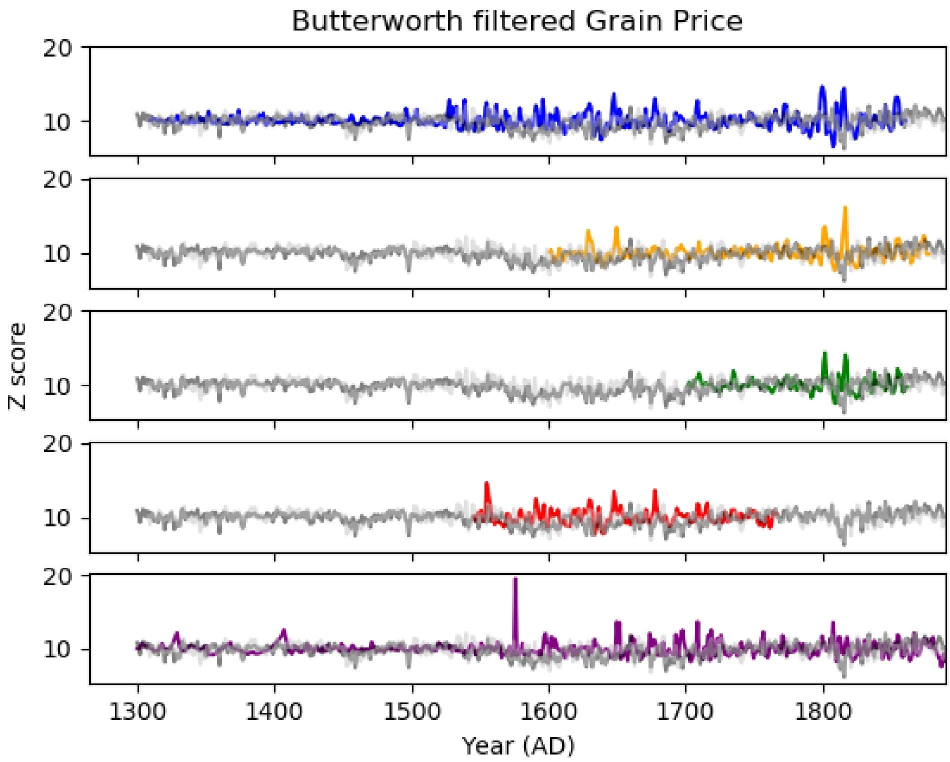
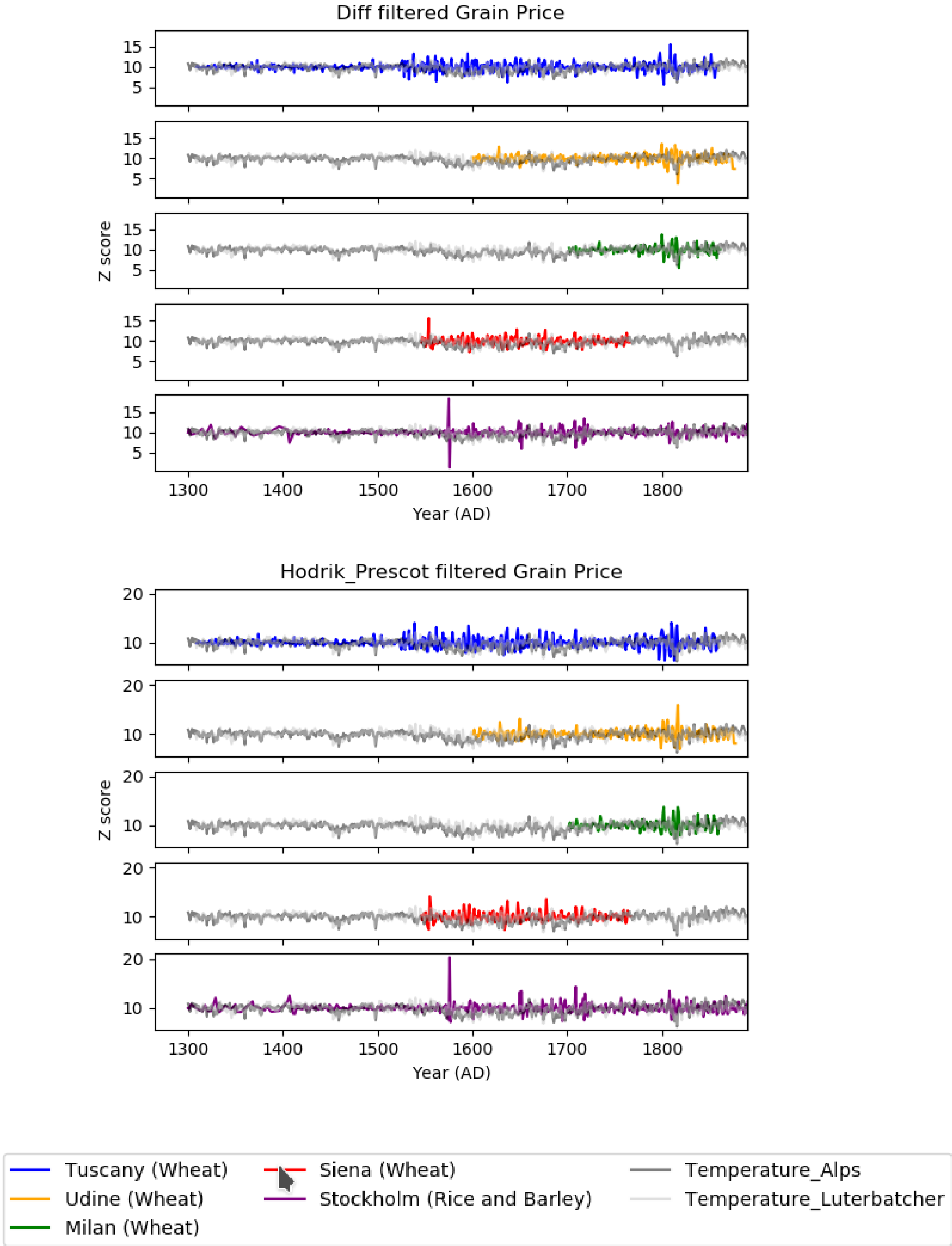
9.0 Appendix

Appendix 1: Timeseries of Grain Price Data

Plot of Standardised GP, and the De-trended GP for all cities reviewed. Results were given a Z-score (+10) and plotting against the year of sales. (Legend below)



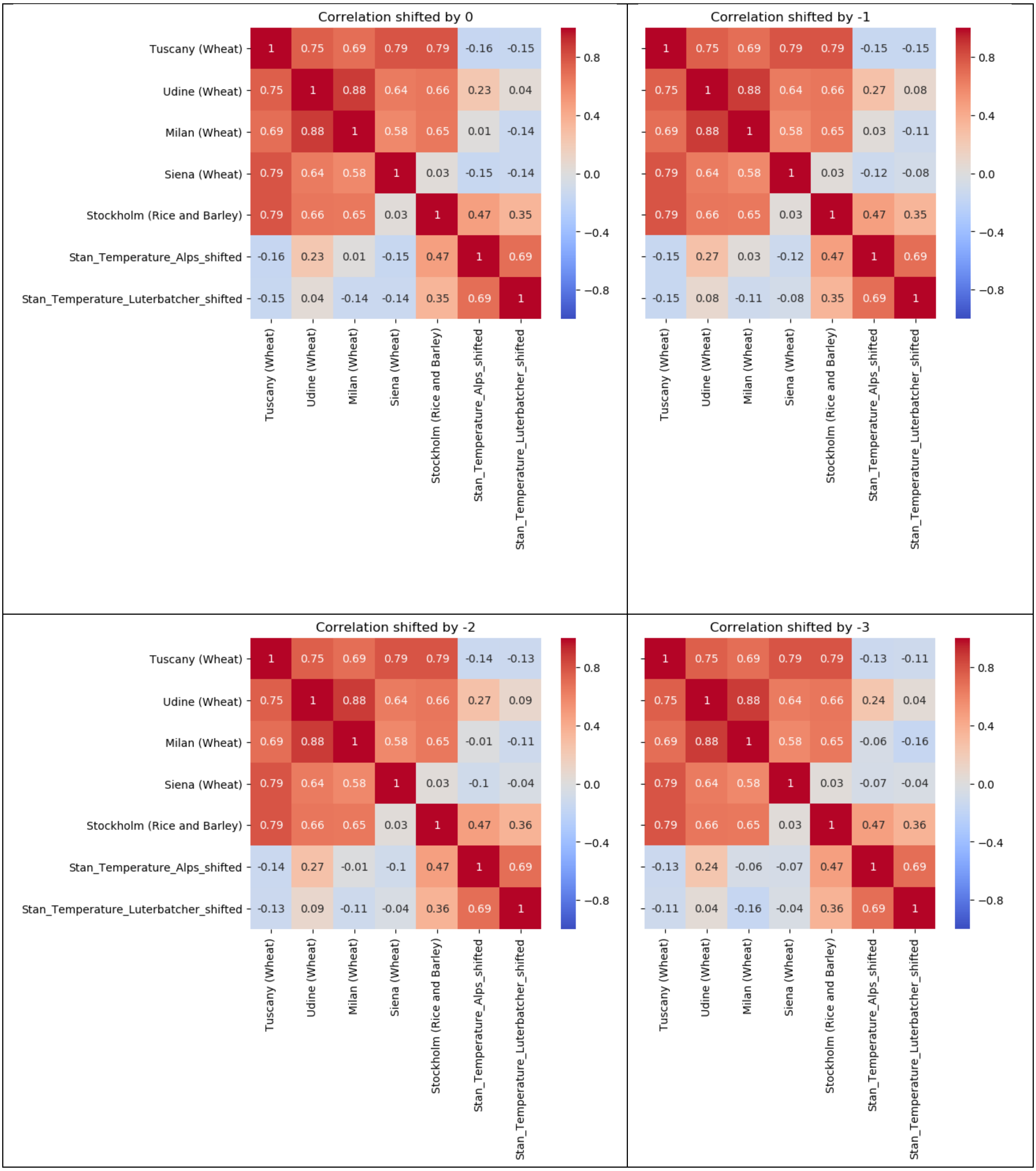



Diff filtered Grain Price
Z score
Year (AD)
Hodrik_Prescot filtered Grain Price
Z score
Year (AD)
Tuscany (Wheat)
Udine (Wheat)
Milan (Wheat)
Siena (Wheat)
Stockholm (Rice and Barley)
Temperature_Alps
Temperature_Luterbatcher

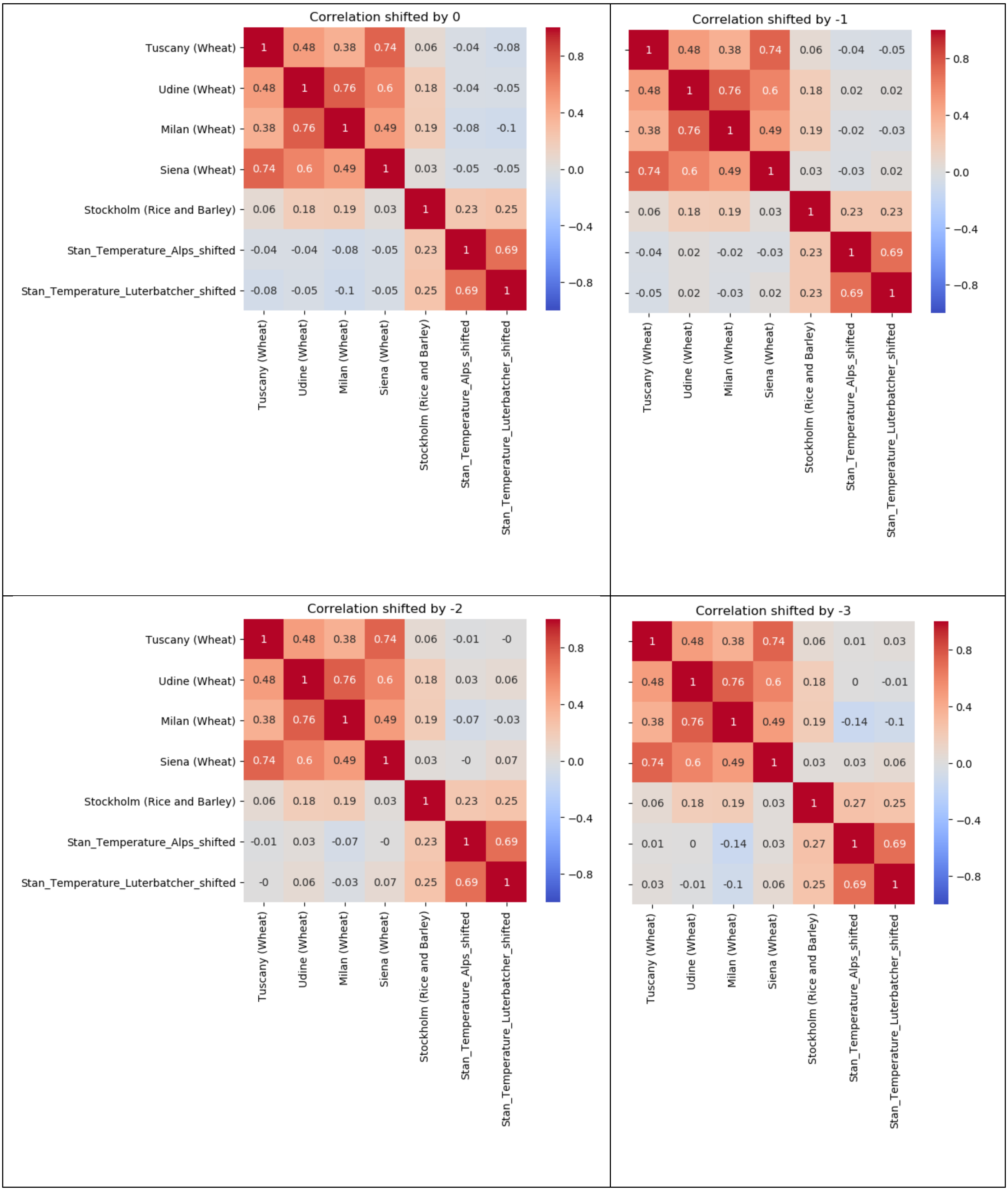
Appendix 2: Correlations with GP:

Below are correlation plots between GP records and temperature, with a lag (donated in title, -1 indicated the temperature was shifted one year forward from the year of sales). Color corresponds to correlation coefficient and the pre-fix (Stan) means temperature was not filtered)

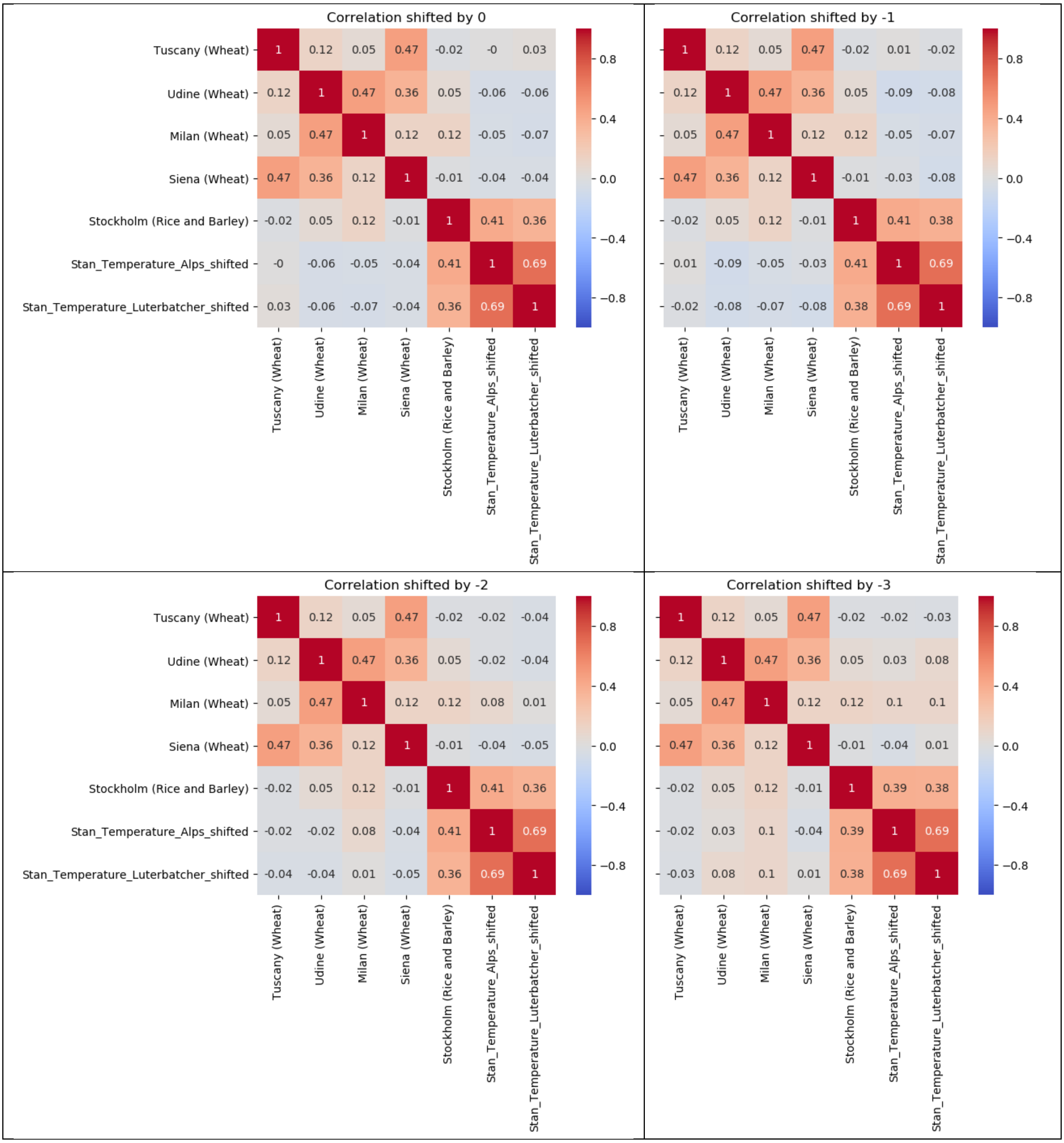
Standardised



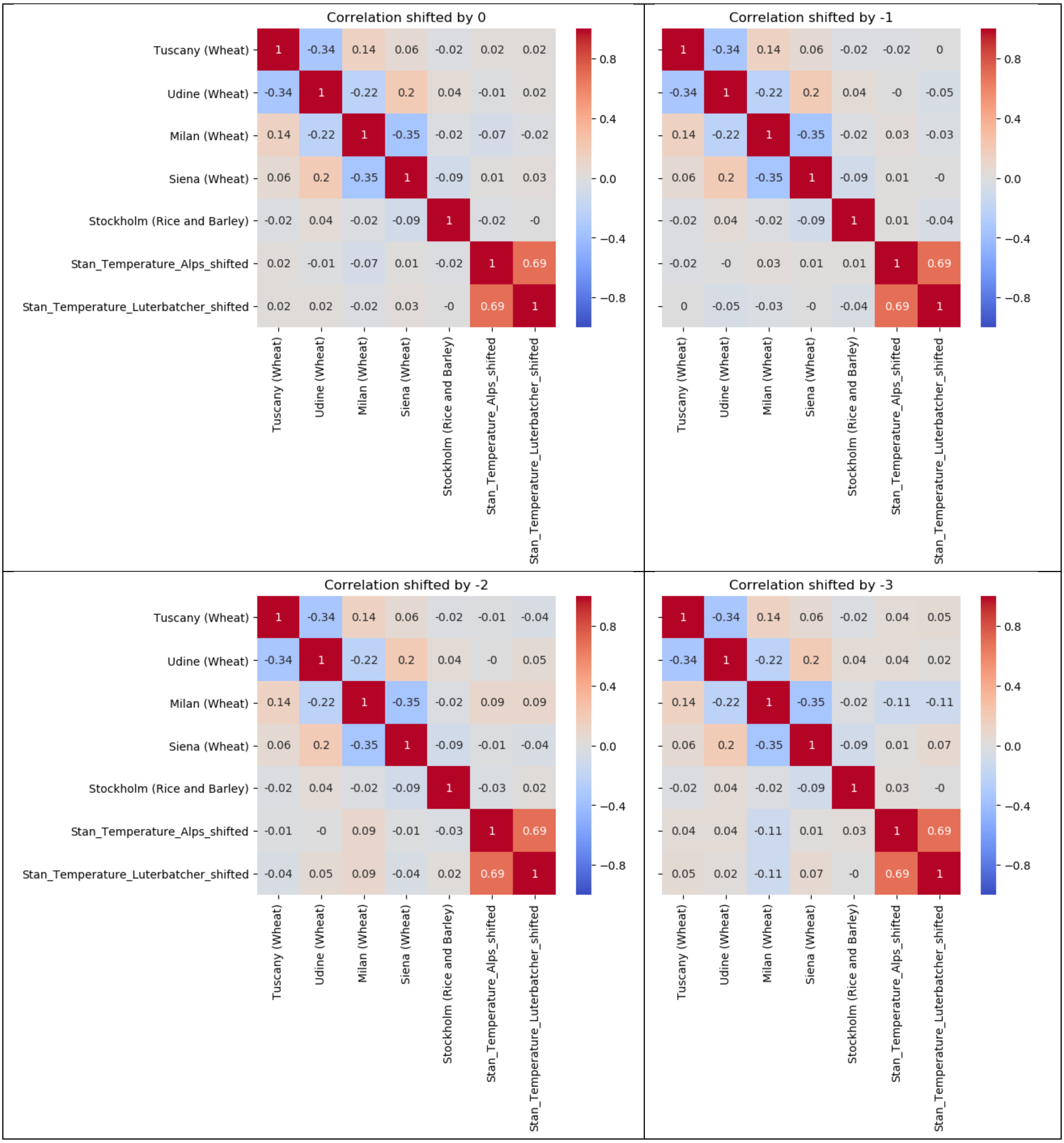
Butterworth Filter



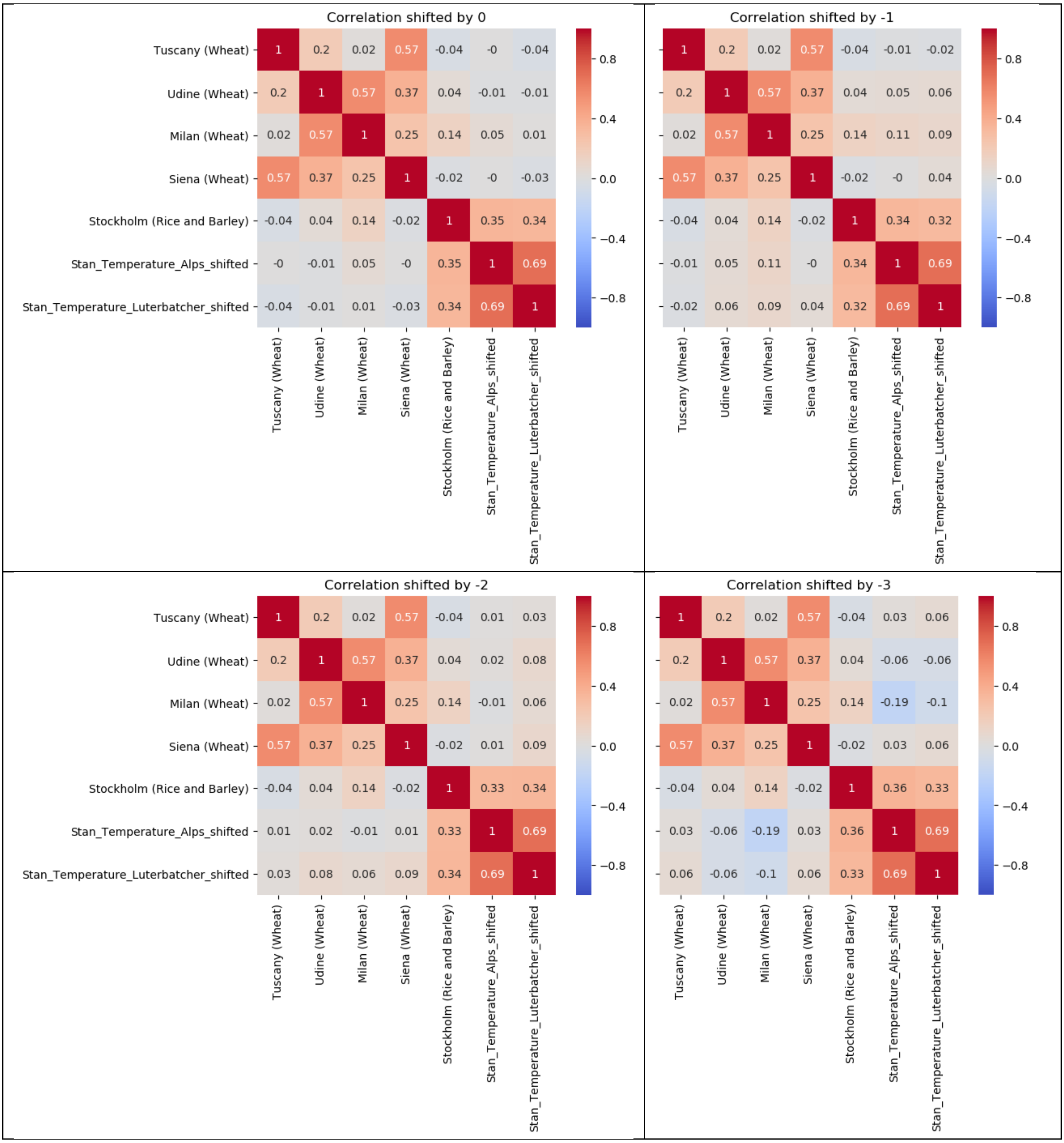
Differences



High Pass


Correlation shifted by 0
Correlation shifted by -1
Correlation shifted by -2
Correlation shifted by -3
Tuscany (Wheat)
Udine (Wheat)
Milan (Wheat)
Siena (Wheat)
Stockholm (Rice and Barley)
Stan_Temperature_Alps_shifted
Stan_Temperature_Luterbatcher_shifted

Hodrick-Prescott



Appendix 3: Granger Causality

Granger causality analysis for each GP record, and with detrending.

Filter	Causal Linkage (Null Hypothesis)	Statistic	Critical Value	P value	Conclusion
Butterworth Filter					
	Alpine Temperature Reconstruction does not Granger-Cause Tuscany GP	0.94	3.85	0.33	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Tuscany GP	4.07	3.85	0.04	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Udine GP	0.31	3.85	0.58	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Udine GP	1.01	3.85	0.32	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Milan GP	0.98	3.86	0.32	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Milan GP	0.71	3.86	0.40	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Siena GP	1.06	3.86	0.30	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Siena GP	2.00	3.86	0.16	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Stockholm GP	2.93	3.85	0.09	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Stockholm GP	3.01	3.85	0.08	Fail to Reject
Diffences					
	Alpine Temperature Reconstruction does not Granger-Cause Tuscany GP	1.16	3.85	0.28	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Tuscany GP	0.57	3.85	0.45	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Udine GP	0.19	3.85	0.66	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Udine GP	2.36	3.85	0.12	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Milan GP	4.50	3.86	0.03	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Milan GP	1.11	3.86	0.29	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Siena GP	0.00	3.86	0.98	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Siena GP	0.01	3.86	0.91	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Stockholm GP	6.53	3.85	0.01*	Reject

	Luterbatcher Temperature Reconstruction does not Granger-Cause Stockholm GP	0.41	3.85	0.52	Fail to Reject
High Pass					
	Alpine Temperature Reconstruction does not Granger-Cause Tuscany GP	0.69	3.85	0.41	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Tuscany GP	0.02	3.85	0.88	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Udine GP	0.91	3.85	0.34	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Udine GP	5.33	3.85	0.02	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Milan GP	0.17	3.86	0.68	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Milan GP	0.09	3.86	0.76	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Siena GP	0.96	3.86	0.33	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Siena GP	2.16	3.86	0.14	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Stockholm GP	2.75	0.34	0.10	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Stockholm GP	0.34	0.34	0.56	Fail to Reject
Hodrick-Prescott					
	Alpine Temperature Reconstruction does not Granger-Cause Tuscany GP	0.78	3.85	0.38	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Tuscany GP	4.94	3.85	0.03	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Udine GP	0.78	3.85	0.38	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Udine GP	1.69	3.85	0.19	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Milan GP	2.31	3.86	0.13	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Milan GP	0.91	3.86	0.34	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Siena GP	0.97	3.86	0.32	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Siena GP	2.58	3.86	0.11	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Stockholm GP	6.68	3.85	0.01‡	Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Stockholm GP	3.97	3.85	0.05*	Reject
Standardised					

	Alpine Temperature Reconstruction does not Granger-Cause Tuscany GP	0.05	3.85	0.82	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Tuscany GP	5.24	3.85	0.02*	Reject
	Alpine Temperature Reconstruction does not Granger-Cause Udine GP	0.09	3.85	0.77	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Udine GP	0.02	3.85	0.87	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Milan GP	0.81	3.86	0.37	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Milan GP	1.09	3.86	0.30	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Siena GP	0.50	3.86	0.48	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Siena GP	2.52	3.86	0.11	Fail to Reject
	Alpine Temperature Reconstruction does not Granger-Cause Stockholm GP	1.69	3.85	0.19	Fail to Reject
	Luterbatcher Temperature Reconstruction does not Granger-Cause Stockholm GP	0.15	3.85	0.70	Fail to Reject

*Significant at 0.05 level (2-tailed) (P<0.05)

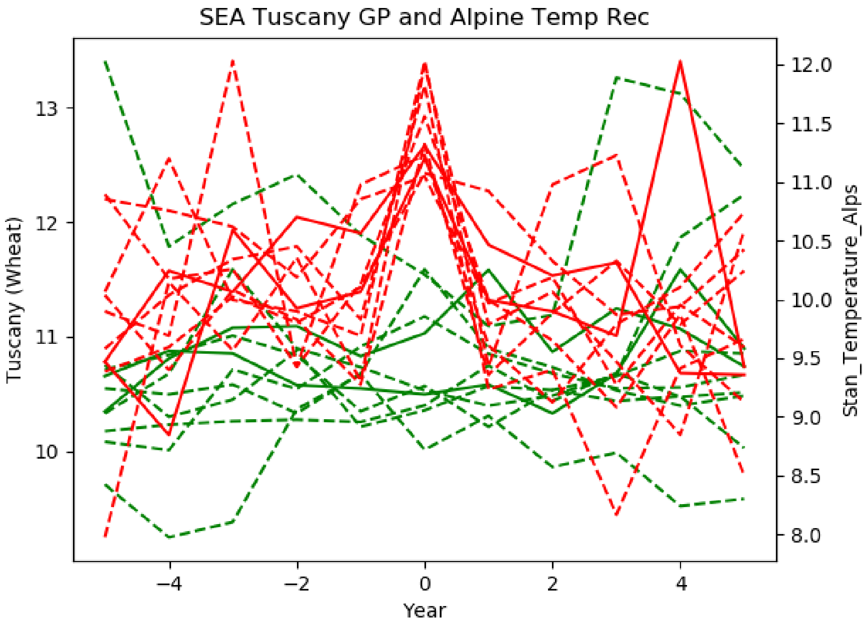
ɨ Significant at 0.01 level (2-tailed) (P <0.01)

Appendix 4: Superposed Epoch Analysis (SEA)

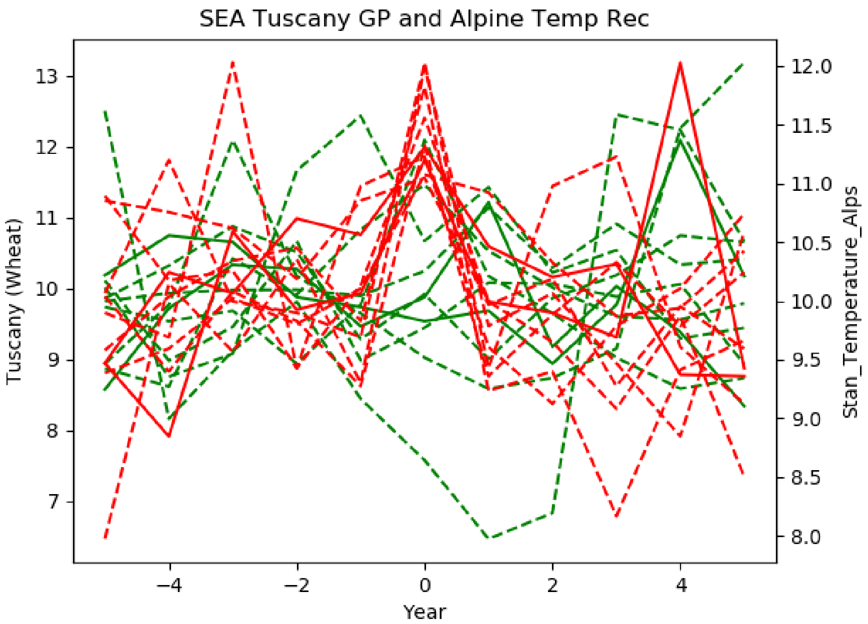
Superposed Epoch Analysis for the Tuscany GP record, showing the temperature peak (red, right axis) and how the price of grain responds (green, left axis). By superimposing the response, we can see if there is a common reaction in which case the argument would be that the two events are linked Dashed lines represent a period, within the subset, that contains war. Meanwhile, solid lines mean throughout the series there was periods of peace.

Alpine Temperature Reconstruction

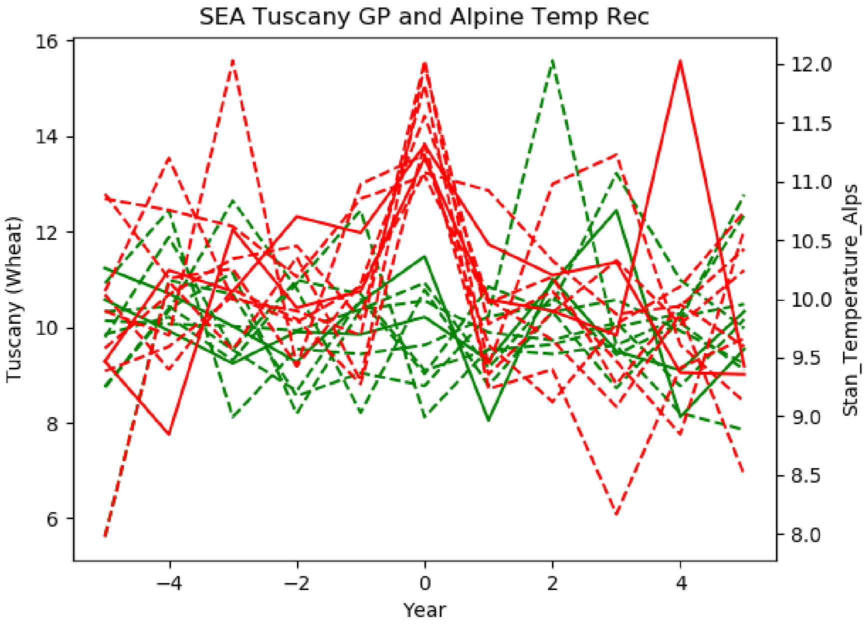
Standardised



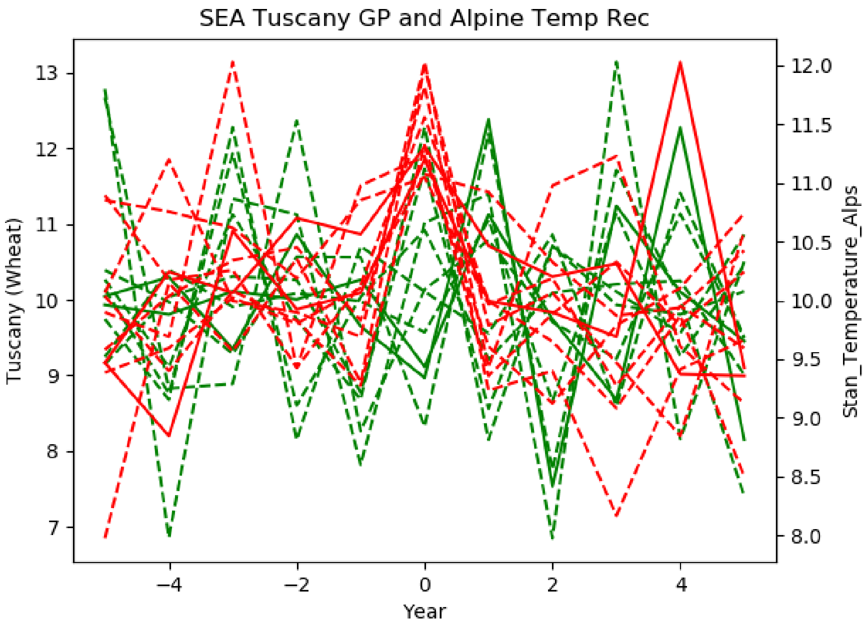
Butterworth



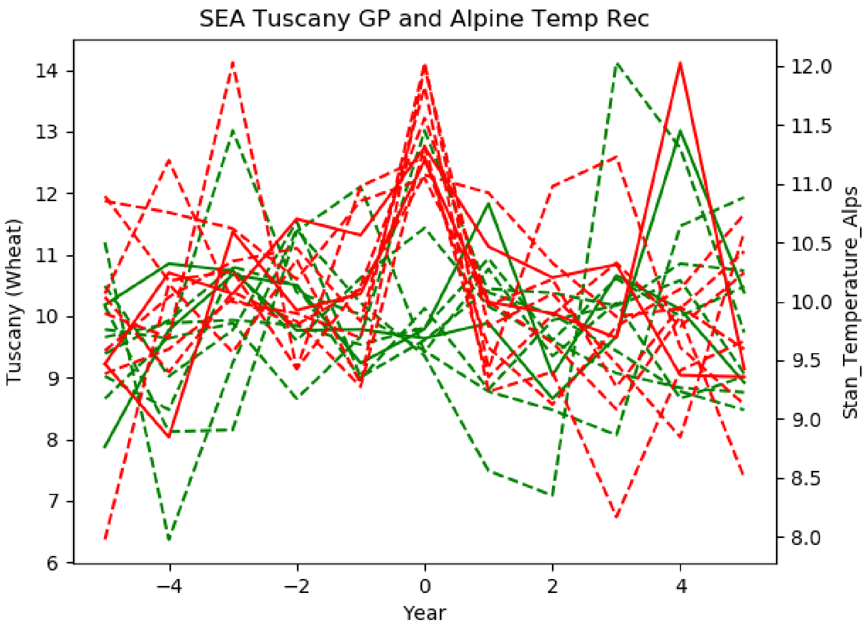
Differences



High Pass

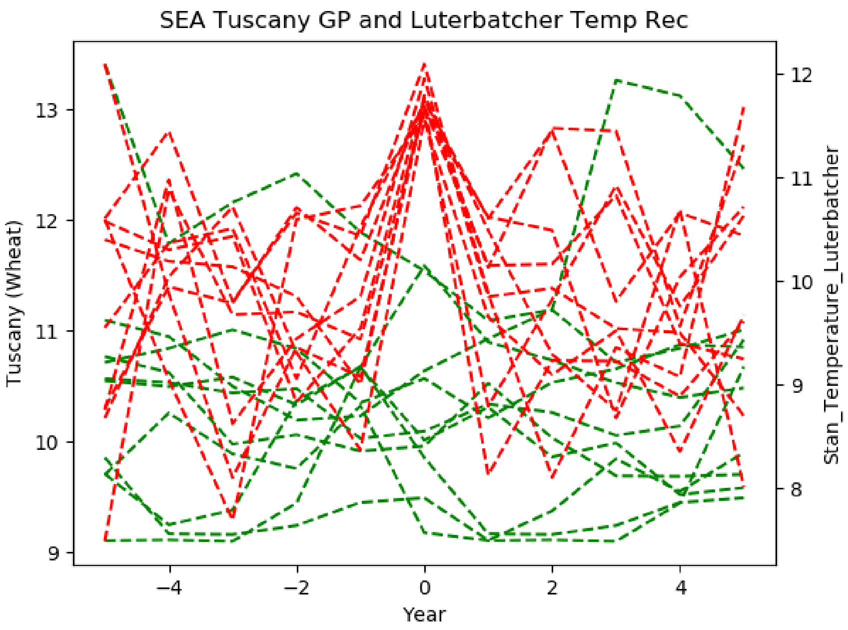


Hodrick-Prescott

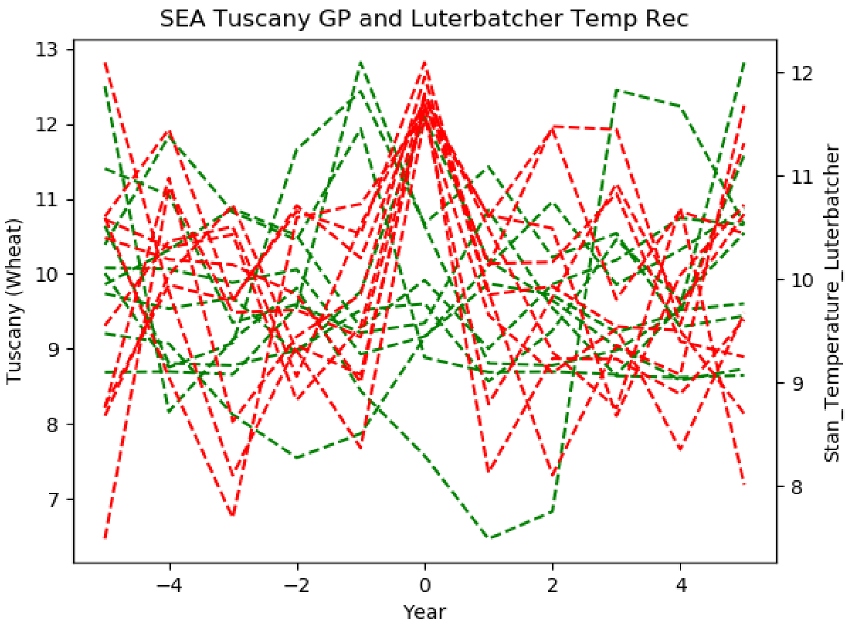


Luterbatcher Temperature Reconstruction

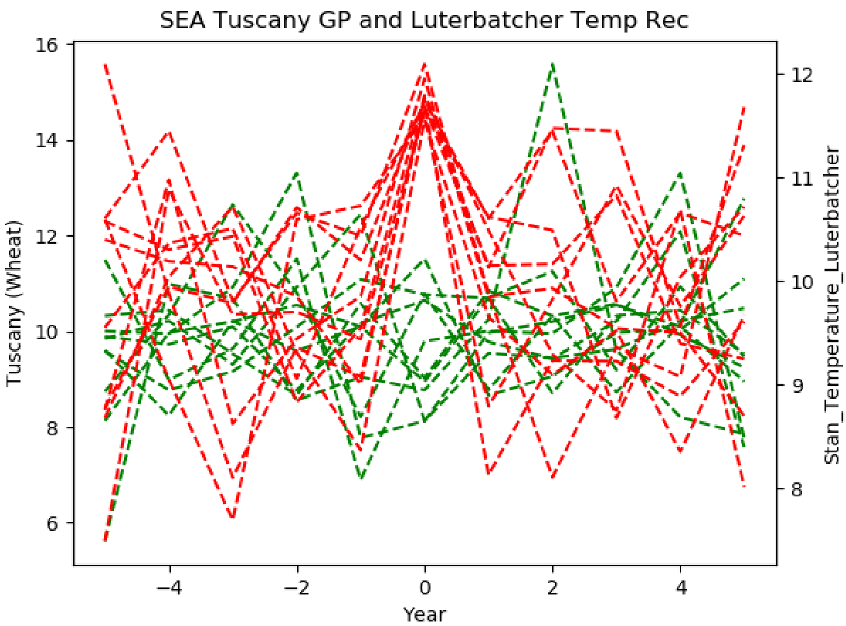
Standardised



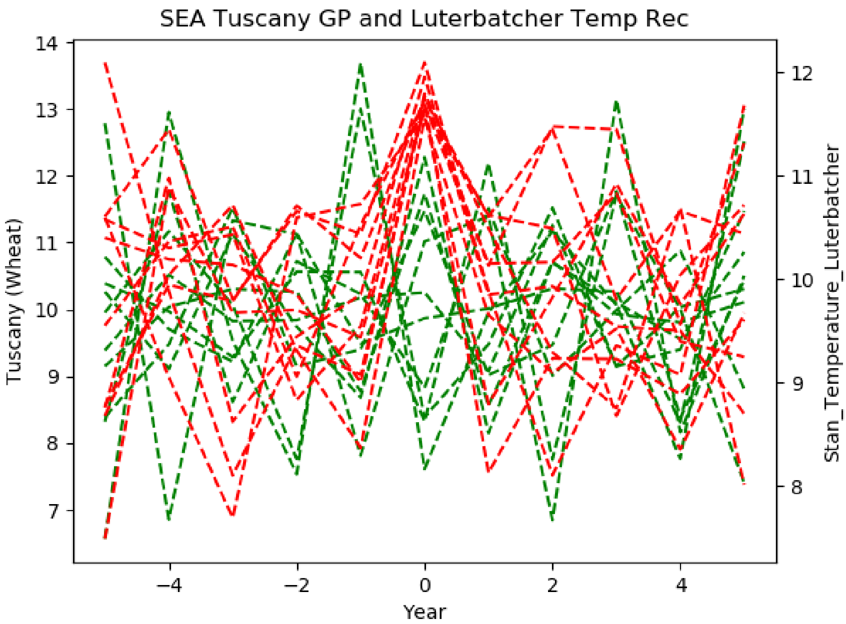
Butterworth



Differences



High Pass



Hodrick-Prescott